Verification of PyDHN - a Python library for the thermo-hydraulic simulation of district heating networks - through the DESTEST

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Abstract

Due to the scarce availability of monitoring data and, when available, possible confidentiality issues, inter-model comparisons are a valuable way to verify the consistency of results in simulations of District Heating Networks (DHN).

This paper presents the verification of PyDHN through the DESTEST, a benchmark test developed as part of IBPSA project 1, currently providing comparison with six other DHN models.

We conducted two network exercises (CE0 and CE1) out of the four included or planned in the test and suitable for our tool. The results for the steady-state exercise (CE0) show an accuracy of 84.77%. To simulate the thermal transient exercise (CE1), a simple quasi-dynamic pipe model is developed as a custom component. As the results of only one alternative model,are currently available for CE1, we show a good agreement between the results of the two models on most indicators with an average absolute NMBE of 17%.

Highlights

- PyDHN is tested against exercises CE0 (static) and CE1 (dynamic) of the DESTEST
- A steady-state model (CE0) and a quasi-dynamic model (CE0 and CE1) are used
- Results of CE0 show an accuracy of 84.77% using the steady-state model
- Results of CE1 show a good agreement (17% NMBE) with the available comparable results for most KPIs

Introduction

District Heating Networks (DHNs) constitute an efficient technology to distribute heating energy at the urban scale, and are regarded as one of the potential solutions to reduce the carbon footprint of space and water heating. Most existing DHNs are designed and operated experimentally, using for instance simple rule-based approaches that leave significant room for improvement (Jansen et al., 2023). Since monitoring data at high-granularity of the piping network for data-driven models is hardly available, most studies in this direction rely on comprehensive thermo-hydraulic simulations to develop and evaluate different solutions. However, most existing simulation tools are either closed-source or not flexible enough for research purposes (Kudela et al., 2020). In some cases, DHN models are available as part of larger simulation tools addressing different aspects of urban energy systems such as building thermal demand, at the expense of a larger set of required inputs. To address this gap, the authors have recently introduced PyDHN, a novel Python library for thermo-hydraulic simulation of meshed DHNs. The tool specifically addresses DHN modeling and supports the creation of reproducible simulation workflows, possibly with custom test components, and is openly available to both researchers and practitioners. Furthermore, while most existing tools for the simulation of DHNs use a variation of the node method for the hydraulic part, PyDHN is based on the loop method, which is generally faster and has more stable convergence properties (Osiadacz and Pienkosz, 1988). In particular, we introduced a modified version of the method that uses user-defined set-points to reduce the computational complexity and the inputs of the hydraulic simulation, while also allowing the user to impose fixed operational parameters and introduce more complex models.

The aim of this paper is to verify the results of PyDHN against the DESTEST, a benchmark test for District Energy Systems models recently developed as part of IBPSA Project 1 (Saelens et al., 2019), as part of a more comprehensive validation procedure of the tool, which is the object of further publications. In particular, the ability of the tool and underlying models to carry out both steady-state and dynamic simulation is investigated.

Existing libraries

While not included in the DESTEST, several other simulation tools have been recently introduced as Python libraries. Among these, DHNx (Röder et al., 2021) supports the simulation and optimization of

DHNs, however it is currently limited to networks with radial topology. This limitation can be overcome by using aggregation techniques to reduce the topology to an equivalent radial network, at the cost of accuracy and information loss. Pandapipes (Lohmeier et al., 2020) is a tool for steady-state simulations of multi energy grids with a focus on gas and water networks, including meshed DHNs. The main advantages of Pandapipes are the possibility of coupling DHN and power simulations, as well as a more accurate modelling of fluid properties. However, both Pandapipes and DHNx do not support a bottom-up approach through custom components and have currently not implemented the possibility of running dynamic simulations, which are particularly relevant for short-term planning. Furthermore, they both rely on user-defined heat transfer coefficients for thermal calculations. Finally, DiGriPy (Vorspel and Bücker, 2021) is a simulation tool based on the TESPy framework (Witte and Tuschy, 2020). The simulation requires few basic data and is therefore suitable for early design stages or simplified simulations. While these tools, together, cover several practical use-cases, an open-source library that has a bottom-up structure, supports both steady-state and dynamic simulation and is flexible enough to be used at different design stages is still missing. PyDHN was developed to fill this gap, and this work will investigate its suitability for this scope.

Methods

The verification follows the guidelines from the DESTEST documentation (De Jaeger et al., 2022) as from the latest update (2022-03-02), and evaluates several KPIs related to temperature, pressure and energy losses in a simple radial network. The application is limited here to the two common exercises (CE0 and CE1) related to DHNs, as the exercises on building performance simulations are not applicable to PyDHN. Since a detailed ground model is not included in the current release of the library, the application of CE2 is also not included. The results presented here include the comparison with the results of five DHN models, of which three obtained with Modelica Buildings Library (Wetter et al., 2014), one with SIM-VICUS (Hirsch and Nicolai, 2022) and two with TRNSYS (University of Wisconsin–Madison. Solar Energy Laboratory, 1975). For CE1, only the results of one study conducted with the Modelica Buildings Library is currently available. The evaluation metric (KPI, as for Key Performance Indicator, in the DESTEST terminology) used for the comparison is the default one proposed by the DESTEST, that is the Normalized Mean Bias Error (NMBE). The physical indicators on which the NMBE is calculated are the ones proposed by the exercises and will be detailed in the following sections.

The software library is mainly intended for steady-state simulations. We argue in fact that steady-state models provide a sufficiently high degree of accuracy, especially for typical temporal granularities of hours for which dynamic simulations would not provide significant added value for most applications and medium-sized networks. As such, the steady-state models are extensively presented in another paper (redacted preprint, 2023) including a first verification of the results using the DESTEST Common Exercise 0, as well as other verifications with experimental data.

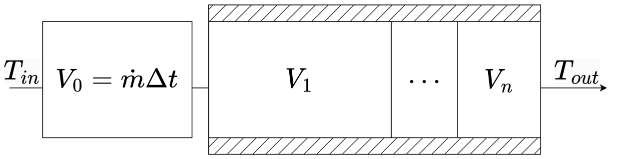

Figure 1: Schema of the pipe discretization in small volumes.

This paper provides instead insights on a quasi-dynamic model that is intended for essentially dynamic problems as the one proposed by the CE1. For the sake of completeness and in addition to CE1, both the steady-state and quasi-dynamic models will be applied to CE0, so as to discuss the advantages and inconveniences of the two models in a static setting.

Quasi-dynamic pipe model

The present work expands the network model presented in (redacted preprint, 2023). While this section focuses on the new implementations, the reader can refer to the original work for a detailed description of the main models used in the software, whereas a brief summary is given here below.

The DHN is divided into several components for which a function ϕ linking the pressure change Δp (Pa) and the mass flow $\dot{m}$ (kg/s) and a function ψ computing the outlet temperature T_{out} (°C) as a function of the inlet temperature T_{in} (°C) need to be specified. The simulation is then carried out using a decoupled approach based on the loop method for the hydraulic part and on the node method for the heat transfer. This work introduces a custom quasi-dynamic pipe component that considers the displacement of water volumes, as well as the thermal inertia of the system. Due to the pressure waves' speed being comparable to that of sound, the hydraulic part is solved with the same steady-state model described in the original work. For the thermal part, the pipe at time step t is schematized as a series of n volumes of water $V_i, i = 1, ..., n$ (m^3) with density ρ_i, ($\mathrm{kg/m}^3$) and specific heat capacity $c_{p,i}$ (J/(kg · K)), having a temperature T_i (°C). Within a step size Δt, a new volume of water $V_0 = \frac{\dot{m} \cdot \Delta t}{\rho_0}$ (m^3) enters the pipe and pushes the existing volumes in the direction of the flow (see Figure 1).

The heat losses are then computed for each volume separately using a two-node thermal network model similar to the one-capacity model presented by Dénarié et al. (2019). The water node is connected the corresponding segment of the internal pipe of volume $V_{p,i}$, which has uniform temperature T_p and exchanges heat with the ground, with temperature T_g (°C), through the insulation layer and the pipe casing. The system of equations to be solved for each volume is then:

$$0 = \frac{T_i - T_p}{R_p}\Delta x_i + C_i \frac{dT_i}{dt} \tag{1}$$

$$\frac{T_i - T_p}{R_p}\Delta x_i = \frac{T_p - T_g}{R_{ins}}\Delta x_i + C_{p,i}\frac{dT_p}{dt} \tag{2}$$

Here R_p (K·m/W) is the linear thermal resistance between the water and the internal pipe, computed as the sum of contributions from the internal convection and the pipe layer and R_{ins} (K·m/W) is the linear thermal resistance of the remaining pipe layers and the ground, as given in (redacted preprint, 2023). Δx_i (m) is the length of the considered pipe segment, C_i the heat capacity of the water volume and $C_{p,i}$ the heat capacity of the pipe segment. Deriving T_p from (1) as:

$$T_p = T_i + \frac{C_i R_p}{\Delta x_i}\frac{dT_i}{dt} \tag{3}$$

and substituting (3) into (2), a second order linear differential equation for the temperature of the volume of water is obtained and solved by imposing the boundary conditions $T_i(t - \Delta t) = T_{i,t-\Delta t}$ and $T_i(\infty) = T_g$.

After computing the new temperatures for all water volumes, the outlet temperature of the pipe is calculated as the weighted average of the temperatures of the m volumes leaving the pipe:

$$T_{out} = \frac{\sum_{i=0}^{m} V_i T_i}{\sum_{i=0}^{m} V_i} \tag{4}$$

Similarly, the new pipe wall temperature is then estimated as the weighted sum of all segments:

$$T_p = \frac{\sum_{i=0}^{n} V_{p,i}(T_{i+1} + \frac{C_i R_p}{\Delta x_{i+1}\Delta t}\Delta T_{i+1})}{\sum_{i=0}^{n} V_{p,i}} \tag{5}$$

The heat loss can be finally evaluated as the sum of losses over the $n+1$ volume elements:

$$\dot{Q} = \sum_{i=0}^{n+1} V_i c_{p,i} \rho_i \Delta T_i \tag{6}$$

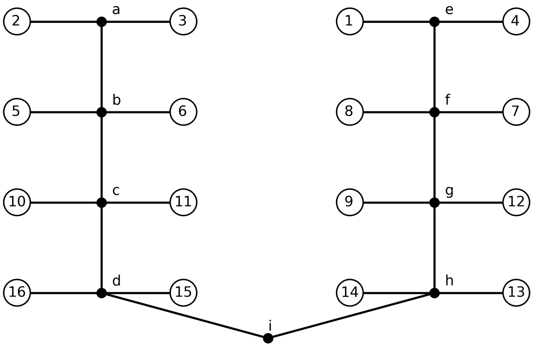

Figure 2: Layout of the radial network used in the DESTEST. The node i is the source node, while the consumers are the numbered circles.

With $\Delta T_i = (T_i(t) - T_i(t - \Delta t))$ (K). In order to take into account the fact that some volumes are leaving a pipe within the considered time step, the actual transport time $\Delta t'$ is used in the previous calculation as step size:

$$\Delta t'_i = min\left(\Delta t, \frac{L - x_i}{v}\right) \tag{7}$$

Where L (m) is the total length of the pipe and x (m) is the initial distance of the center of the volume from the pipe entrance. For the incoming volume, the transport time is then computed as half of the chosen time step.

Network Common Exercise 0

The first Common Exercise (CE0) relates to the steady-state simulation of a simple radial network with 16 consumers and one producer (Figure 2). The network is perfectly symmetrical and pipes in the supply and return lines share the same characteristics.

A single scenario is considered where the same mass flow of 553 kg/h is imposed to all consumers, as well as a fixed temperature difference of 30 K at all substations. The heat source and the heat exchangers are considered ideal, and the specified boundary conditions are always met with no secondary effects. Heat losses to the ground are not includeded in the test, whereas the outer surface of the pipe insulation is considered to have a fixed temperature of 10°C. The water has constant properties taken at 50°C. More detailed specifications are given in (De Jaeger et al., 2022).

The verification is conducted by comparing the simulation results with those of other reference tools on different physical indicators and against a reference value computed as the average between the reference tools. At present, the tools included in the benchmark are the Modelica buildings library, TRNSYS and SIM-VICUS.

The physical indicators included are related to mass

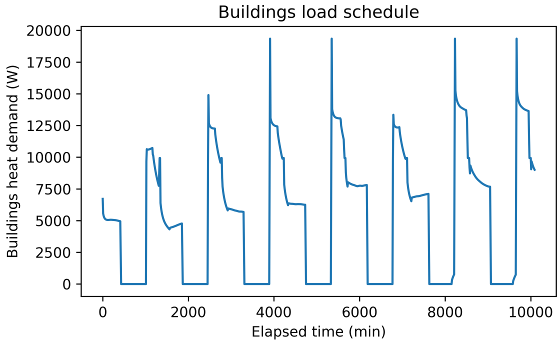

Figure 3: Common demand profile of all buildings for CE1.

flow (kg/h), pressure drop (Pa), fluid temperature (°C), heat loss (W) and total heat load (W) in eighteen different locations of the supply and return lines. By default, the Normalized Mean Bias Error (NMBE) is used as KPI, although for CE0 the results are single values and not time series.

The verification on CE0 was carried out for both the steady-state and the quasi-dynamic model. A cold start was assumed for the quasi-dynamic model with temperatures equal to those imposed to the outer surface of the pipe as boundary condition (10°C). The simulation of one hour with time steps of one minute was then considered, and the results averaged over the whole hour.

Network Common Exercise 1

The Common Exercise 1 (CE1) extends CE0 by providing load schedules for the connected buildings with updates every 10 minutes. A single profile for all 16 buildings is given, following a cyclic pattern with time steps of zero demand (Figure 3).

The simulation is run for 7 days, considering time steps of 10 seconds, and the results evaluated at each 15-minute interval. The main simplifications introduced in the previous common exercise are used also in CE1, including the boundary conditions and ideal characteristics of source and consumer nodes. All specified set-point temperatures, loads and mass flows are assumed to be exactly met, without limitation of power, differential pressure or flow rate. Only a lower limit of 28°C on the outlet temperature of substations is introduced in this exercise, to prevent implausible temperatures to be injected in the return network, even though the temperature drop in pipes with null mass flow is still considered. In order to prevent arbitrarily chosen initial conditions to affect the result of the first time step, a preconditioning period of one hour was run using the initial load profile.

The results are compared with the available reference data, which currently includes only one study using the Modelica buildings library. Of the 9 KPIs included on the verification for CE1, the pressure loss at consumer 1 is currently not available in the reference data, and is therefore not used for the comparison. The NMBE is again used as the main metric for the comparison, whereas it should be noted that the reference values are simply the results of one single tool, and should not be then intended as a DESTEST reference value, which is normally the average of multiple tools.

Results

We present here the results of the two exercises using both the steady-state model and quasi-dynamic model for CE0 and only the quasi-dynamic model for CE1.

Network Common Exercise 0

Preliminary results on the first common exercise, consisting of the steady-state simulation of a given DHN, show that all the considered KPIs are within the upper and lower bounds of the reference tools. The list of errors for all KPIs is given in Table 1.

Table 1: Results of the quasi-dynamic ($NMBE_1$) and steady-state ($NMBE_2$) models on CE0.

KPI	Node(s)	$\mathbf{NMBE_1}$	$\mathbf{NMBE_2}$
$\dot{m}$	i supply	-0.07	-0.07
Δp	i-e supply	-1.04	-1.04
Δp	a-i return	-3.55	-3.55
Δp	i-h return	-5.18	-5.18
T	i supply	0	0
T	h supply	0.02	0.01
T	g supply	0	0.01
T	f supply	-0.01	0.01
T	e supply	-0.02	0.01
T	1 supply	-0.03	0.01
T	i return	-0.32	-0.28
T	h return	-0.28	-0.22
T	g return	-0.36	-0.30
T	f return	-0.42	-0.35
T	e return	-0.44	-0.36
T	1 return	-0.44	-0.37
$\dot{Q}$	i-h supply	-7.48	9.60
$\dot{Q}$	i	-0.63	0.58

The test reported an accuracy grade on the reference values of 84.77% using the steady-state model, in line with the highest result among the reference tools (85.17% for TRNSYS), and 75.20% with the quasi-dynamic model.

The highest deviations from the reference value were found in KPIs related to the hydraulic part of the simulation, which is the same for both the steady-state and dynamic models. In particular, NMBEs of -1%, -4% and -5% were reported for the pressure drops between nodes i and e in the supply network and between nodes a and i and i and h in the return network. These errors can be explained by the large difference in results among the different reference tools, of which the reference value is an average. Between nodes i and h (see Figure 4), for instance, the outputs of the reference tools ranged from 5658 Pa to 7913 Pa, with just two results above 6000 Pa.

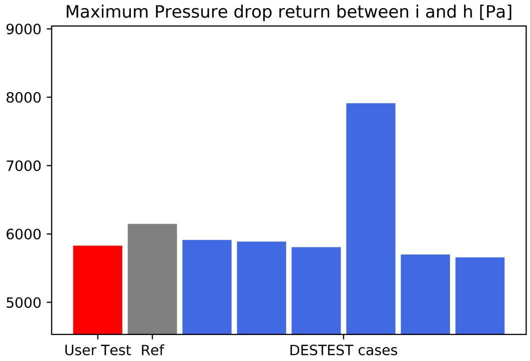

Figure 4: Output of the DESTEST comparison tool for the pressure drop between nodes i and h of the return line.

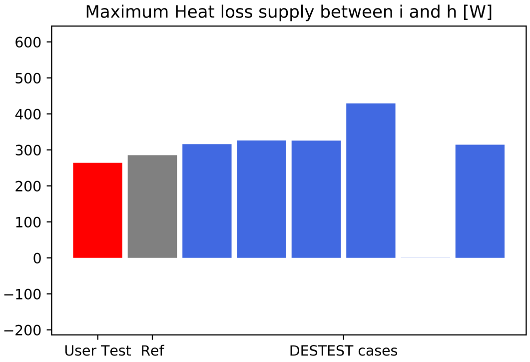

Figure 5: Output of the DESTEST comparison tool for the heat loss between nodes i and h of the return line using the quasi-dynamic model.

The reference value was then 6146 Pa, on which the reference tool with the closer output had a NMBE of 4%.

This problem was also present in the KPIs for the thermal part, although much less pronounced. On these, both the steady-state and the quasi-dynamic model showed a good agreement with the reference values, with a NMBE below 1% for most indicators. A notable exception is the heat loss in the supply pipe between nodes i and h, where a value of 0.45 W in one of the reference tools, most likely a unit error, negatively affected the reference value. Here, all other reference outputs were above 300 W, while the average was only 285 W. For this indicator, the steady state model estimated a value of 314 W, while the quasi-dynamic model returned a value of 264 W. Both these outputs were below most other tools, with the quasi-dynamic model having the lowest prediction of all (see Figure 5).

Some discrepancies can be finally noticed in the nodal temperatures of the return line, despite the different tools having good agreement in the supply part of the network. These differences are partly due to the different handling of temperature drops in substations by the reference tools. In most cases in fact, the exact set-point of 30 K is not met, and small variations can be observed by comparing the inlet and outlet temperature of the reference tools for substation 1. These might be due to oscillation in the implemented controlling schemes, which do not appear using ideal models.

Network Common Exercise 1

The second common exercise extends CE0 by varying the heat demands of connected buildings at nearly regular intervals of around 10 minutes for one week. This configuration is introduced as a mean of comparing dynamic simulation tools on KPIs similar to those used in CE0. However, reference results are currently publicly available for only one tool (based on the Modelica Buildings Library) and are not yet included in the comparison tool. For this reason, an actual accuracy value could not be calculated, and only the main differences in results with the Modelica Buildings Library are discussed in this section. An overview of the results is given in Table 2.

Table 2: Results of the quasi-dynamic model on CE1.

KPI	Node(s)	NMBE
T	*1* supply	-7.47
T	*1* return	-10.95
T	i return	2.89
$\dot{m}$	*1*	0.23
$\dot{Q}$	*1*	-0.86
$\dot{Q}$	i-h supply	82.62
$\dot{Q}$	Network, losses	13.91
Δp	i-h return	14.24

With respect to substation 1, where several KPIs are evaluated, the peak loads were not met in the results of the reference tool, which possibly employed a continuous controller. This was not the case with PyDHN, as an ideal substation model was used instead (Fig 8). For the power in fact, a NMBE of -1% between the two tools was found, and a significant difference in temperatures at the substation (NMBE of -7% and -11% on the inlet and outlet temperature respectively), and to a lesser extent in mass flow (0.23%). The highest error was found when the load schedule was at zero: in these conditions, the temperatures simulated in previous time steps were maintained in the reference data, while they decreased quickly with the model presented in this paper (Figure 6). Excluding periods of zero load, a much lower NMBE is found for both the inlet (-0.26%) and outlet (-1.24%) temperature.

While the pressure losses were not reported for this consumer in the reference data, the different output for the pressure losses can be evaluated in the pipe connecting the nodes i and h in the return network. Here, a NMBE of 14% was found, with PyDHN simulating higher losses than Modelica Buildings, despite having very similar results on the same indicator in CE0. In this case, the discrepancy is most likely linked to the different amount of mass flow in the

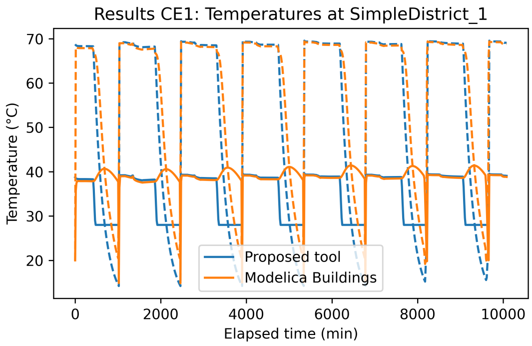

Figure 6: Temperature at consumer 1, result comparison with the reference tool. The dotted lines are the inlet temperature, while the solid lines are the outlet temperature.

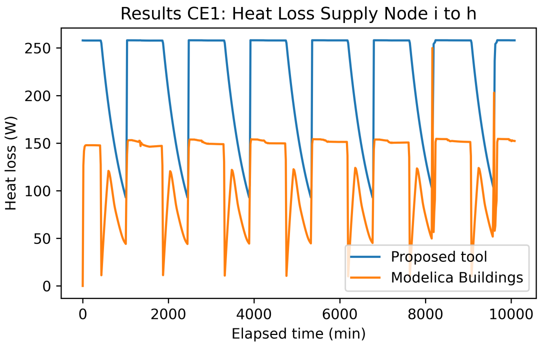

Figure 7: Heat loss between supply nodes i and h, result comparison with the reference tool.

network in the two models when the loads peak. In particular, since the mass flow is higher in the proposed tool, higher pressure losses are also expected, as they approximately scale with the square of mass flow. Heat losses in the same reference pipe were also evaluated among the physical indicators: in this case, PyDHN simulated higher losses than Modelica Buildings (83%, Figure 7), whereas for the same indicator in CE0, it estimated a lower value than that of all other tools. While the return temperature of the producer showed good agreement with the comparison tool (difference of 3%), the heat losses in the network - computed according to the DESTEST documentation as the difference between the heating station power and the consumers' total load - had a higher discrepancy of 14%. Overall, the average absolute NMBE of the tested tool against Modelica Buildings is 17%.

Discussion

The previous section presented the results of a verification using an intermodel comparison such as the one proposed by the DESTEST. While an accuracy grade is given in the benchmarks, it should be noted that since this is an intermodel comparison without ground truth, and with potentially high variability on the outputs of the reference tools, which may even fall outside the boundary conditions of the simulation, small differences in accuracy are not to be taken as an indicator of the relative performance of the models. Nonetheless, we believe that benchmarks like the DESTEST are extremely valuable for comparing different approaches and identify potential pitfalls and problems of existing and future tools and methods.

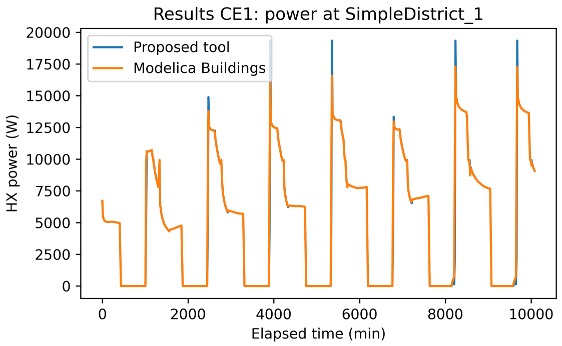

Figure 8: Power at consumer 1, result comparison with the reference tool.

In a steady setting such as the one of CE0, for most indicators, the steady state model achieved slightly better results than the dynamic one, while being *de facto* faster, in the sense that a typical steady-state simulation consists of longer timesteps (e.g., hours) than dynamic ones (e.g., minutes). While the two models are identical for what concerns the hydraulic part, and therefore achieved the same scores on the related KPIs, notable differences can be seen on the thermal transient behaviour. Both models have low heat losses in the supply pipe going from node i to h, however the value of the quasi-dynamic model is lower than all other tools. A possible explanation for this behaviour is that both models subtract the dissipation of hydraulic energy into heat due to friction from the losses, which are usually neglected in heat transfer models.

The second verification, CE1, was carried out by comparing the results of the quasi-dynamic model against the only reference tool available, which was based on the Modelica Building Library. The two tools use different approaches to model the behaviour of the network, leading to different results during peak periods. In fact, while the building load was always met with our simplified approach, this was not always the case with the comparison tool, where a lower power, and a lower mass flow, were simulated. The profile of the return temperature within the reference substation was also different, showing a delay between the lowered demand and the sharp decline in temperature.

Despite these differences, the results of the two models agree on most indicators, showing that a simplified, ideal model is suitable for most situations.

Although the verification on the two common exercises is not a replacement of verification with measurements, which are the object of another work (redacted preprint, 2023), we argue that the intramodel comparison brings several advantages:

- test's input data and output results are public and accessible on the web;
- the test is fully reproducible by anyone;
- the test can be enforced as part of the software release routine to guarantee that the same level of accuracy is achieved also in further releases.

. Regarding the last point, we acknowledge that both PyDHN outputs - in the case of changes to the underlying models - and the results from the DESTEST - in the case of new tools being added to the benchmark - are subject to change. Notwithstanding, we plan to maintain at least the same level of accuracy in future releases, which will be checked as part of the software CI/CD routine. The authors are committed to disclose any major change to this rule, for example in a subsequent publication.

Conclusion

This paper presented the results of a verification using an intermodel comparison such as the one proposed by the DESTEST. Two common exercises were completed, a steady-state simulation of a simple radial network (CE0) and a dynamic simulation of the same network with varying load profiles (CE1). Two pipe models were tested on CE0, one steady-state and one quasi-dynamic based on a two-node thermal network model. The quasi-dynamic model was then also tested on CE1 for which only reference results of Modelica Buildings were available.

For CE0, the test shows an accuracy grade on the reference values of 84.77% using the steady-state model, in line with the highest result among the reference tools (85.17% for TRNSYS), and 75.20% with the quasi-dynamic model. The verification of these accuracy grades is included as part of the software release routine. For CE1, despite the use of an ideal control scheme, a good agreement with the results of the comparison model was found for most indicators, except the heat losses.

We believe that this work provided new insights on the reliability of the models included in our software library. The results will be published as open-data so that they can be reproduced by anyone.

Future work will be addressed at investigating the possibility of using hybrid models, driven by physics-aware machine learning, to reduce the computational burden of the tested models and to employ them for design and operational optimization.

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