CitySim against DESTEST: a validation of Building and District Heating Network simulation

Rodrigue Dubon – Energy Informatics Group, Idiap Research Institute – dubon.rodrigue@idiap.ch
Kaempf Jerome H. – Energy Informatics Group, Idiap Research Institute – jerome.kaempf@idiap.ch

Abstract

The decarbonization of urban areas requires reliable and precise enough urban energy modeling tools that are capable of simulating the complex behaviors of both individual buildings and those integrated within district energy systems. These tools require rigorous validation and benchmarking to ensure predictive accuracy and general usability. This paper presents the validation of CitySim, an open-access and open-source urban energy modeling tool, under the District Energy Simulation Test (DESTEST) framework. The DESTEST framework comprises a series of Common Exercises (CE) designed to evaluate building thermal dynamics and District Heating Network (DHN) modeling capabilities by comparing several modeling tools' predictions. In this study, CitySim's building energy performance is benchmarked against established modeling tools, including EnergyPlus, TRNSYS, and Modelica-based libraries (AixLib and Buildings). For buildings' thermal dynamics, CitySim employs a simplified thermal resistance-capacitance (RC) model, while for the DHN behaviour it uses a steady-state approach. Results show that CitySim's building dynamics predictions (Buildings CE-1) closely align with those generated by EnergyPlus. Furthermore, CitySim achieves promising performance on the network simulation, notably reaching an 85.6% accuracy with the DHN steady-state common exercise (Network CE-0), outperforming all other participating tools. These findings validate CitySim's robustness and accuracy on the DESTEST's case studies, relative to traditional and commercial modeling software. Future work will focus on refining the building CEs and extending CitySim's capabilities to include the DHN thermal dynamics modeling which would allow its performance evaluation with the dynamic common exercise (Network CE-1).

1. Introduction

The global push towards carbon neutrality requires significant actions on urban energy systems, which are currently responsible of a vast majority of global greenhouse gas emissions (International Energy Agency, 2025). To achieve this goal of carbon neutrality, urban planning must evolve from focusing on individual buildings to account the multiscale complexity of district-wide interactions. This is only feasible through a deep understanding of individual building performances and how their interactions impacts the overall district energy systems efficiency.

The performance of buildings' envelopes mostly dictate their thermal needs to achieve high indoor environmental quality while reducing their carbon footprints. In this context, the thermal dynamics of the buildings become a critical factor, especially with global warming impacts (Ciancio et al., 2020). Improving the energy efficiency of the buildings is further pushed by the European Commission through the recent Energy Performance of Buildings Directive which mandates that all new buildings must achieve nearly zero-emission (European Commission, 2024). This creates a high demand for retrofitting strategies (de Oliveira et al., 2024) and precise energy-related performance measurements to ensure compliance with the European policy or to identify the best retrofit strategy. Obviously, deploying on-site measurement devices has prohibitive upfront cost. Therefore, the reliance on simulation tools has gained traction. Consequently, the accuracy of these simulation tools to precisely predict the buildings' dynamics have become no longer just a research concern but a legal and financial necessity for involved stakeholders.

However, achieving concrete and long-term decarbonization require multiscale actions by looking beyond individual buildings to the interactions at the district level. District Heating

Networks (DHN) represent a key component within this objective (Frederiksen & Werner, 2013). DHNs have significant potentials to systematically reduce emissions within the heat supply sector as they facilitate the integration of significant share of renewables and waste heat recovery, while coupled with high efficiency heat transport at the city level (Lund et al., 2014). The synergy between building-level demand and network-level supply holds the greatest potential to effectively decarbonize our cities. Therefore, precise multiscale simulation tools are needed which are capable of precisely predicting individual building's dynamics and thermal demands but also modeling the behavior of the DHNs and the effective supplied thermal energy.
Robust urban energy modeling tools are then required to address this challenge. This paper precisely addresses this challenge by presenting CitySim simulation tool (Walter & Kaempf, 2015) and its validation under the District Energy System Test or DESTEST (Saelens et al., 2019). CitySim developed previously for building dynamics modeling has been refined to model DHN steady-state behavior (Cognet, 2020).
This paper presents firstly its performance against the DESTEST. The DESTEST is divided into several Common Exercises (CE) with CEs on both building-level and DHN-level simulations under which different simulation tools are benchmarked against each other. More precisely, this paper presents the performance of CitySim in capturing the behavior of a single family house dwelling and a symmetrical DHN which are respectively the Building CE-1 and Network CE-0 against well-established tools such as EnergyPlus, TRNSYS and Modelica-based libraries.

2. CitySim models

In this section, we briefly describe CitySim's modeling approach of both the building and the DHN behavior.

2.1 Building simulation model

CitySim relies on a simplified thermal resistance-capacitance (RC) approach. Each building is composed of three envelopping elements (roofs, walls, and floors) and is represented as a single or multiple thermal zones. Each zone is modeled by four nodes (indoor air and furniture, roof, wall and floor nodes) and each node is associated with temperatures and capacitances. The indoor node represents the average indoor air temperature T_a which allows to compute the heating and cooling demands of the zone to achieve a given temperature set-point profile. The indoor node exchanges with the floor, wall, and roof nodes and directly with the exterior air conditions through the windows, infiltration/ventilation and transmitted solar fluxes. The furniture's thermal inertia is associated to the indoor air node capacitance. Floor node exchanges directly with the ground while the wall and roof nodes exchanges with the exterior air conditions using convective heat transfer coefficients. Floor, roofs and walls are defined through composites with their capacitances and conductances depending on their layered materials. By default, CitySim assumes that wall, roof and floor temperatures are uniform within every thermal zone. Further details on the building model of CitySim can be found in (Walter & Kaempf, 2015).

2.2 District Heating Network simulation model

DHN is a complex urban heat supply system where heat is traditionally produced at heat sources and transported via a heat carrier fluid (e.g., water) to heat consumers such as the buildings to fulfill their heating demands. Modeling DHN behavior requires simulating both hydraulic and thermal behaviors of the fluid. Practically, these two dynamics can be modeled disjointly because of the differences in their temporal characteristics. At the submission of this paper, CitySim models both hydraulic and thermal behavior in a steady-state manner. Presented DHN modeling has been developped by Cognet (2020). Furthermore, CitySim can couple the DHN simulation with the building

simulation at the substation level. However, this is outside the scope of this paper which focuses on both simulation approaches independently.

2.2.1 Hydraulic model

The steady-state hydraulic model accounts for predicting the temporal evolution of the pressures and massflow rates through the network. CitySim relies on the loop method which views the DHN as a two-layered looped graph where the nodes represent the pipes junctions and the edges represent the substations, the heat producers and the transport pipes. We recall that pipes are divided into similar but oriented in opposite direction pair of pipes. Supply pipes transport heated water from heat producers to substations while return pipes returns the water back to the heat producers for reheating. Within the loop formulation, pressure loss ΔP balances are ensured within every internal loops (Eq. 1). Pressure losses through the pipes are functions of the water mass flow rates $\dot{m}$ given by the Darcy-Weissbach formula represented by φ. At the nodes, mass conservations are ensured. Over the whole network, this leads to a non-linear system equations where the unkown are the mass flow rates and pressure losses, solved for every time step using iterative algorithm such as the Newton-Raphson method. In Eq. 1, (i,j) defines the pipe between the nodes i and j.

$$\forall \text{loop}, \sum_{(i,j)\in loop} \Delta P_{(i,j)} = 0 \quad \text{with } \Delta P_{(i,j)} = \varphi(\dot{m}_{(i,j)}) = 0 \qquad (1)$$

2.2.2 Thermal model

The thermal model predicts the evolution with time of the water temperature over the network within the supply and return layers. Heat producers and heat consumer substations are viewed as plate heat exchangers. At heat producers, water is heated to reach a given target supply temperature at the supply mass flow rate from the return's available temperature. Producers' supply temperatures and mass flow rates are usually imposed by control strategies. At the consumers' substations, heat is retrieved from the network to fulfill a given heating demand of the substation connected to the buildings' demand from simulation or forecasting. Energy conservation is enforced at every node through enthalpy balance. The critical part of DHN thermal model is the manner to model the heat transport through the transmission pipes. Within CitySim, this is modelled through a single steady-state transport equation. For every pipe, the temperature of water at its outlet T_{out} is directly a function of the water temperature at its inlet T_{in} subjected to heat loss to the outside of the pipe with the soil at the temperature T_{ext} (see Eq. 2). Total thermal equivalent resistance R_{th} accounts for the water convective resistance inside the pipes, conductive resistance through the pipes' wall and insulation and the soil convective resistance. CitySim also considers the heat gained from the water friction ϕ which depends on the water mass flow rate and pressure loss. c_p represents the specific heat capacity of water and L indicates the length of the pipe.

$$T_{out} = T_{ext} + (\phi R_w/L) + (T_{in} - T_{ext}) \exp(-(R_{th} c_p \dot{m})^{-1}) \qquad (2)$$

3. DESTEST

The extended description of the DESTEST Common Exercises (CE) and validation processes are presented in (Saelens et al., 2019). Here, we recall only the CE considered in this work which are the Building CE-1 and Network CE-0, detailed in following subsections.

3.1 Building CE-1

In the bulding CE-1, the objective is to model the thermal behavior of a single-family dwelling. Cooling system, shading device and daylight saving time are not considered. The studied building is a simple cubical block consisting of 2 floors modeled as 2 thermal zones (see Fig. 1). Upper floor represents the “night zone” while the lower floor represents the “day zone”. Each zone has a length of 8 meter, a width of 8 meter and a

height of 3.5 meter. Each wall of the building has a window of 1.4 meter height and 4 meter width with U-value of 3.15 W/(m^2·K) and g-value

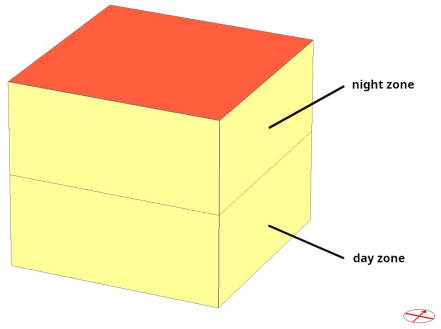


Fig. 1 - Illustration of the building CE-1 case study from CitySim

of 0.78. The opaque elements (walls without windows, floors, and roofs) have standard U-values of 1.07 W/(m^2·K), 0.81 W/(m^2·K), and 0.71 W/(m^2·K) respectively. However, CitySim does not consider these values and computes its own from the composites of materials and their properties. These composites characteristics can be found in the DESTEST official documentation. Infiltration rate is assumed constant over the day (0.4 ACH). The occupancy profile is modelled deterministically following standard profiles and governs the target indoor air temperatures profiles as well as the internal heat gains (see Table 1). The heating system, assumed ideal, aims to meet the target indoor air temperature profiles. Total heating demand corresponds then to the integral over time of the total thermal power needed to achieve the desired indoor temperature.

Table 1 – Day zone / Night zone schedules

	Target indoor temperature (°C)	**Internal heat gain (W/m^2)**
7am - 5pm	16 / 16	8 / 1.286
5pm - 11pm	21 / 18	20 / 1.857
11pm - 7am	18 / 20	2 / 6

The simulation is performed for one year with 1 hour time step using the weather data from Brussels in 2007. Ground temperature is assumed to be constant at 10°C at all time.

3.2 Network CE-0

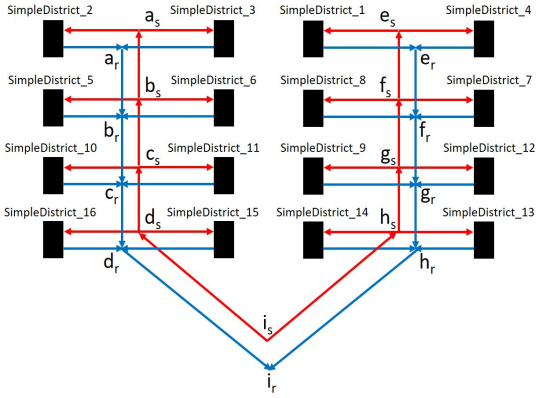


Fig. 2 – DHN case study layout; source: (Saelens et al., 2019)

The objective of this CE is to assess the performance of CitySim's steady-state simulation models of DHN against other simulation tools' predictions. The considered network is a residential district with 16 single-family dwellings connected with a conventional distribution pipe with radial and parallel structure. Each building is connected to its own substation buried next to the buildings. Fig. 2 shows the spatial layout the DHN with red lines indicating the supply pipes and blue lines indicating the return pipes. All the elements of the network are placed underground at a depth of 1.5 meter, including the buildings' substations and the pipes. Therefore, static pressure differences are neglected. The heat producer is placed at node "i" and injects heated water at a constant temperature of 70°C. The soil temperature at the depth of the pipes is assumed also constant at 10°C. Pipes' internal roughness is 0.007 millimeter. Simulation is performed for one week period with a 10-minute time step which is the granularity of the provided heating demands profiles. Simulation results are then resampled to a 15-minute time step resolution consistent with the DESTEST official documentation.

3.3 Comparison metrics and simulation tool

To evaluate CitySim's performance, DESTEST compares its time-varying predicted values with the predictions of other simulation tools on

Table 2 - Simulation tools' performances on Building CE-1 (reported values are in percentage)

	CitySim	EnergyPlus	AixLib	Buildings	BuildingSystems	DIMOSIM	IDEAS	TRNSYS
Heating power NMBE	2.62	1.87	1.48	5.31	-26.62	-5.94	-5.32	-0.72
T_a day zone NMBE	-0.13	-0.25	-0.12	-0.03	0.02	0.11	0.26	-0.14
T_a night zone NMBE	0.03	-0.11	-0.11	0.02	-0.2	0.25	0.23	-0.11
Accuracy score	79.44	53.43	70.59	90.25	38.02	45.85	30.31	69.01

different physical quantities. The other simulation tools considered in this work include EnergyPlus, TRNSYS, AixLib, Modelica librairies (Buildings and BuildingSystems), DIMOSIM and IDEAS. We also consider PyDHN, a python based DHN simulation library (Boghetti et al., 2024). These simulation tools are then ranked according to their differences from the collective average, referred to as accuracy score. Differences in the physical values are measured via the Normalized Mean Bias Error (NMBE). The accuracy score is calculated as 100% minus the weighted average of the normalized absolute NMBE values, where the NMBE of each considered KPI (e.g., heating demands, indoor temperatures) is re-scaled using the best and the worst NMBE values observed among all compared models.

4. Results and Discussion

4.1 Building CE-1

The results of the building simulation for CE-1 are summarized in Table 2, where CitySim's performance is evaluated alongside other tools' performance. Based on annual averages, CitySim's prediction of total heating power is largely aligned with the benchmark, maintaining a low NMBE of 2.62%. This level of precision highlights CitySim's capability to accurately predict buildings' temporal heating needs despite its simplified modeling approach. The temporal evolution of heating power for a representative spring week (March 21–25) is illustrated in Fig. 3. Even though CitySim employs a simplified RC model, its predicted heating power aligns closely with the transient results from AixLib and TRNSYS. Additionally, we observe an average relative difference of 4.95% with EnergyPlus' predicted heating power profile

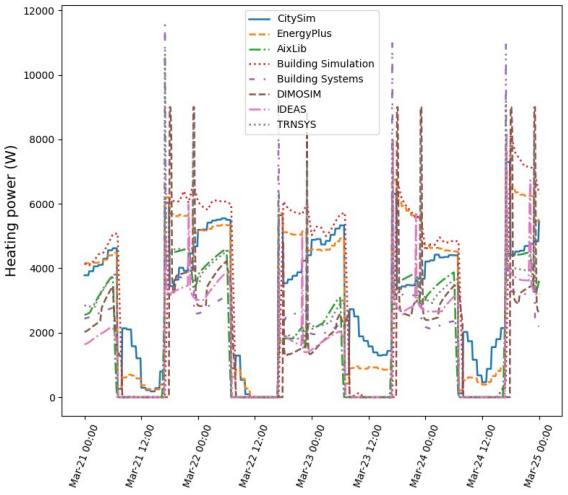


Fig. 3 – Heating power (W) profiles

using EnergyPlus's predictions as baseline. Overall, CitySim's predicted power profile falls within the average of the simulation tools and is very close to EnergyPlus. In contrast, BuildingsSystems, IDEAS and DIMOSIM predict several peaks in their heating power profiles (see Fig. 3) which are not predicted by the other simulation tools. It explains the relatively high heating power NMBE of these simulation tools. These discrepancies are also observed in Fig. 4 and Fig. 5 which display indoor air temperatures for respectively the day and night zones. Both DIMOSIM and BuildingSystems tend to predict

higher indoor air temperature than the other simulation tools during the low heating demands time slot (i.e., [7am-5pm]). In line with the predicted heating demands, CitySim and EnergyPlus show very similar indoor temperature profiles with an average relative

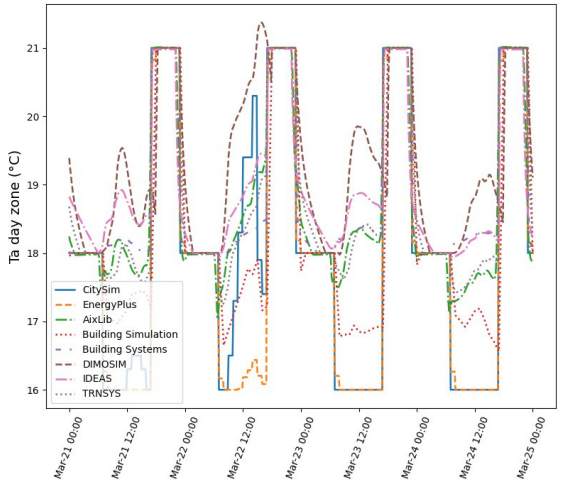


Fig. 4 – Day zone indoor air temperatures (°C) profiles

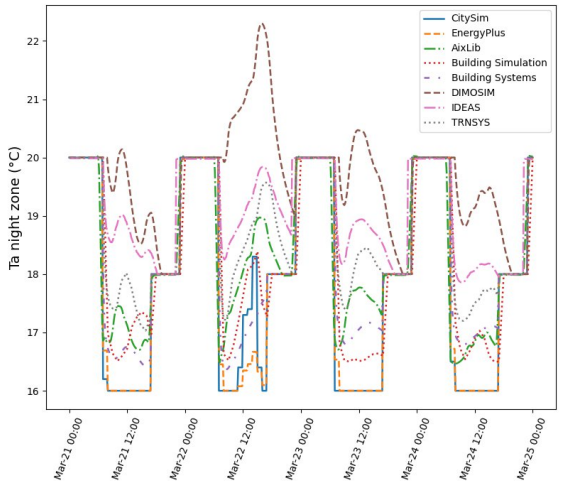


Fig. 5 – Night zone indoor air temperatures (°C) profiles

difference of 0.46% between them considering EnergyPlus as reference. Notably, the primary differences in CitySim's and EnergyPlus' predicted indoor temperatures occur during the [7am-5pm] time slot, suggesting different sensitivities to internal and solar gains during these transition periods. In terms of comparative ranking, CitySim achieves an overall score of 79.44% relative to the benchmark, positioning CitySim at 2nd out of the eight evaluated tools, notably ahead of EnergyPlus (see Table 2). Also, the behaviors of the other simulation tools (except of EnergyPlus) during the low heating demands time slot (i.e., [7am-5pm]) are not realistic according to the the Building CE-1 guidelines and necessitate further investigation.

4.2 Network CE-0

The accuracy scores of the different simulation tools compared within the Network CE-0 in this paper are summarised in Table 3. PyDHN's accuracy value is retrieved from (Boghetti & Kaempf, 2023). Reported values show that CitySim exhibits the highest accuracy score with 85.59%, marginally above PyDHN's accuracy of 84.77%. TRNSYS and Modelica Buildings yielded accuracy scores of 81.85% and 70.02%. CitySim's presented results are obtained from performing the DESTEST Network CE-0 with TRNSYS and Modelica Buildings but without PyDHN which ensures unbiased comparison between PyDHN's and CitySim's performance. The relatively high accuracy scores across all considered tools suggest that the predictions remain generally consistent. These accuracy results validate CitySim's capability to accurately model the steady-state behavior of DHNs, effectively capturing pressure fluctuations, mass flow rate evolution, and thermal loss distribution.

Table 3 – Accuracy scores of the different simulation tools on the Network CE-0

Simulation tools	**Accuracy scores (%)**
CitySim	85.59
PyDHN	84.77
TRNSYS	81.85
Modelica Buildings	70.02

Table 4 – NMBEs of CitySim and PyDHN on Network CE-0

	CitySim	PyDHN
Mass flow rate i_s	-0.07	-0.07
Pressure drop i_s to e_s	-1.04	-1.04
Pressure drop a_r to i_r	-3.54	-3.55
Pressure drop i_r to h_r	-5.17	-5.18
Temperature i_s	0	0
Temperature h_s	0.01	0.02
Temperature g_s	0.01	0
Temperature f_s	0.01	-0.01

Temperature e_s	0.01	-0.01
Temperature $SD1_s$	0.02	-0.01
Temperature i_r	-0.18	-0.28
Temperature h_r	-0.12	-0.22
Temperature g_r	-0.2	-0.30
Temperature f_r	-0.25	-0.35
Temperature e_r	-0.27	-0.36
Temperature $SD1_r$	-0.28	-0.37
Thermal loss i_s to h_s	9.41	-9.60
Total supplied power	0.45	0.58

Table 4 reports the NMBE for CitySim and PyDHN across the various KPIs defined for the Network CE-0. To maintain clarity and facilitate direct comparison, only the two most performing tools are presented in the table, with PyDHN values retrieved from (Boghetti & Kaempf, 2023). CitySim demonstrates exceptional performance in predicting the hydraulic and thermal steady-state behavior of the DHN case study. The results in Table 3 indicate nearly identical hydraulic performance between CitySim and PyDHN, characterized by similar NMBE values for both mass flow rates and pressure drops. This alignment is expected, as both tools utilize comparable hydraulic models based on the loop method. Minor deviations emerge in the thermal modeling part, particularly regarding the estimation of transport losses and the resulting delivered temperatures at the most distant node. CitySim achieves a NMBE of -0.28% for the return temperature at this node, whereas PyDHN shows a slightly higher NMBE of -0.37% (see Table 3). Results have shown that the lower score observed for Modelica Buildings is primarily attributed to thermal loss discrepancies, where the NMBE reached 10.78%.

4.3 Discussion

The results presented in this work validate CitySim's current capabilities in modeling both standalone building behavior and DHNs operations within the DESTEST framework. While CitySim is a well-established open-source tool for building and urban energy modeling, its DHN simulation features are a recent addition by (Cognet, 2020). To the authors' knowledge, this study represents the first comparison of CitySim's steady-state DHN module with other simulation tools under the DESTEST framework. The high degree of accuracy observed in the Network CE-0 confirms that the tool is robust for steady-state hydraulic and thermal analysis. Ongoing developments are focused on integrating dynamic DHN modeling capabilities to capture transient thermal behavior and address the DESTEST Network CE-1. Additionally, it is important to note that the benchmark values reported in this paper are inherently relative to other simulation tools considered, as they are derived from the ensemble average of the participating simulation tools. Consequently, these values may change if tools are added to or removed from the comparison, which is why we considered PyDHN and CitySim separately. To support the advancement of open science and comparative benchmarking, the result files from this study can be made publicly accessible upon request. Given CitySim's open-source framework, these results can also be easily reproduced.

5. Conclusion

This paper presented the performance of CitySim's simulation capabilities using the DESTEST comparison framework, specifically focusing on the Building Common Exercise 1 (CE-1) and the Network Common Exercise 0 (CE-0). The results demonstrate that CitySim is highly effective for urban energy modeling, yielding performances that are similar to, and in several instances exceed, those of established public and commercial simulation environments. At the building scale, CitySim achieved a 2.62% NMBE in heating power prediction for the Building CE-1 (with an average difference of 4.95% with EnergyPlus' prediction alone). On this CE, CitySim scores 79.44%, outranking several transient and commercial simulation tools by ranking 2nd out of the eight models evaluated. Regarding the District Heating Network (DHN) scale, CitySim achieved an overall accuracy of

85.59% for the Network CE-0, representing the highest accuracy among all participating tools and effectively capturing the complex hydraulic and thermal behaviors of the case study. These high levels of accuracy provide a robust validation of CitySim's current architecture and underscore the value of expanding the tool toward a dynamic transient model for DHNs, which will be the primary focus of future works.

6. Acknowledgement

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7. Nomenclature

T_a	Indoor air temperature (°C)
T_{out}	Water temperature at pipes' outlet (°C)
T_{in}	Water temperature at pipes' inlet (°C)
T_{ext}	External temperature (°C)
R_{th}	Pipes' total thermal resistance (K•m/W)
c_p	Water specific heat capacity (J/kg/K)
$\dot{m}$	Water mass flow rate (kg/s)
ΔP	Pipes' pressure losses (Pa)
ϕ	Heat gains from friction (W)
L	Pipe length (m)

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