Modelling of District Heating Systems: Comparative Evaluation of White-box Modelling Approaches

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Abstract. District heating systems are prevalent in most European countries, and such energy delivery methods can be crucial to decarbonisation objectives. To appropriately size and design the control of such networks, the modelling of district heating networks should have a good representation of the demand-side, which is the set of buildings connected to the network. Instead of simplified modelling of the demand, whole-building simulation tools can be invoked in this case, like EnergyPlus. More recently, equation-based libraries have been developed in Modelica for component-based simulation of HVAC systems. Modelica-based libraries offer easier model composability and are particularly interesting for control fine-tuning; on the downside, the model setup can be more complex, with more validation needed.
This paper conducts a comparative study of the Modelica LBNL Buildings library against EnergyPlus, based on an archetype-based hypothetical case in the UK with a small-scale district heating system. The methodology resides on models developed in the two tools with the same level of modelling detail. The comparison helps understand software differences in the modelling procedure, computational time, relative accuracy of energy predictions and heating system variables. The results indicate Modelica Buildings library yields similar accuracy in terms of heat transfer calculation through thermal zones as EnergyPlus, whilst capturing additional energy consumption caused by the dynamic changes at system startup and the realistic controllers used in the Modelica district heating models. Meanwhile, the Modelica Buildings library's outputs show the fluctuations of system variables, indicating different operation patterns and control effects against EnergyPlus. This study also proves that the Modelica Buildings library is the better tool for district heating simulation in the context of dynamic performance evaluation and control testing, based on overall capabilities, limitations, and prediction differences.

Keywords. Modelica, Buildings library, EnergyPlus, District heating system, Comparative evaluation.
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1. Introduction

District heating systems (DHS) are critical enablers to reduce carbon emissions, as they can improve operational efficiency and integration with distributed renewable energy sources. It is estimated that by 2050, around 18% of heating demand in the UK will be satisfied by district heating networks [1]. With the new generation district heating networks relying on distributed energy sources and digital technologies, advanced control strategies are bound to become more dominant and widely used. Meanwhile, the development of Building Energy Simulation (BES) tools and their integration in design workflows has highlighted the value of building and HVAC system design and operation. As an application of BES software, a proper simulation-based model of district heating system would significantly support the decision-making process, optimise the control strategies, facilitate diagnosis of potential performance gaps and ultimately reduce the energy consumption of district heating system [2, 3].

In recent years, state-of-the-art simulation programs such as EnergyPlus have enabled highly accurate building- and district-level simulations [4]. These tools proved highly successful but also with limitations: the unclear separation of the integration methods with the models imposes restrictions on such tools' modelling capabilities and extensibility. One such example is the modelling of hybrid thermal and electrical energy networks. The more precise separation of concerns led to general-purpose modelling specifications like the Modelica language, which advocates an acausal, component-oriented, equation-based modelling approach. Although developed initially for other industry verticals, the benefits in energy modelling are now appreciated. Several building-related libraries in Modelica have been developed, such as the LBNL Buildings library [5]. The library provides detailed room models like EnergyPlus and HVAC and controls components for dynamic simulations. Recent research has already found several remarkable merits and weaknesses of the Modelica libraries. Modelica uses acausal couplings between components, brings fewer constraints and general coupling directions during the model development, and adopts variable time steps during simulations [6, 7]. However, as Modelica building-related libraries are brand-new for developers and users, their capabilities and potentials have not been yet evaluated, especially in district heating studies. Therefore, this paper conducts a comparative software assessment to understand the relative differences between the two tools. A comparative evaluation can be practical since models with different levels of detail can be tested without any empirical data from actual buildings [8].

2. Analytical comparison of EnergyPlus and Modelica libraries

In the study of district heating systems, EnergyPlus is a detailed energy simulation tool in demand-side calculations and is suitable for HVAC system simulations [2, 4]. It was initially designed for building-level simulation, but the continued development of EnergyPlus has resulted in the addition of new features, including the capabilities to support district energy simulations. In the demand side calculation, EnergyPlus provides a convenient process to develop 3D geometry of building envelope model assisted by SketchUp plugin, which gives users capabilities to construct detailed building models. Meanwhile, in the HVAC calculation, EnergyPlus allows to build up component-based system layouts by linking “nodes” together and provides idealised system controllers such as the setpoint manager and the system availability manager to adjust temperature setpoints and the on/off states of HVAC systems. As a HVAC component, boiler models are available in EnergyPlus [4], and small-scale district heating systems can be simulated under the plant loop simulation. For example, Andrić et al. [9] used EnergyPlus to simulate the district heating demands, with a plant-loop simulation to compute a small-scale district heating system. Furthermore, as EnergyPlus has been developed for many years, it has been well validated by Building Energy Simulation TEST (BESTEST) and HVAC BESTEST [10], so many industry standards recognise it as the most acceptable tool to be compared with other simulation tools. Hence, EnergyPlus provides a detailed envelope model development procedure and is regarded as a reference tool in the demand-side calculation.

Meanwhile, Modelica is a component-oriented and object-oriented language, initially for large-scale physical models [5]. Recent studies have identified advantages in Modelica compared to state-of-the-art BES tools such as EnergyPlus [11] and TRNSYS [12]. First, Modelica adopts acausal language instead of the causal modelling used in EnergyPlus, which is advantageous for showing system structures and connecting different components. Li et al. [13] and Schweiger et al. [14] concluded that the acausal characteristic of the language could lead to developing more coherent HVAC component models. Conversely, EnergyPlus integrated those numerical solvers with equations, followed by declaring execution sequences and changing program states, so it is tricky to integrate with existing equations when creating new models [6, 15]. Second, Modelica provides capabilities to simulate dynamic components with more advanced controls. At the same time, EnergyPlus usually assumes steady-state and idealised controllers if not enabling the features from Energy Management System in EnergyPlus [7, 16]. In Modelica, the simulation timestep also varies to ensure proper integration and avoid inaccurate results caused by the averaging performance over a fixed time step [6]. Third, unlike single-domain EnergyPlus, a few Modelica libraries have already adapted to multi-scale models and developed the increasing number of systems in district heating domains. Since 2007, the Buildings library has been developing into an open-source tool with over 500 validated components such as detailed envelope models, multi-zone airflow, occupants, fluid dynamics, HVAC components and advanced controllers [5, 17]. With these advantages, it is feasible for us to integrate building-level and district-level components for the district heating simulation. District energy system cases were also tested under the IEA EBC Annex 60 project [7] and are further validated in IBPSA Project 1 [18].

Recently, a developing tool, Spawn of EnergyPlus (SOEP), enables the coupling between the Modelica Buildings library and EnergyPlus [19]. SOEP reuses the calculations of building models in EnergyPlus with the support of HVAC and control models from the Buildings library. It automatically sets up a co-simulation framework and can combine the “best” performance from both EnergyPlus and Buildings library. However, since SOEP is still in development and public users preferred to use a single tool during the modelling rather than co-simulating between tools, this paper mainly focuses on making a standalone-software comparison, highlighting the differences in building-level and system-level simulations, respectively.

3. Methodology

3.1 Case description

A conceptual case of a district heating system was developed and executed in the Buildings library and EnergyPlus, simultaneously following the same modelling procedures to compare software performance in district heating simulations. Different building typologies were considered to form up buildings in the district heating cases. Building geometry and parameters were selected from English archetypes meta-models generated by Symonds et al. [20], which is based on the 2010-2011 English Housing Survey [21]. According to the top three dominant dwelling types from English Housing Survey, five detached houses (D), two semi-detached houses (S) and three terrace houses (T) were selected to form a street layout in the district model, demonstrated in Figure 1. Each dwelling was regarded as a single thermal zone, and internal surfaces were not detailed since we focused on energy consumption per house. The network shown in Figure 1 was designed as a branch of the radial heating network, with pre-insulated water pipes connected with the heating source.

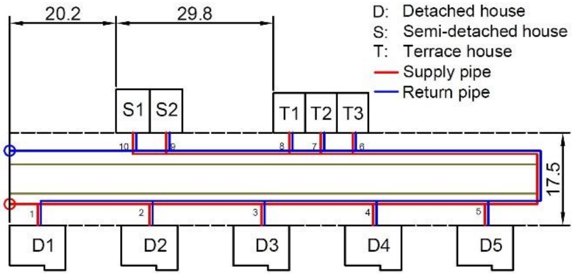

Fig. 1 – Typology of proposed district heating network.

A proper district heating system layout was designed for the two models in the comparative evaluation of white-box modelling approaches. Major components in DHS include boilers as heat sources, distribution network, radiators in each of the ten dwellings as the heating emitters [22]. A bypass connection between the supply pipe and return pipe controls the proper amount of hot water into radiators. The heating network's nominal supply and return water setpoints were 75 °C and 65°C, and the room air setpoint was 20°C, per the British standard [22, 23]. Pipelines, radiators, and boilers were sized correctly and based on the manufacturer database. Other relevant building and HVAC parameters are given in the appendix.

Before forming a complete heating system, a P controller and a PI controller were adopted to adjust the room air temperature and water outlet temperature from the heating source, respectively. In addition, control parameters in the heating system were fine-tuned to reduce system oscillations and avoid unstable operations in the simulation.

As comparative testing, this study obtained all identical building and HVAC parameters and then input those parameters into both tools to control external discrepancy [8]. Hence, we generated the two comparative models in Modelica and EnergyPlus, respectively, demonstrated in Figures 2 and 3. Modelica models were built by simply linking the models of heating system components and their controllers with each other, while in EnergyPlus, all components were connected with a list of nodes, and the control was modelled as a system variable or as a high-level controller attached in the node. Therefore, some control parameters cannot be executed in EnergyPlus, which leads to alternative modelling approaches with similar settings. For the inter-software comparison, we consider the relative deviations in predictions, computational costs, modelling capabilities and limitations as the comparison indices.

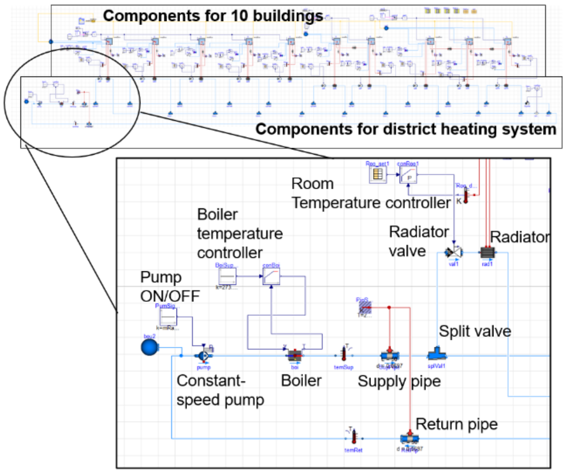

Fig. 2 – Modelica district heating model in Dymola.

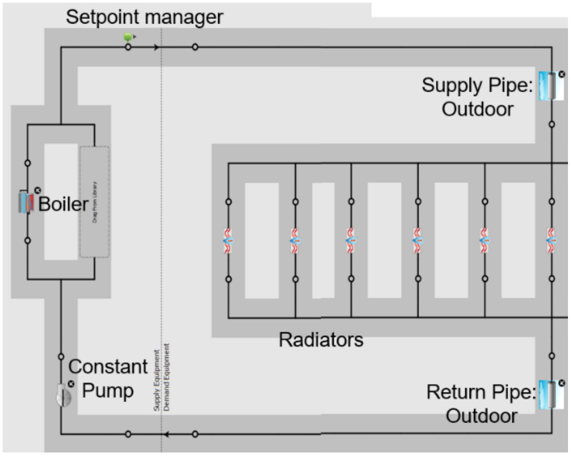

Fig. 3 – District heating model in EnergyPlus, visualized in Openstudio.

3.2 Modelling environment

The Modelica model was developed in Dymola, a commercial implementation of the Modelica specification; this is one option, with others open-source but less mature, such as OpenModelica. The model also used components from the Modelica Standard Library 3.2.3 and the LBNL Buildings library 5.0.1. Comparatively, EnergyPlus version 8.9 was used in the simulation. All simulations in the Modelica Buildings library and EnergyPlus were executed in the same computer with Intel Core i7-7700HQ 8-core 2.80GHz processor. Recommended by the Buildings library, we used the DASSL solver (A Differential/Algebraic System Solver) [24] with a tolerance of 0.001 in the Modelica-related simulation.

3.3 Comparison criteria

We introduced a series of validation steps in the district heating system, in a matter akin to BESTEST [10], to perform a better software comparison. The iterative validations included building-level comparisons evaluated by the free-floating temperature in Case 1FF, the heating demands in Case 1 and the cross-comparison on heating demands and energy consumption between Cases 2 to 4. Detailed descriptions of the iterative validated steps are shown in Table 1. These iterative validations demonstrated the potential impacts of models with different levels of detail on their simulation results, which facilitated locating the cause-and-effect in the comparative evaluation. The deviations of software accuracy, therefore, would be quantified as the bias error, relative deviation σ and Root Mean Square Error (RMSE), given in equations (1), (2) and (3), respectively, where $\hat{y}(t)$ and $y(t)$ represent the model results from the Buildings library and EnergyPlus respectively at the time n.

$$\Delta(t)=\hat{y}(t)-y(t) \quad (1)$$

$$\sigma = \frac{\hat{y}(t)-y(t)}{y(t)} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_1^n[\hat{y}(t)-y(t)]^2}{n}} \quad (3)$$

Tab. 1 – Descriptions of iterative validation cases.

Name	Descriptions
Case 1FF	Free-floating buildings
Case 1	Add the ideal air heating system from Case 1FF
Case 2	Add heating components in buildings from Case 1
Case 3	Add the heating network and boiler from Case 2
Case 4	Add heating schedules from Case 3

4. Result analysis

4.1 Heating demands (Case 1 and Case 1FF)

As a part of comparative evaluation of white-box modelling approaches, the accuracy of demand-side modelling could heavily affect the following district heating system predictions. The free-floating temperature was a crucial index to justify the accuracy of heat transfer through the envelope. Figures 4 and 5 illustrate the daily and yearly difference of free-floating temperature of detached house 1 in Case 1FF. Predictions from both tools were quite similar, with mean bias error and RMSE being close to 0. The similarity of the results showed that Modelica simulation could deliver accurate heat transfer calculations as EnergyPlus. However, minor deviations were found, including continuous half-hour delays in the daily results from the Buildings library possibly caused by different translations of weather profiles and a significant variation in the first week of yearly profiles due to the lack of warm-up procedures in the Modelica Buildings library.

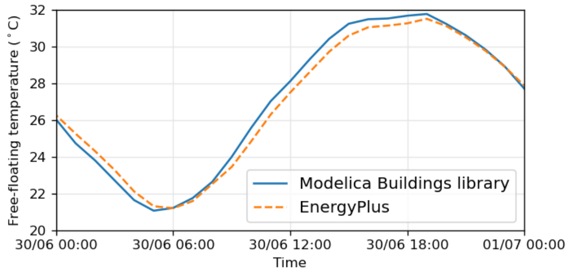

Fig. 4 – Comparison of daily free-floating temperature on Jun 30th.

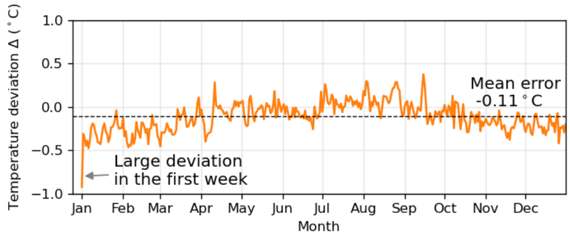

Fig. 5 – Deviations on yearly free-floating temperature.

Table 2 describes the annual heating load in the demand side of each archetype in Case 1. However, it was estimated that the annual heating demands of each archetype in the Buildings library were about 3.3% lower than the EnergyPlus results. This means that Modelica models required less energy to heat the space, attributed to the heat transfer process between the radiators and room air. It could be caused by the room models in the Buildings library were not accounting for detailed geometries, leading to the difference of surface areas. Since the 3% deviation was not significant, it proved that the model developed in the Buildings library had accurate building-level calculation as EnergyPlus even though the models in the Buildings library were built from simplified geometry inputs.

Tab. 2 – Calculation and comparison of each archetype's annual heating demands (kWh/m[2]) in Case 1.

Archetype	Buildings library	Energy-Plus	Relative deviation
Detached	208.19	215.01	-3.17%
Semi-detached	199.79	206.64	-3.31%
Terrace	181.15	187.16	-3.21%

4.2 Evaluation of iterative cases

A series of iterative cases were tested to identify the effects of model complexity on the model prediction from the Buildings library and EnergyPlus. These four cases were related to different heating system configurations, from simplified to detailed levels. Table 3 and Figure 6 show the daily heating demands in winter. Significant deviations were observed after implementing the district heating system in Case 4 since the mean bias error grew from -5.05 kWh to 10.28 kWh. A higher value of RMSE in Case 4 also indicated that results from the Buildings library had more considerable oscillations. Meanwhile, a lower prediction from EnergyPlus in Case 4 was observed as it adopted idealised controllers instead of realistic and less-ideal PI controllers. Figure 7 demonstrates the case comparison on the annual total energy consumption between these iterative cases from both software, indicating increased deviations observed in more complicated models. From Cases 2 to 4, the Buildings library had higher energy consumption than EnergyPlus by 2.75%, 3.94% and 10.18%, respectively. It could be explained by the extra energy consumption from extra components in Modelica models, such as the valves in the heating network. Thus, these differences in Modelica highlight the energy consumption from realistic HVAC and control components, with more capabilities in the district heating models.

Tab. 3 – Deviations of daily heating demands in Case 1 against Case 4.

Deviations	Case 1	Case 4
Mean bias error (kWh)	-5.05	10.28
Relative deviation (%)	3.39	8.96
RMSE (kWh)	6.14	10.64

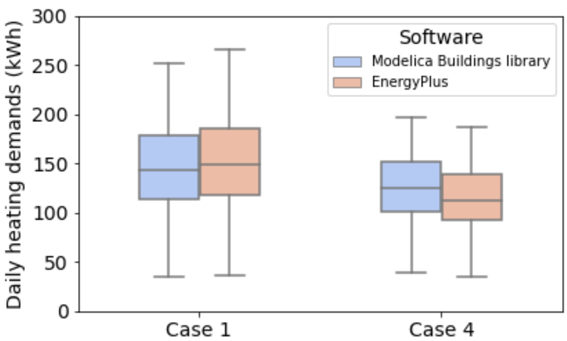

Fig. 6 – Predictions of average daily heating demands of detached house 1 in Case 1 against Case 4 in winter.

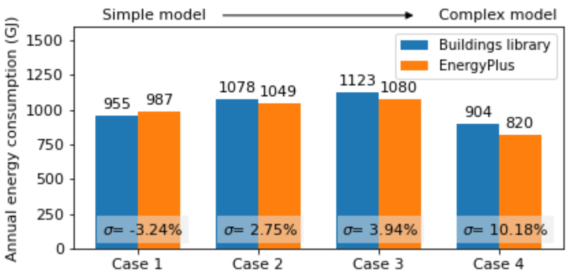

Fig. 7 – Comparison on annual energy consumption of iterative cases: Case 1 to Case 4.

4.3 Heating system variables

Figure 8 depicts a different prediction of hot water return temperature in Case 4, with operation hours displayed in grey. It showed that both tools computed close results, but a lower return temperature was captured in the Buildings library. Moreover, significant discrepancies were found when the heating system switched on. The Buildings library captured a lower return water temperature at around 55 °C before reaching a stable temperature. An analysis of the district heating system done by Kicsiny [25] proved that control errors in a heating system caused this type of fluctuation. By contrast, the temperature in EnergyPlus was kept above 65 °C, as the controllers were idealised without considering the transient process, and the simulation was executed in a fixed time step. Hence, EnergyPlus could only examine limited errors in the system variables, particularly in the transient condition.

Furthermore, a different characteristic was found in the part-load condition when contrasting the boiler's power and water flow rate variables through radiators, given in Figures 9 and 10. It was found that the model in the Buildings library simulated a one-half flow rate at around 0.5 kg/s and a slightly lower heating power at the part-load condition, compared to the results from EnergyPlus. Meanwhile, in Figure 11, the outlet temperature of radiators in the Buildings library was consistently lower than that of EnergyPlus, typically sending water at 50°C at the part-load operation against around 62 °C in EnergyPlus. A possible explanation was that two tools used different ways to compute the hot water distribution in heating networks. EnergyPlus could maximise the flow rate through the radiators to ensure the design temperature difference between the inlet and outlet, and then distribute the extra amount of water into the bypass branch. However, the Buildings library with pressure-based calculations varied the water flow rate according to the resistances in each branch, which caused a dramatic difference in the comparison.

4.4 Computational cost

Simulation time was a crucial index to estimate the computational cost of each modelling tool. Figure 12 shows the simulation time with the average simulation timestep of the free-floating case (Case 1FF) against the district heating case (Case 4) in two modelling environments. In the free-floating case, although Modelica adapted to a longer time step, its computational time was still higher than most simulations in EnergyPlus, due to higher computational cost caused by the transit conduction algorithms in the heat transfer calculation. Moreover, after adding heating system components, the DASSL solver in Modelica simulation reduced its timestep automatically, while its computational time was even higher than the EnergyPlus' one. Therefore, it proves that Modelica spent higher computational costs in a model with more controllers.

5. Discussion

As developed to be the basis of the next-generation tool, the Modelica Buildings library has been validated under BESTEST [5]. In terms of relative accuracy, our findings revealed that the Modelica Buildings library performed proper heat transfer calculations, although the Building library's model did not use the 3D building geometry. The results conclude that lower detail levels in geometry does not affect the overall heating demand calculation significantly.

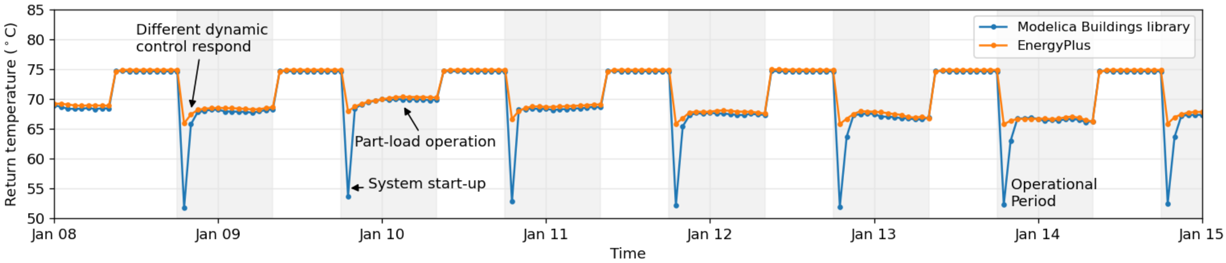

Fig. 8 – Comparison on hot water return temperature in Case 4.

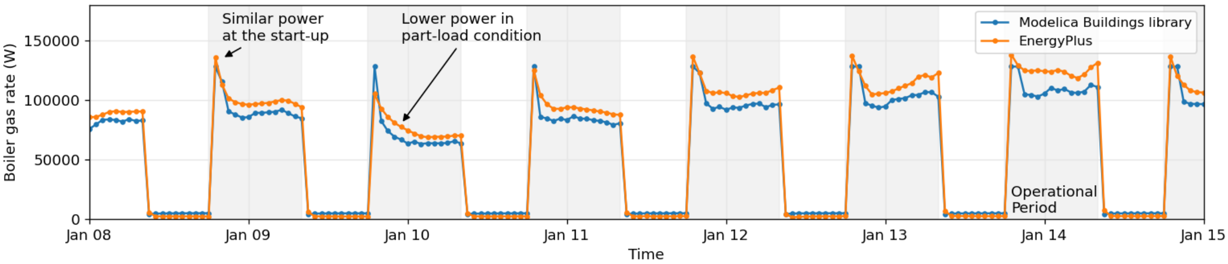

Fig. 9 – Comparison on boiler power rate in Case 4.

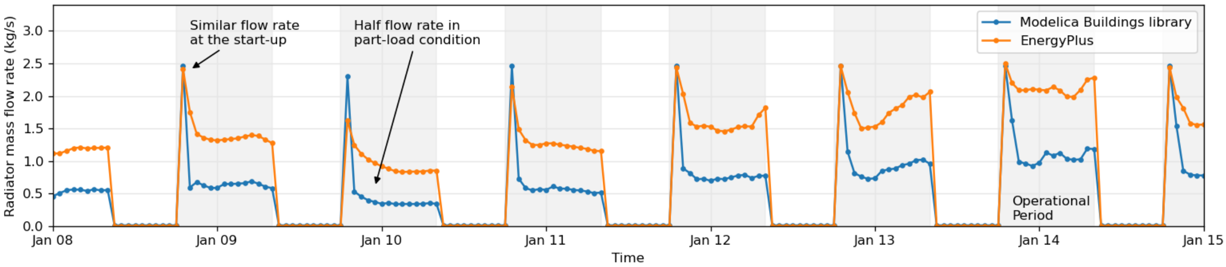

Fig. 10 – Comparison on total mass flow rate of all radiators in Case 4.

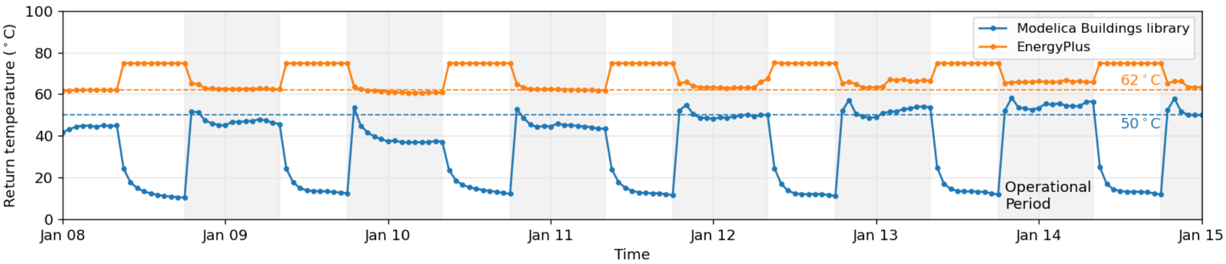

Fig. 11 – Comparison of radiator outlet temperature in detached house 1 in Case 4.

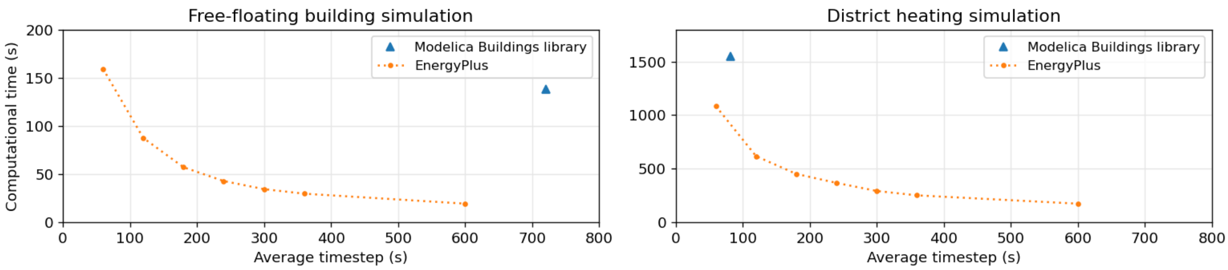

Fig. 12 – Comparison of simulation time in two cases (Case 1FF and Case 4) with different timesteps.

However, a substantial deviation was found when the heating system was involved. On the one hand, discrepancies between Modelica and EnergyPlus grew gradually with a more complicated system introduced, which proves that Modelica Buildings library uses less idealised models than EnergyPlus. On the other hand, the Buildings library captures the dynamic response from the control system, such as the startup period. Wetter et al. [26] stated that modelling an actual control sequence can reduce up to 30% HVAC energy consumption. Therefore, the Buildings library computes dynamic behaviour correctly, provides accurate control modelling, and ultimately reduces the performance gap caused by model simplification.

Surprisingly, the Buildings library did not reduce computation cost in the district heating system model, especially for the free-floating building model. It is probably due to (1) thousands of DAEs leading to inefficient coding in the detailed zone model; (2) too many closed-loop controllers involved in the model, which leads to higher computational cost when the states or the values of the controllers are changed [27]. These consequence indicates that adopting co-simulation by coupling EnergyPlus with Modelica would be a worthwhile endeavour to reduce computational complexity.

Based on the current findings, we summarise in Table 4 the capabilities and limitations of these two white-box modelling approaches. For example, the Buildings library has more detailed options to model the district heating system but it is more restricted in capturing building geometry. On the other hand, the district heating system implemented in EnergyPlus is entirely controlled by the idealised controllers and has unrealistic assumptions on the bypass water flow rate. Such comparisons and summaries have been acknowledged by the development of SOEP [19], which aims to avoid software limitations and use all capabilities by setting up the co-simulation framework.

Tab. 4 – Capabilities and limitations of the Modelica Buildings library against EnergyPlus.

Level	Simulation aspect	Buildings library	EnergyPlus
Building	Geometry	N	C
	Shadow calculation	N	C
District	Radiator	C	I
	Valve	C	N
	Bi-directional flow	C	N or I
Control		C	I

Note: C: Capable; N: Not capable; I: Idealised.

6. Conclusion

Overall, this study is a comparative evaluation of different white-box modelling approaches, between the Modelica LBNL Buildings library against EnergyPlus, based on a conceptual case of a district heating system. The Buildings library yielded similar outputs as EnergyPlus at the demand side in the case-by-case comparisons. However, significant deviations were found at the district system level after adding realistic controllers into the heating network. It indicates that only the Modelica Buildings library could capture dynamic changes and compute active energy consumption previously omitted by EnergyPlus. The analysis also suggests that the Modelica Buildings library is less computationally efficient than EnergyPlus in a model with higher level of details. This comparative evaluation summarizes different capabilities of two modelling approaches, which is beneficial for the selection of district heating modelling tools. As co-simulation would become more accessible, future work could focus on improving co-simulation frameworks to avoid software limitations and make a trade-off between prediction accuracy and computational cost.

7. Acknowledgements

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8. Appendices

Tab. 5 – Other information for model development.

Parameters	Description
Location	London
Boiler capacity	108800W
Boiler efficiency	0.849
Radiator capacity	14100W (Detached); 8500W (Semi-detached); 7100W (Terraced)
Pipe length	50m (Supply); 50m (Return)

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