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Influence of Temporal- and Spatial Resolutions on Building Performance Simulation Models: A Danish Residential Building Case Study

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Abstract. This study aims to assess the accuracy of a building performance simulation (BPS) model developed in IDA ICE software, focusing on heating energy use and indoor air temperatures in a low-energy multi-story residential building located in Northern Denmark. Six apartments were analyzed, and a comparative analysis was conducted between the measured parameters and the results obtained from BPS models with different spatial and temporal resolutions. The findings indicate that while the BPS models can provide reasonably accurate estimates of heating energy use, they may not fully capture the nuanced response to factors such as indoor air temperature This highlights the importance of incorporating qualitative inputs and environmental variables into these BPS models, including heating and/or cooling setpoints, internal gains, and weather conditions. Overall, this study provides insights into the limitations and opportunities of BPS models for accurately estimating heating energy use and indoor air temperatures in low-energy residential buildings.

1. Introduction

Building performance simulation (BPS) white box models have been widely used in building design for several decades, providing architects and engineers with insights into the expected performance of buildings. However, the use of default values for input parameters meant that these models often failed to accurately predict the actual performance of buildings once they were in operation [1-3]. This difference between the predicted and actual energy performance is known as the energy performance gap (EPG) and has been a persistent problem in the building industry [4]. With the increasing digitalization of the building sector, including the use of sensors to collect data on BPS models fed with the data from the installed sensors. Specifically, there is potential for these models to be transformed into digital twins (DTs) of buildings in operation [5]. DTs can be virtual replicas of real-world buildings that are continuously updated with data from sensors and other sources. DTs can serve multiple purposes, such as performance predictions, fault detection and diagnosis, stress testing with extreme conditions to test robustness, and optimization of control strategies. Despite the potential benefits of DTs as BPS models, they remain complex models that are difficult to implement on a large scale, and there is sparse knowledge on spatial- and temporal resolutions predicting heating energy use and indoor air temperature in multi-story residential buildings [6].

This paper aims to address this issue by conducting an investigation into the influence of varying temporal and spatial resolutions of input parameters on the accuracy of heating energy use estimation for a model of a multi-story apartment building located in Northern Denmark. The findings from this study will contribute to our understanding of how these resolutions impact the accuracy of heating energy use and indoor air temperature estimations.

2. Methodology

2.1. Case study

This study focuses on a residential multi-story building which was erected in 1949/50 and renovated in 2012/13. The building is located in the Northern Denmark region in an urban, semi-sheltered area that is surrounded by equal or lower-height multi-story and single-family houses. It is 3-story high with a basement and attic that has a total floor area of 2160 square meters (m^2). The building is divided into five staircases of either three or six apartments. In total there is 24 apartments. This analysis includes one staircase of six apartments, which have one of the layouts shown in Figure 1. The apartments to the left are 72 m^2 whereas the apartments to the right are 55 m^2. Table 1 below describes the building properties.

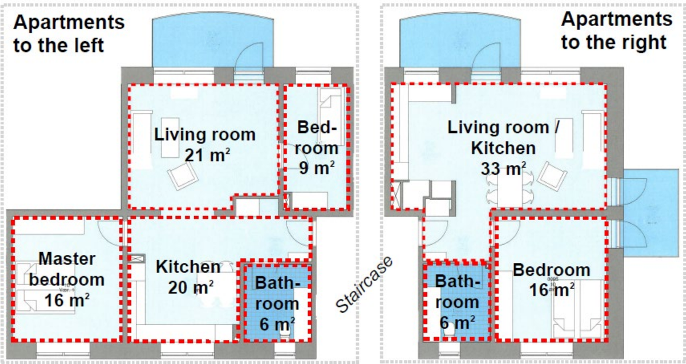


Figure 1. Floorplan of the apartment types with room type and floor area.

All rooms in the apartments are heated and cooled by hydronic floor heating, and ceiling cooling. The heating demand is entirely covered by the ground source water-to-water heat pump which is placed in the basement. Each apartment is equipped with a decentralized Air Handling Unit (AHU) supplying constant air ventilation (CAV).

The case study has several sensors logging various parameters in both the apartments and at system level monitored with a Building Management System (BMS) down to 5-minute resolution extracted with a Representational State Transfer Application Programming Interface (REST API). Relevant for this study, the following parameters have been studied: indoor air temperature (°C) and setpoint temperature for heating in each room (°C) at room level. Furthermore, the heating power (kW) which is integrated over the desired time to convert to heating energy use (kWh) at apartment level. The reference- and the BPS model data were aggregated (sum) from the highest resolution (5-minutes) to the desired resolution for comparisons.

Table 1. Case study building properties.

Building properties	**Value**
U-values (W/m^2 K)	
Floor	0.77
Walls	0.15
Roof	0.08
Windows	1.10
Other envelope properties	
g-value	0.71
Total window area per apartment (Ground fl. to Second fl. Apt.)	**Left apt:** South: 6.8 m^2, North: 5.7 m^2 **Right apt:** South: 6.6 m^2, North: 3.5 m^2, West: 4.3 m^2
Infiltration rate at 50 Pa	1.5 h^{-1}
HVAC parameter	
Designed ventilation air flow rate	90 m^3/h Supply airflow in bedroom and living room Exhaust airflow in kitchen and bathroom

2.2. Modelling framework

Four BPS models were created in the IDA ICE software. Table 2 describes the temporal and spatial resolution scenario models developed in this study.

In the multi-zone model, each room is modelled as individual thermal zone with unique heating set-point, whereas in the single zone model, the whole apartment is a thermal zone with the same heating setpoints assigned to all rooms. The heating setpoint is defined as the average of the logged values of the apartment during the defined heating period.

The heating period was defined from 19.01.2022 – 01.05.2022 and 01.09.2022 to 19.01.2023. The January dates are chosen due to availability of data. This period is chosen as the "heating period" as the heating was activated in all the apartments.

Table 2. The description of the temporal and spatial resolution scenario models developed in this study.

Model descriptions Spatial- and temporal resolution data	**5-minute resolution**	**60-minute resolution**	**Daily resolution**	**Monthly resolution**
Reference: Monitored heating energy use data from each apartment (six apartments in total)	X	X	X	X
Model A: Multi-zone (MZ) model (IDA ICE software) Reference MZ (control modeling of low-resolution inputs)	X	-	-	-
Model B: Multi-zone (MZ) model (IDA ICE software) Hourly MZ (control modeling of high-resolution inputs)	-	X	X	X
Model C: Single-zone (SZ) model (IDA ICE software) Reference SZ (simplified approach, low-res. data)	X	-	-	-
Model D: Single-zone (SZ) model (IDA ICE software) Hourly SZ (simplified approach, high-res. data)	-	X	X	X

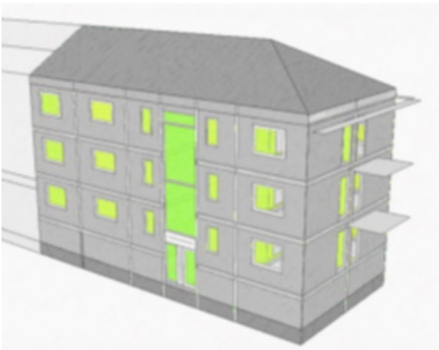


Figure 2. Snip from the geometry of the IDA ICE model.

Figure 2 shows a snip from the geometry from the IDA ICE software model of the multi-story building. The BPS models were designed to resemble the real conditions of the case study as detailed as possible. This included the heating system, the occupant presence, internal loads, solar shading, occupant behavior (heating setpoints and window opening). The IDA ICE input values can be found in the GitHub repository stated in the end of this article. The weather file used was modified using monitored weather data from a grid (10kmGridValue) as close to the study case as possible from the Denmark Metrological Institute (DMI) [7]. The derived parameters were outdoor air temperature, relative humidity, wind speed and direction. Diffuse and direct solar radiation was used from the ASHRAE IWEC2 weather file located in "Skagen", Denmark [8].

3. Results and discussion

3.1. Heating period total energy use

Table 3 presents a yearly comparison of all BPS models and their corresponding temporal resolution against the reference data with the same resolution. The reference data is naturally similar for all resolutions due to the aggregation. The analysis reveals that the largest differences between the BPS models and reference data are observed at the 5-minute and 60-min resolutions. The models' performance at higher resolutions is performing relatively better, with smaller deviations observed between the models and reference data.

Table 3. Yearly comparison of all models and temporal resolution.

Reference data and model description	**Sum of yearly total energy use [kWh/year]**	**Deviation from Reference [%]**
Reference data; 5-, 60- min, daily and monthly resolution	14.644	-
5-min. res.		
Model A – Multi-zone	15.906	9
Model C – Single-zone	15.903	9
60-min res.		
Model B – Multi-zone	15.817	8

Model D – Single-zone	15.390	5
1-day res.		
Model B – Multi-zone	15.908	9
Model D – Single-zone	15.484	6
1-month res.		
Model B – Multi-zone	12.998	-11
Model D – Single-zone	12.605	-14

3.2. Heating energy use load duration curves

The load duration curves for the reference data and BPS models with different resolutions can be seen in the Figure 3 below. All the BPS models show discrepancies in both the higher and lower values, leading to a higher heating energy use in the BPS models.

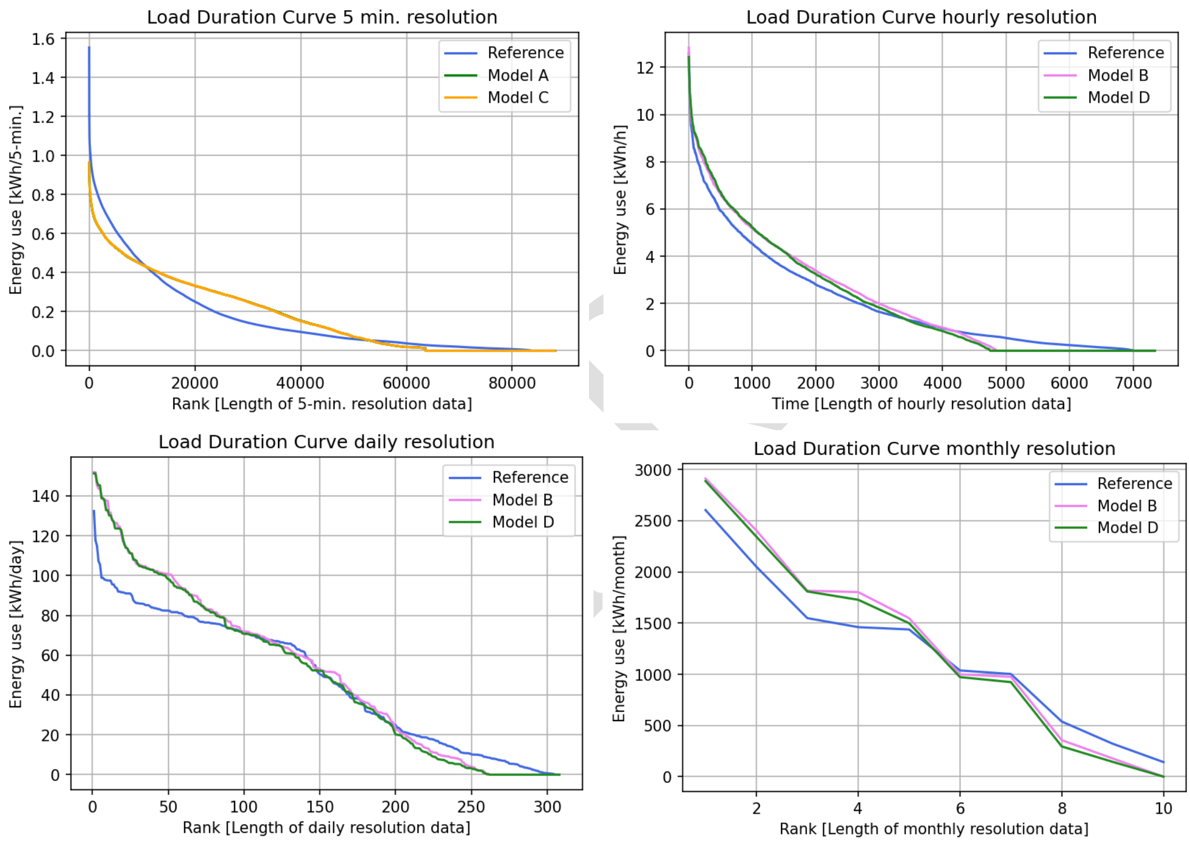
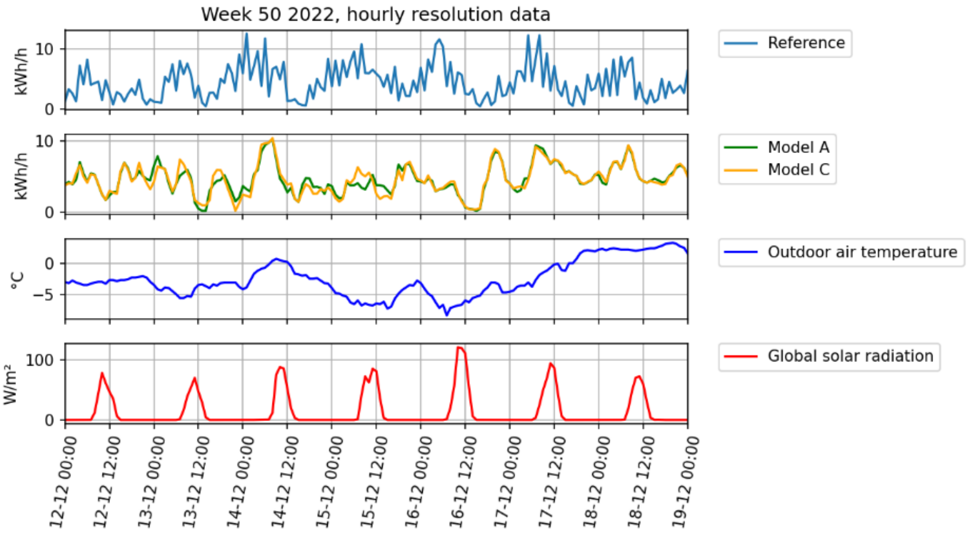


Figure 3. Heating energy use load duration curves for all defined resolutions. Top left 5-minute resolution, top right hourly resolution, bottom left daily resolution and bottom right monthly resolution.

3.3. Highest heating energy use week for the heating period: Week 50, 2022

Figure 4 provides a weekly overview of the heating period, displaying the hourly resolution of the reference data and corresponding BPS models. The explanatory variables: outdoor air temperature, and global solar radiation (from Tylstrup weather station in North Jydland) are plotted below to visualize their effects on heating energy use. The reference data shows a natural trend of increasing the heating energy use with decreasing outdoor air temperature due to heat loss through the building's envelope. Additionally, the heating energy use tends to decrease with increased global solar radiation around noon. However, the BPS models shows greater sensitivity to the global solar radiation, with little or no delay observed in decreased heating energy use, unlike the reference data where a delay is apparent. This may be attributed to the models' simplified representation of the building's thermal characteristics, which may not fully capture the complexities of the building's response to varying environmental conditions.



Furthermore, the analysis reveals that there is no significant difference in performance between the multi-zone and single-zone BPS models, indicating that the single-zone model is sufficient for capturing the building's thermal behaviour accurately.

Figure 4. Highest heating energy use week over the heating period: Week 50, 2022.

3.4. Indoor air temperature

Figure 5 presents the load duration curves for the multi-zone indoor air temperature of the reference data and the BPS models at both 5- and 60-minute resolutions. Each legend in solid- (reference data) and dashed line (BPS model) colour is corresponding to each apartment. The indoor air temperature data were averaged over the defined heating period for each of the six apartments.

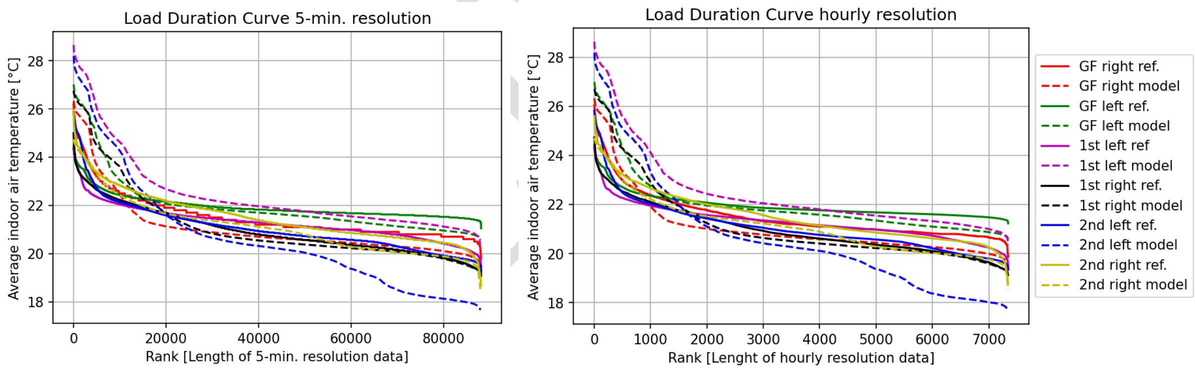


Figure 5. Load duration curves for the multi-zone indoor air temperature of the reference data and the BPS models at both 5- (to the left) and 60-minute (to the right) resolutions.

The analysis reveals that there is no significant difference between the 5- and 60-minute resolution data for either the reference data or the BPS models. However, a larger fluctuation of the 5-minute resolution reference data and BPS models was expected as this resolution would capture the dynamics in the apartments faster than the 60-minute resolution. All the BPS models show higher calculations of higher indoor air temperatures, as well as over a more extended period, represented by the dashed line in the figure. The discrepancy may be attributed to the model inputs, either at system or at the apartment level.

4. Conclusion and suggestions for future work

This study demonstrates how the spatial- and temporal resolutions of the input data affect the potential of building performance simulation (BPS) models to provide reasonably accurate estimates of a building's heating energy use and indoor air temperature. The findings suggest that low-resolution (hourly or lower) data may be necessary to capture the nuances accurately for the heating energy use. However, to capture the nuanced response to variables such as indoor air temperature accurately, qualitative knowledge on model inputs, including human-building interactions, may be necessary. Furthermore, modeling of multi- and single zones does not make a significant difference in buildings with similar temperatures within rooms. Furthermore, this study highlights the importance of considering environmental variables in BPS models and the need to calibrate them for accuracy and reliability in calculating heating energy use and indoor air temperature. As seen in the heating energy use load duration curves, there is a discrepancy that requires further investigation. Additionally, the study underscores the importance of further research on different levels of detail in modeling inputs, including building geometry complexity, zoning, and inclusion of elements in buildings that are often disregarded. The findings of this study may have practical implications for building designers and operators seeking to optimize building energy performance and indoor comfort using a BPS model. It can also contribute to the discussion on the comprehensiveness of a monitoring system a building (number of sensors and the resolution of the data) in order to capture and build a representative BPS model.

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Data Availability Statement

The data, the IDA ICE inputs, and supplementary material used in this article can be found at the following GitHub repository: https://github.com/aauphd2024. The analyses are performed using Python 3.8.16/Spyder 5.

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