Regression analysis of the energy consumption of tertiary buildings

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Abstract

Energy signature methods are applied over three tertiary buildings in the UK, Sweden and Spain, based on both simulations and experimental data, for pre- and post-retrofit scenarios. Variations in their energy profiles relate to differences in climate severity, usage pattern (continuous/discontinuous) and HVAC scheduling. This study discusses the impact of such particularities for obtaining a steady-state linear regression model of the dependence of heating energy load against climate data. The choices of dataset and time step have important implications for the results obtained.

1. Introduction

Energy signature models estimate the energy consumption of a building as a function of external climate data. They are typically presented as a plot of total energy consumption versus ambient air temperature [1]. However, the static nature of such methods does not consider variations induced by dynamic effects. Furthermore, use patterns and user behavior are known to have a critical impact on energy consumption. The use of daily intervals can provide additional insight into unusual energy demands compared to monthly or weekly signatures [2]. Finally, additional

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challenges are posed by the application of energy signature methods to non-residential buildings and air conditioning systems, as assumptions that hold for heating systems of residential buildings do not necessarily apply [3].

This paper discusses the suitability of different time intervals, resampling and aggregation techniques for obtaining a steady-state energy signature model of non-residential buildings. Three buildings of tertiary use are considered as case studies, assessing the impact of climate severity, usage pattern and HVAC operation on their characterization through linear regression methods.

Fig. 1. (a) University Building in the United Kingdom; (b) Secondary School in Sweden; (c) Hospital Building in Spain.

These three buildings have different uses and occupancy schedules, and cover a range of European climates (oceanic, continental/subarctic and Mediterranean).

The University Building (Fig. 1a), which houses a faculty located within an educational campus in the United Kingdom, was originally built in the 1970s. The Secondary School (Fig. 1b) is an aggregation of buildings constructed over many years, located in a Swedish city. Finally, the Hospital Building (Fig. 1c) is a facility located in the outskirts of a large city in the Mediterranean coast of Spain.

All three buildings underwent retrofit interventions to improve their energy efficiency and reduce consumption. For each of the case studies, there is available data for the original building prior to interventions (up to March 2015) as well as for the retrofitted state (from April 2016).

2. Method

Data sourced from simulations and monitoring campaigns have been compared, for both pre- and post-retrofit periods.

For both simulations and measurements, regression analysis has been performed in order to obtain the dependence of heating energy load against climate data. The mathematical identification of this dependence has been expressed as a simple linear regression, relating the rate of energy consumption Q (in kW) to external ambient temperature T (in °C), as follows: $Q \sim C_0 + C_1 \cdot T$

In order to assess the potential impact of different climate- and usage-induced patterns on the regression analysis, three different resolutions have been considered, with hourly, daily and monthly intervals. In this context, the use of energy consumption rate and temperature in the equation above (instead of energy consumption and degree-days) allows for a direct comparison of average performance among time intervals of differing length (e.g. hour to day, or January to February). It also allows the resampling of experimental measurements including missing values to coarser time intervals, as the resampling is carried out by averaging rather than by aggregation.

3. Analysis and results
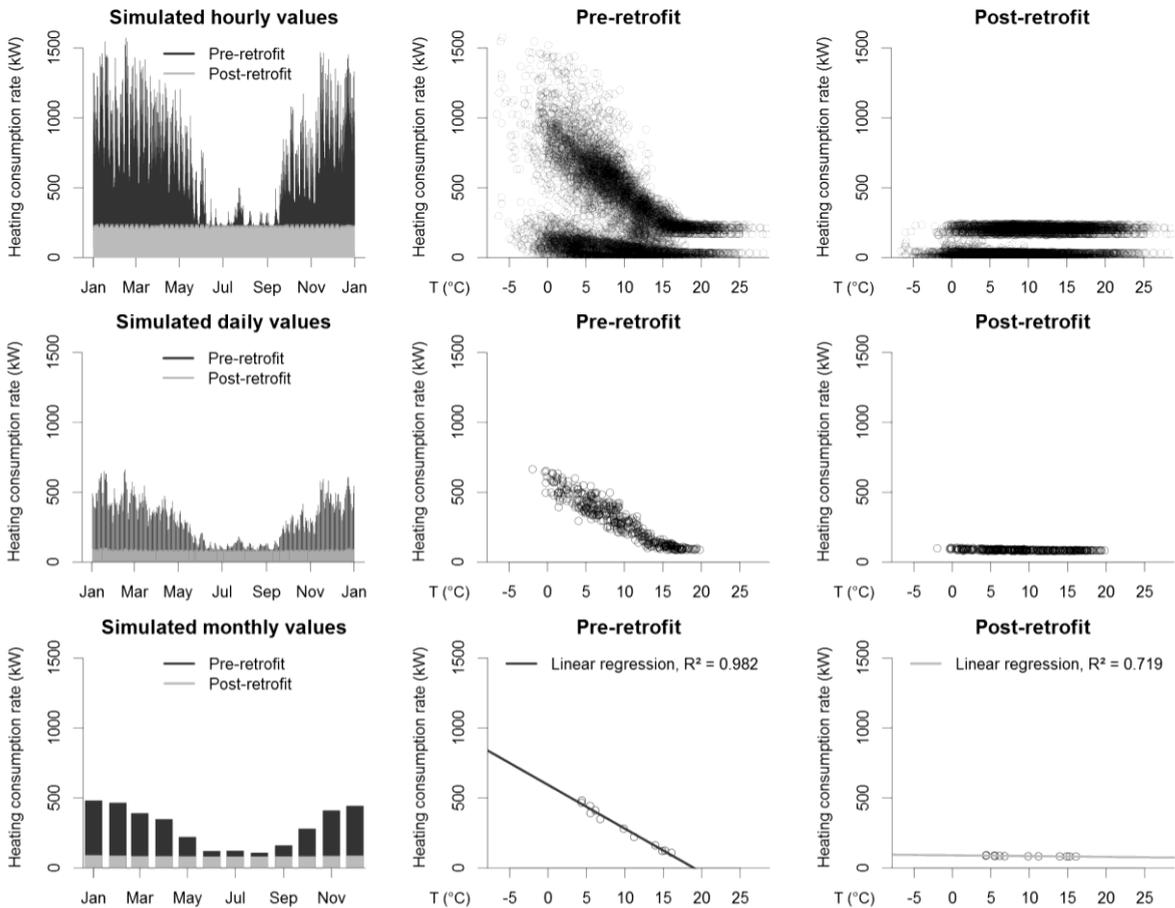
3.1. University Building

Fig. 2. University Building data from simulations, with hourly (top row), daily (middle row) and monthly (bottom row) resolution. Heating energy consumption rate over time (left) and dependence on external ambient temperature (middle and right).
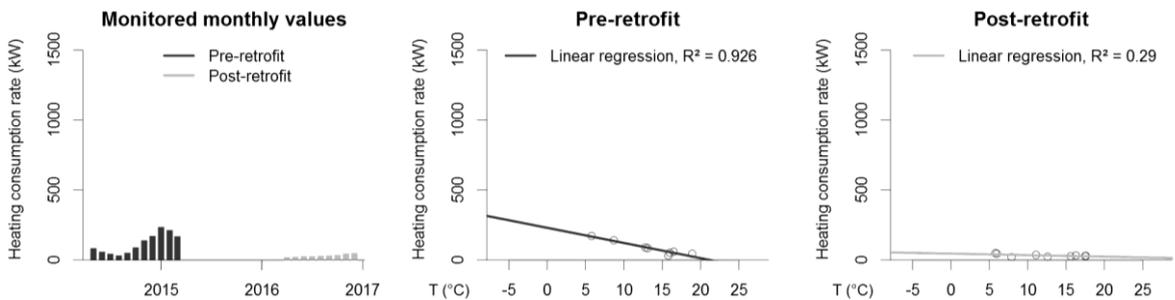

Fig. 3. University Building data from measurement, with monthly resolution.
Heating energy consumption rate over time (left) and dependence on external ambient temperature (middle and right).

The data in the hourly simulations of the University Building (top row in Fig. 2) is split in two very segregated sets, corresponding to daytime (peak energy consumption) and night-time (lower consumption). In the simulations with daily resolution (middle row in Fig. 2), the day/time pattern is neutralized but some variance still remains,

presumably related to occupancy. Pre-retrofit hourly and daily simulations show a quasi-linear relationship between consumption rate and external temperature below 18 °C, and a baseline energy consumption at higher temperatures, probably related to water heating. In contrast, post-retrofit simulations show an energy consumption that keeps within the baseline and varies very little with external temperature. Finally, averaging simulation data into monthly averages (bottom row in Fig. 2) allows for a better fit into a simple linear regression model.

The original building followed a seasonal pattern with energy consumption closely correlated to temperature (middle column in Fig. 2), while the post-retrofit simulation has little or no seasonal pattern (right column in Fig. 2). Results from monitoring (Fig. 3), while generally showing a lower consumption than predicted by simulations, confirm the foreseen reduction in energy use both in its extent and distribution along the temperature scale.
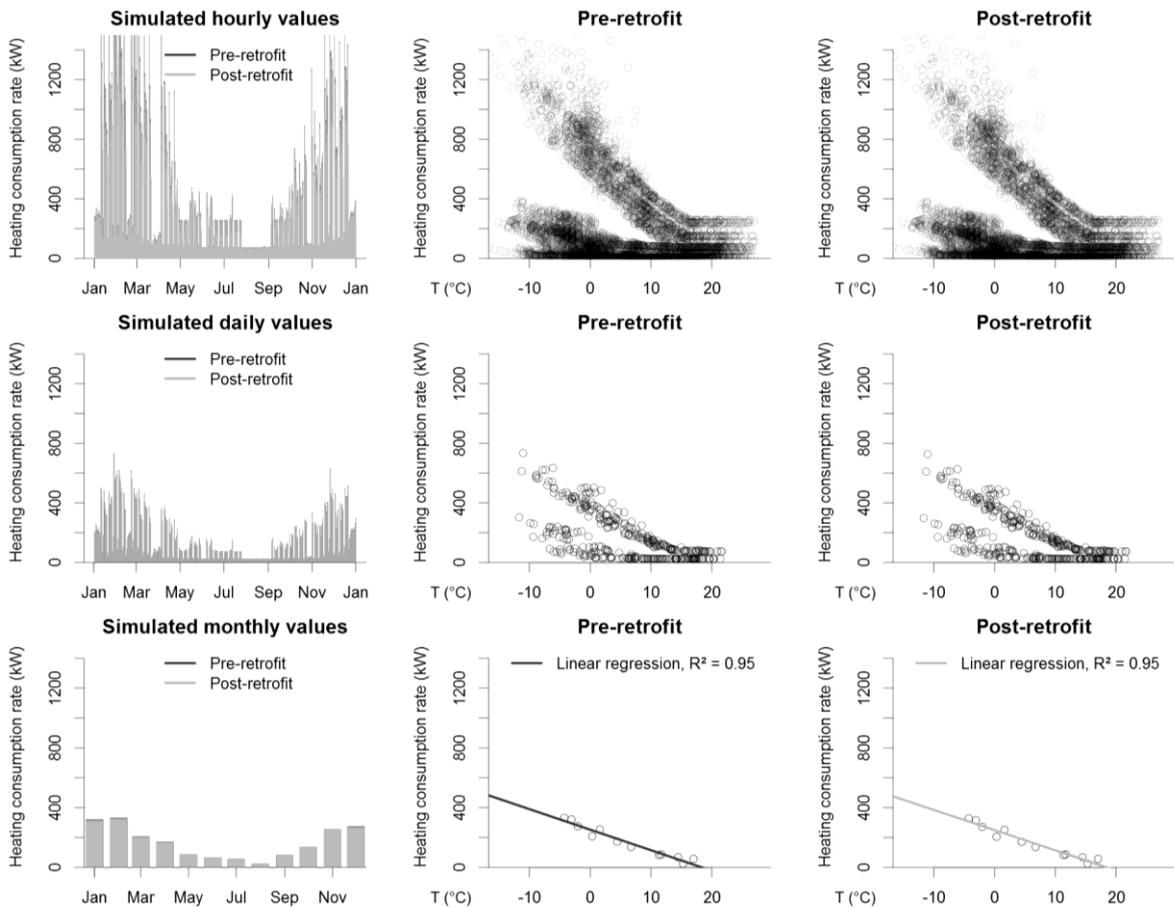
3.2. Secondary School

Fig. 4. Secondary School data from simulations, with hourly (top row), daily (middle row) and monthly (bottom row) resolution. Heating energy consumption rate over time (left) and dependence on external ambient temperature (middle and right).

The simulations for the Secondary School expect little change in energy consumption after the retrofit intervention. Both hourly data (top row in Fig. 4) and daily data (middle row in Fig. 4) are split in two separate sets. Interestingly, this segregation remains in the daily simulations (in contrast to the University Building) because the variance in energy consumption attributed to occupancy (school days vs. weekends/holidays) is stronger than the day/night cycle. Note that a constant baseline consumption is achieved above rather low temperatures (14 °C with the building in use, and 7 °C when unoccupied), indicating a good level of insulation in the building envelope. Again, resampling simulation data into monthly intervals achieves the best fit for a linear regression model.
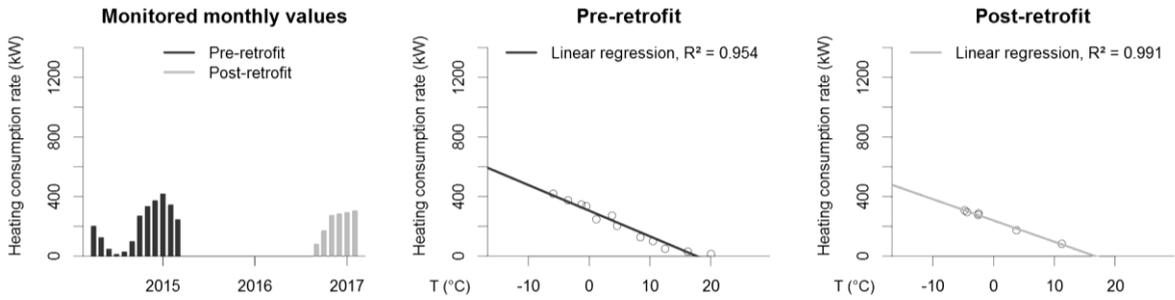
Fig. 5. Secondary School data from measurement, with monthly resolution.
Heating energy consumption rate over time (left) and dependence on external ambient temperature (middle and right).

The strong correlation of energy use with occupancy and the predicted temperature thresholds for baseline energy consumption were confirmed by monitored data. Albeit the seasonal pattern concurs, the measured reduction in energy use is higher than expected by simulations. The accuracy of these results might be affected by the relatively limited extent of the retrofit interventions and the scarcity of summer data for the post-retrofit period.
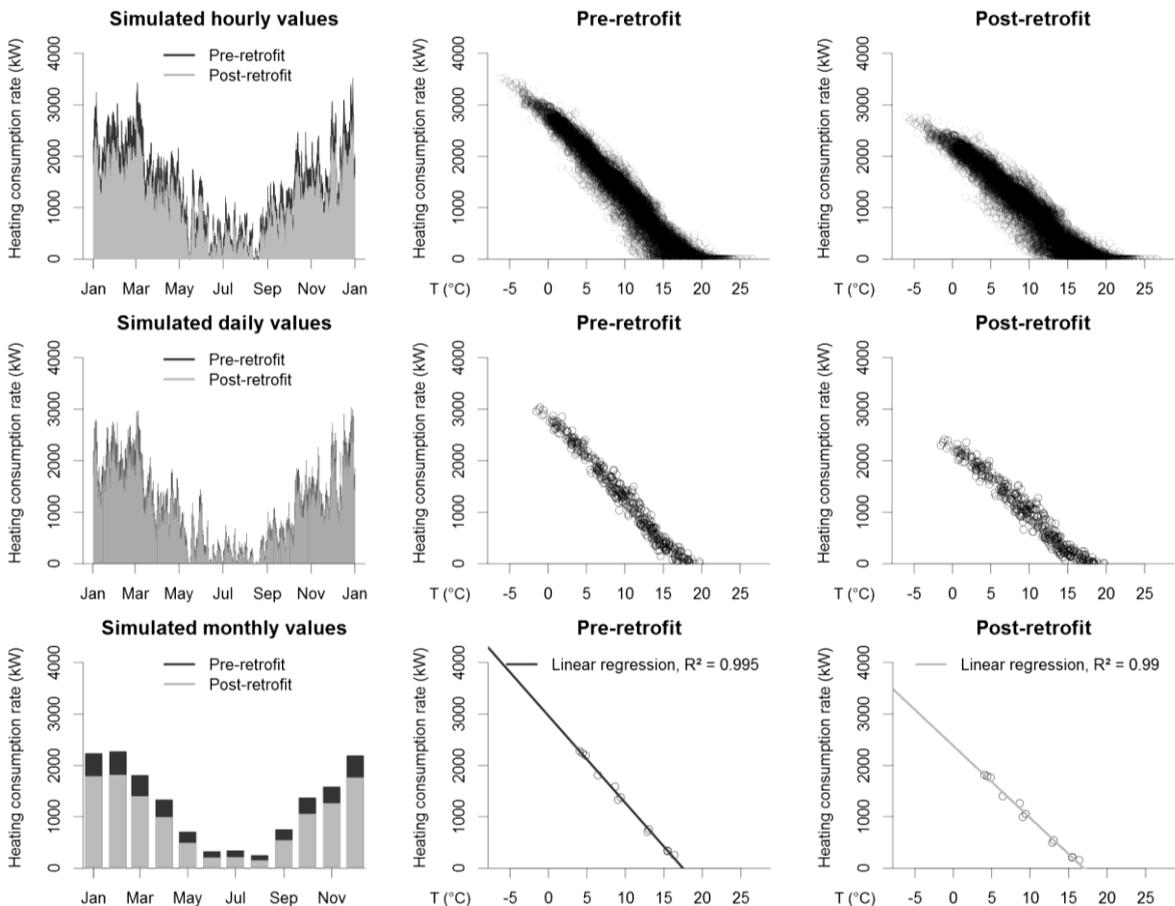
3.3. Hospital Building

Fig. 6. Hospital Building data from simulations, with hourly (top row), daily (middle row) and monthly (bottom row) resolution.
Heating energy consumption rate over time (left) and dependence on external ambient temperature (middle and right).

Simulations for the Hospital Building (Fig. 6) show little variation of energy use at nights or weekends, due to the continuous usage requirements associated to a hospital. In addition to this, the simulations show no indication of a baseline energy consumption, which can be attributed to poor levels of insulation as well as to the absence of high temperatures in the dataset. These factors result in a somehow exceptional condition in that energy use has a strong linear correlation with external temperature, even when measured at hourly intervals. Despite the 20-30% reduction in energy use expected by simulations, measurements (Fig. 7) show no evidence of a decrease in energy use.
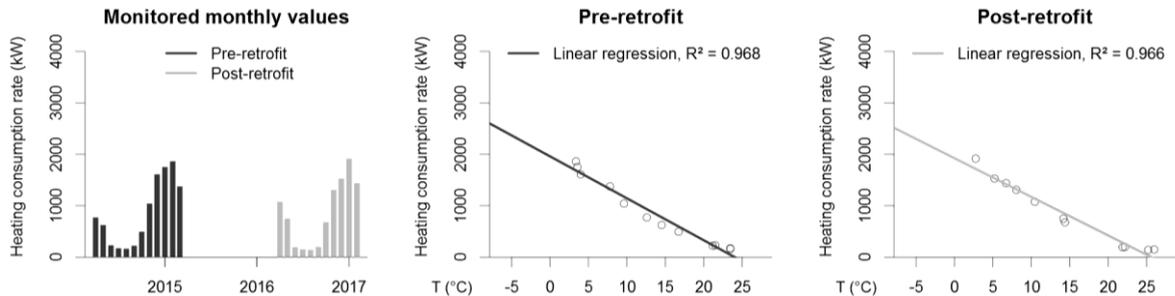

Fig. 7. Hospital Building data from measurement, with monthly resolution.
Heating energy consumption rate over time (left) and dependence on external ambient temperature (middle and right).

4. Conclusions

The energy performance of three buildings of tertiary use has been evaluated using energy signature methods. For each building, the impact of energy efficiency interventions was observed, by comparing pre- and post-retrofit data from simulations and measurements. Reductions in energy consumption from measurements matched simulations for one of the buildings, exceeded predictions in another one, and fell short of expectations in the latter case.

Three different types of transient patterns have been observed for energy use, based on annual, weekly and daily cycles. Seasonal variations over the year are directly related to climate, can be traced with monthly measurements of external temperature and energy use, and contain information about the energy signature of the building. The weekday/weekend pattern can only be measured using readings of at least daily resolution, while the day/night cycle requires sub-daily (e.g. hourly) measurements. While the latter two patterns contain information on the short-term energy performance of the building, these can only be indirectly determined in the absence of occupancy data.

The optimum time step adopted for energy signatures depends on the usage pattern of the building, as well as the availability of data. Buildings that are in continuous use (such as hospitals) allow daily measurements, while a discontinuous use might require longer intervals in order to balance disruptions correlated with usage patterns.

Weekly time steps pose an intermediate case between daily and monthly intervals. Even though they have not been considered in this study, they might prove suitable for datasets of limited size such as the ones assessed here.

Acknowledgements

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