Urban-scale dynamic building energy modeling and prediction using hierarchical archetypes: A case study of two Danish towns

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Introduction

It remains practically infeasible to gather all the required data inputs for physics-based urban building-by-building energy modelling (Reinhart and Davila, 2016). Simplifications may therefore be necessary, e.g. through archetype segregation of the building stock to reduce the task of data acquisition and calibration of uncertain parameters. The authors of this extended abstract recently proposed a novel hierarchical archetype calibration methodology that allows a robust probabilistic inference of unknown archetype input parameters for unseen buildings belonging to an archetype (Kristensen et al., 2018). The methodology has been proven fast and accurate for urban-scale predictions of aggregated building energy use under uncertainty.

In this contribution we demonstrate how hierarchically calibrated archetype models of Danish detached single-family houses (SFH's) can accurately predict the urban district heating energy use of unseen buildings in two different suburban towns. We end up by discussing the various practical applications of such urban models.

Methods

Data

Three-hourly district heating (DH) energy consumption data for 27,000 SFH's located in the municipality of Aarhus, Denmark, were coupled with six building-specific data fields from the Danish Building and Dwelling Register (BDR): 1) usage type, 2) construction year, 3) footprint, 4) number of floors, 5) basement and 6) attic area utilized for living/heated. The DH time series consisted of combined energy use for space heating and on-site domestic hot water (DHW) preparation.

Archetype segregation

The building stock was partitioned into nine SFH archetypes following the building stock segregation performed Danish Building Research institute as part of the European research project TABULA (Wittchen and Kragh, 2012). Only the construction year was used for segregation. The nine archetype age groups are shown in Table 1.

Building energy modeling

The DH energy use time series of each building was modeled using the hourly dynamic resistance-capacitance model of ISO 13790:2008 that treats each building as a single thermal zone, in combination with a simple DHW consumption model. The only available and known data inputs were the footprint, number of floors, and the heated basement and attic area (besides basic climate data logged from a nearby weather station). All other inputs necessary to simulate the BEM were unknown at the level of individual buildings. A-priori probability density functions (PDF's) or fixed values were therefore given each uncertain input parameter at the level of archetypes to reflect historical data and educated guesses.

Hierarchical archetype calibration

The archetype calibration methodology proposed by (Kristensen et al., 2018) was applied to infer a-posteriori PDF's for six of the uncertain parameters per archetype: 1) window-floor ratio, 2) U-value of ext. walls/roof, 3) capacity of thermal mass, 4) infiltration airflow@50pa, 5) occupant density, and 6) room heating set point temperature. The methodology applies a Bayesian hierarchical formulation that binds training buildings together around a shared archetype estimate whereby the inference draw strength from all training building datasets simultaneously. The methodology allows training buildings that are very "likely" to dominate the inference of uncertain parameters, while outlying/unlikely buildings are given less weight – a process known as "shrinkage". Each archetype was trained on a sample of 35 randomly selected SFH's from the dataset, each with time series of three-hourly DH energy use of January 2017 (248 data points).

Urban case towns for prediction

Two suburban case towns were selected for validation of the urban-scale predictive capabilities of the archetype framework: 1) "DK-8250 Egå" and 2) "DK-8330 Beder" (Table 1). February 2017 (224 data points) was used for validation.

Table 1
Classification of case town buildings into nine archetypes.

Archetype partitioning	DK-8250 Egå	DK-8330 Beder
Arch. 1 (1851-1930)	105 (4.9%)	56 (8.1%)
Arch. 2 (1931-1950)	37 (1.7%)	43 (6.2%)
Arch. 3 (1951-1960)	74 (3.4%)	12 (1.7%)
Arch. 4 (1961-1972)	1166 (54.2%)	302 (43.8%)
Arch. 5 (1973-1978)	369 (17.1%)	83 (12.0%)
Arch. 6 (1979-1998)	226 (10.5%)	149 (21.6%)
Arch. 7 (1999-2006)	129 (6.0%)	37 (5.4%)
Arch. 8 (2007-2010)	21 (1.0%)	4 (0.6%)
Arch. 9 (2011-2015)	26 (1.2%)	4 (0.6%)
Total, n_b	2153 (100%)	690 (100%)

Results

The measured and simulated DH energy use of the two case towns is shown in Fig. 1 and measures of predictive performance are given in Table 2.

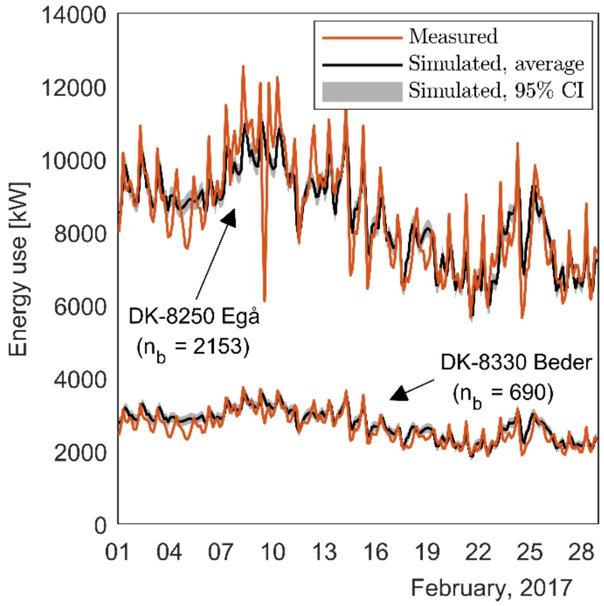

Fig. 1. Measured and simulated aggregated DH energy use (three-hourly) of two suburban towns, respectively. Simulated energy use consist of the 95% central posterior density region derived from aggregating 1000 random simulations from each of the individual building energy models. The average of the 1000 aggregated simulations is highlighted in black.

Table 2
Measures of predictive performance.

Metric	DK-8250 Egå	DK-8330 Beder
NMBE	0.4%	4.2%
MAPE	6.8%	7.2%
CVRMSE	9.0%	8.5%
R^2	74.0%	78.4%

The simulated energy use fit the measured energy use very well. The entire energy consumption of the validation period was predicted within a 4.2% error margin for both towns when measured with the normalized mean bias error (NMBE) metric. The accuracy of which individual data points (three-hourly values) were predicted was measured with the mean absolute percentage error (MAPE) metric to be within 7.2%. The coefficient of variation of the root mean squared error (CVRMSE) and the coefficient of determination (R^2) measures the variability of the residuals and thus the explanatory power of the predictions. The two urban models explained approx. 74%-78% (R^2-values) of the variability in the measured time series.

Discussion

Urban-scale models of this kind may allow city governments, utility companies, and other energy policy stakeholders that work on the urban scale of neighborhoods, cities, or even entire building stocks, to plan and predict the effect of various energy efficiency measures and production strategies. The application of simple and publicly available building and property information as the only need-to-have input data about the buildings to be predicted (besides measured energy use datasets from a subsample of buildings for the initial archetype calibration) provides a flexible platform that can easily be expanded or further developed. Because the model structure is based on thermodynamic principles, it may also have use in investigating urban-scale effects on e.g. peak loads and overall energy use due to various interventions in the building stock, e.g. retrofitting, city densification or expansion, and building technologies for facilitating demand response programs.

The application of archetypes to represent the building stock is obviously a crude simplification of its true diversity. However, applying a probabilistic representation and calibration of the uncertain archetype parameters on the level of individual buildings through a hierarchical structure like in this study preserves much of the natural heterogeneity that defines the variability within archetypes. This preservation of heterogeneity is crucial for accurate predictions of new and unseen buildings from the archetypes.

The hierarchical archetype framework proves capable of predicting the aggregated energy use of buildings in larger urban areas with high accuracy as demonstrated for two suburban towns in this study. Although the framework remains to be implemented for other buildings than detached single-family dwellings in order to fully represent a true urban area with many different building types, we do not believe this to pose any difficulties for the framework. The temporal resolution of the predictions is in no way limited to three-hourly data points, but solely defined by the underlying physical model structure and quality of calibration data. Urban models of increasing temporal resolution will therefore be possible in the near future as the distribution of smart energy meters proceed to penetrate the marked.

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