Quantifying Uncertainties in an Archetype-Based Building Stock Energy Model by Use of Individual Building Models

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***Abstract*—Focus on reducing energy consumption in existing buildings at large scale, e.g. in cities or countries, has been increasing in recent years. In order to reduce energy consumption in existing buildings, political incentive schemes are put in place and large scale investments are made by utility companies. Prioritising these investments requires a comprehensive overview of the energy consumption in the existing building stock, as well as potential energy-savings. However, a building stock comprises thousands of buildings with different characteristics making it difficult to model energy consumption accurately. Moreover, the complexity of the building stock makes it difficult to convey model results to policymakers and other stakeholders.

In order to manage the complexity of the building stock, building archetypes are often employed in building stock energy models (BSEMs). Building archetypes are formed by segmenting the building stock according to specific characteristics. Segmenting the building stock according to building type and building age is common, among other things because this information is often easily available. This segmentation makes it easy to convey results to non-experts.

However, using a single archetypical building to represent all buildings in a segment of the building stock is associated with loss of detail. Thermal characteristics are aggregated while other characteristics, which could affect the energy efficiency of a building, are disregarded. Thus, using a simplified representation of the building stock could come at the expense of the accuracy of the model.

The present study evaluates the accuracy of a conventional archetype-based BSEM that segments the building stock according to building type- and age. The accuracy is evaluated in terms of the archetypes' ability to accurately emulate the average energy demands of the corresponding buildings they were meant to represent. This is done for the buildings' energy demands as a whole as well as for relevant sub-demands. Both are evaluated in relation to the type- and the age of the building. This should provide researchers, who use archetypes in BSEMs, with an indication of the expected accuracy of the conventional archetype model, as well as the accuracy lost in specific parts of the calculation, due to use of the archetype method.

***Keywords*—Building stock energy modelling, energy-savings, archetype.

I. Introduction

ASSESSING the energy-saving potential of a building stock entails modelling the energy demand of numerous buildings with diverse characteristics [1]. Building archetypes offer a way to summarise these characteristics, whether large amounts of data is available (e.g. from Energy Performance Certificates) or little information is available. Therefore, building archetypes are frequently used in building stock energy models (BSEMs) for assessing the energy-saving potential in national- as well as sub-national building stocks [2].

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Limited access to relevant building stock data is often an obstacle in building stock energy modelling; however, information about the building type and building age is available in most countries. Therefore, segmenting the building stock is by means of these two characteristics is widely used, e.g. in the European project TABULA (Typology Approach for Building Stock Energy Assessment) [3] and EPISCOPE (Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks) [4].

In cases where little or no information is available, example buildings can be used. These can either be real buildings that are deemed representative of a segment of the building stock or artificial buildings constructed on the basis of expert knowledge and historical information about building traditions [5]. Using this approach, defining building archetypes that are representative of the older segments of the building stock is particularly difficult, e.g. if building codes had not been put in place or buildings have been energy-upgraded.

In cases where data on physical properties of the building stock is available, "average buildings" can be constructed. This type of model often rely on central tendency measures (e.g. mean values) or statistical analyses [6] of *input values* from the buildings under consideration, in order to ensure that the archetypes are representative of the building stock they are meant to represent.

Thus, building archetypes offer a simplified representation of a diverse building stock. However, simplification could come at the expense of accuracy, i.e. using representative input values warrants no guarantee of the accuracy of the output (e.g. in terms of the average energy demands of each segment). Moreover, the accuracy depends extensively on the available input data, as well as the particular calculation model.

Therefore, we addressed the accuracy using building archetypes, in relation to the simplicity of the model. This was done by comparing the calculated heat demands from two data based (i.e. average-building) archetype-based models with the corresponding heat demand calculated for each building separately with the purpose of quantifying inherent uncertainties in the archetype approach to building stock energy modelling.

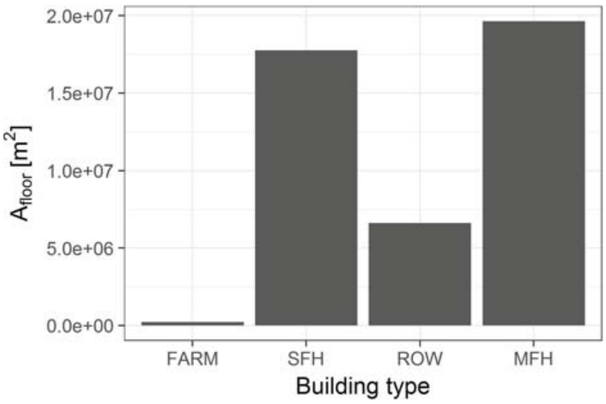

Fig. 1 Distribution of buildings in the considered data set

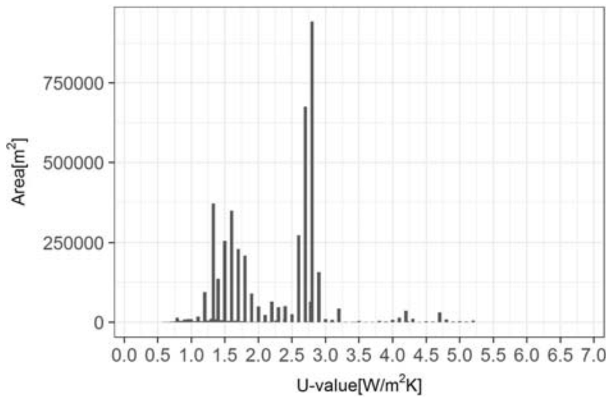

Fig. 2 Thermal properties of all windows in the considered sample

II. Data Description

In the present study, data from the Danish Energy Performance Certificate (EPC) database was used. The Danish EPC database contains information about the physical (including thermal) properties of each building element in each building, making it possible to construct comprehensive 'average building' archetypes. In addition to the information about the thermal properties of the buildings, information about building type and building age was available for all buildings.

Data on 171.283 buildings was used in the study, which included four residential building types; these were farmhouses (FARM), detached single-family houses (SFH), terraced houses (ROW) and multifamily houses (MFH). In all cases, each building was considered as one unit; i.e. multifamily houses and row-houses could potentially contain more than one apartment. The distribution of buildings is depicted in Fig. 1.

Evidently, SFH and MFH constitute the largest fraction of buildings in the considered sample, reflecting the composition of the Danish building stock well.

All data was collected by energy experts data from 2006 to 2015 as part of issuing Energy Performance Certificates. This data is stored by the Danish Energy Agency and was put at the authors' disposal to be used for research purposes.

No information was available about appliances of lighting, for which reason only heat demands were considered. However, as Denmark is a heating dominated country, this should not affect the results notably.

A. Input Values

Transmission losses were calculated on the basis the thermal properties of each part of the building envelope (i.e. U-values, areas and temperature factors). Solar heat gains were calculated for all windows taking the optical properties (i.e. g-values), orientation and shadows on the windows into account.

In order to provide an indication of the diversity of the building physical parameters, the thermal properties of all windows in the sample are depicted in Fig. 2.

Ventilation losses were calculated considering naturally- and and mechanically ventilated areas, including heat recovery.

In addition to transmission- and ventilation losses, heat losses from heat distribution (HD) pipes and domestic hot water (DHW) pipes were calculated, as well as heat losses from DHW tanks. This was also done on the basis of registered heat loss coefficients, lengths and temperature factors.

It should be noted that values in the EPC database are most often based on manufacturer information, e.g. U-values printed on a spacer of a window, or tabulated values listed in the Danish handbook for energy experts [7]. Therefore, some values, such as the air change rate due to natural ventilation, were likely to be very similar in all buildings of the same age.

B. Assumptions and Typical Values

In addition to the input values on the thermal characteristics of the buildings, which were specified by the energy experts, a fixed average indoor temperature of 20 °C was assumed. Furthermore, some standard values were assumed by the energy experts, for which reason they were nearly identical in almost all buildings. These values are listed in Table I.

TABLE I
Assumptions and Typical Values Used in the Heat Demand Calculations

	Value	Unit
Indoor temperature	20	°C
DHW use	250	l/m^2
DHW temperature	55	°C
Time of occupancy	24	h/day
Heat load from persons	1.5	W/m^2
Heat load from appliances	3.5	W/m^2
Ventilation rate	0.3	$l/(s \cdot m^2)$

Naturally, values that were assumed to be identical in all buildings do not affect the accuracy of an archetype-based BSEM compared with an individual building model because no simplifications are made and therefore, no information is lost. Hence, loss of accuracy in the archetype-based model could be ascribed to aggregation of the input values and not the assumed- and typical values.

C. Representative Values

In the present study, comprehensive average-building archetypes were used to represent the building sample. This

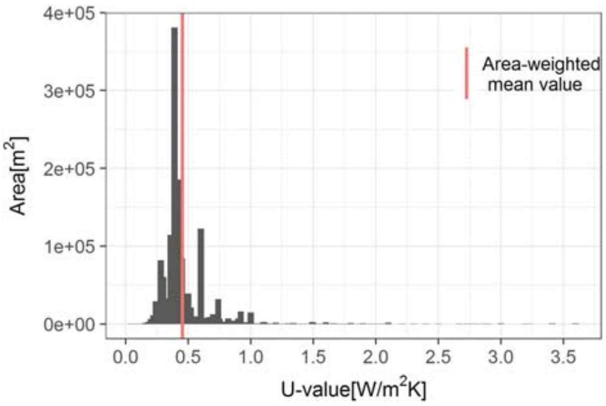

Fig. 3 U-values and corresponding areas of external walls in SFH built between 1961 and 1972. The red line denotes the area-weighted mean value

implied defining values that were representative for each archetype, e.g. a common U-value of the roofs of the buildings belonging to a particular archetype. Area-weighted mean values were used as a measure of representativity, as the mean value is presumably the most commonly used measure, e.g. [8] or [9].

The U-value of external walls in detached single-family houses built between 1961 and 1972 are plotted in Fig. 3 as an example of a typical distribution of the input values in buildings belonging to a particular archetype.

It should be noted that there was a relatively large spread on the input values, especially in older houses among some of which have been energy-upgraded. Aggregating this information into a single value (for each archetype), in terms of the area-weighted mean value, could affect the resultant heat demand as well as the related energy-saving potential.

III. Method

In order to access the accuracy of using an archetype-based model, we compared the calculated the heat demands of two archetype models with the heat demands calculated for each building individually. The first (comprehensive) archetype model was tuned to match the individual building model as much as possible. This included careful definition of all relevant input data, e.g. fractions of buildings that were mechanically ventilated and average heating distribution pipe lengths. Moreover, the comprehensive archetype model relied on the same calculation method as the individual building model. The second (simple) archetype model relied on a simplified (seasonal) calculation method, with the purpose of addressing uncertainties relating to the simplicity of the calculation method.

In addition to the total heat demand, relevant heat loses and heat gains (e.g. heat losses from building services and solar heat gains, internal heat gains and useful heat gains from building services) were compared for each of the archetype models and the individual building model with the purpose of quantifying inherent uncertainties in the archetype modelling approach.

The calculated heat demand comprised heat losses due to transmission and ventilation, as well as to heat losses from building services, i.e. domestic hot water (DHW) tanks, DHW pipes and heating pipes. Heat gains from persons, appliances and solar radiation and useful heat gains from building services were accounted for in all three models. The efficiency of different heat supply technologies (e.g. boilers or district heating exchangers) were not considered in the present study.

It should be noted that the same input data, as well as assumptions, were used in all three models, in order to make them perfectly comparable.

A. Model Description

The heat demands of each building in the sample were calculated on the basis of the monthly mean calculation method described in the European standard EN/ISO 13790 [10]; a description is provided in [11].

The first archetype model was based on the same calculation method as the individual building model, in order to make the two perfectly comparable. The second archetype model was based on a seasonal calculation model in which the Danish heating season served as a basis for calculation of the heat demands in each building archetype. This model was developed as part of the Danish contribution to the European TABULA project [12] and was included in this study to address implications of using a simplified calculation method.

Both archetype models relied on 36 archetypes that were developed based on the building type (farmhouse, detached single-family house, terraced house or multifamily house) and the year of construction. The age-division was based on shifts in Danish building traditions, as well as shifts in energy requirements in the Danish building code; the construction periods are listed in Table II.

TABLE II
Age-Division (Construction Periods) of the Danish Building Stock Used for Defining Building Archetypes

Period	Year of construction
P1	Before 1890
P2	1890 - 1930
P3	1931 - 1950
P4	1951 - 1960
P5	1961 - 1972
P6	1973 - 1978
P7	1979 - 1998
P8	1999 - 2006
P9	After 2006

In order to account for properties that were only present in some buildings (e.g. mechanical ventilation), the share of the heated floor area which was mechanically ventilated was defined for each building archetype. The orientation of the windows in each archetype were assumed to follow the standard distribution defined in the Danish voluntary energy labelling scheme for glazing and windows in which 41 % of the window area was facing south, 26 % of the window area was facing north and 16.5 % of the window area was facing east/west respectively [13]. Shadows on the windows (from surrounding obstacles and the window recess) were modelled as mean values, taking the registered values form the EPC database.

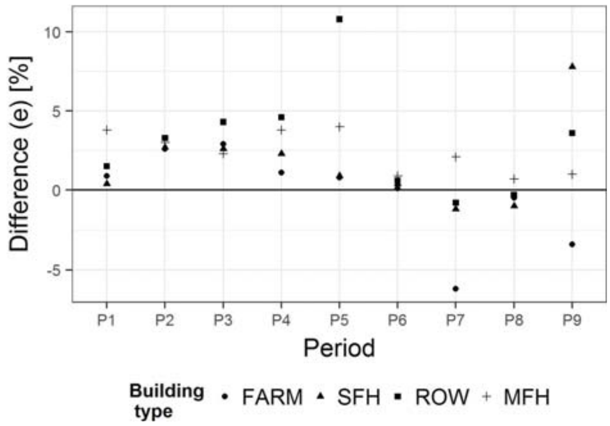

Fig. 4 Difference in average heat demand between the individual building model and the comprehensive archetype model for each building archetype

It should be noted that the the archetypes in this study were data based; i.e. average buildings. This implies that any observed discrepancies could be attributed to simplification of using building archetypes alone. This implies that example building-based archetype models could be subject to additional uncertainty.

IV. Results

In this section, we first compare the results from the comprehensive archetype model with the results from the individual building model. Next, the results from the simple calculation model are compared with the results from the individual building model to address implications of using a simplified calculation method.

A. Accuracy of the Comprehensive Archetype Model

Comparing the average heat demand of each archetype with the corresponding average heat demand from the individual building model served as a first assessment of the accuracy of the comprehensive archetype model.

In Fig. 10, the calculated heat demands of each building in the sample are depicted for each building type in each construction period. The area-weighted mean heat demand of the individual buildings is plotted along with the heat demand calculated in the comprehensive archetype model, as a visual inspection of the accuracy of the archetype model. The calculated heat demands (EUIs) of each archetype segment are listed in Table IV. In most cases, the archetype model yielded results that were within 5 % of the individual building on the aggregate level (i.e. in terms of emulating the area-weighted mean heat demand). However, in terraced houses built between 1961 and 1972 (construction period P5), the archetype model overestimated the total heat demand by 10.8 %.

In Fig. 4, the differences in average heat demand between the two models are plotted against the building period in order to assess whether differences were inherent to the construction period.

Considering Fig. 4, there did not appear to be any notable dependence between the construction period and the difference in heat demand between the two models. However, the archetype BSEM did appear to consistently overestimate the EUI in the early construction periods (i.e. before construction period P6).

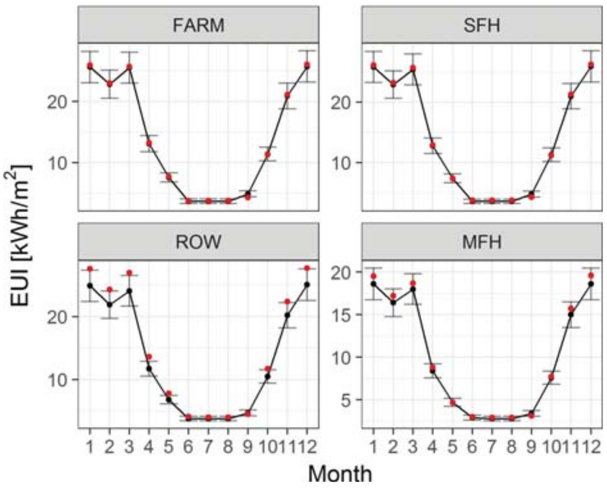

Fig. 5 Monthly heat demand (EUI) in buildings built between 1961 and 1972 (construction period P5). The error bars denote the mean value of the individual buildings ±10%. The red dots denote the heat demands calculated in the comprehensive archetype model

Likewise, the difference between the two models did not appear to be linked to the building type. The average (i.e. area-weighted), minimum- and maximum difference between the two models across building periods are listed in Table III.

TABLE III
Differences (e) in Calculated Heat Demand (EUI) between the Individual Building Model and the Comprehensive Archetype Model across Building Periods

Building type	e_{min}	e_{mean}	e_{max}
FARM	-6.2 %	-0.2 %	2.9 %
SFH	-1.2 %	1.7 %	7.8 %
ROW	-0.8 %	3.1 %	10.8 %
MFH	0.7 %	2.4 %	4.0 %

Neither Table III nor Fig. 4 indicated any notable dependence between the archetype (in terms of building type and construction period) and its ability to reflect the average heat demand in each building segment. Therefore, we checked for seasonal trends, as well as differences in the individual elements of the heat demand.

In the following, we only consider construction period P5, as it displayed a considerable amount of variation in the difference in EUI among the four building types.

1) Seasonal Variations: As errors could even out on an annual basis, we considered the heat demand on a monthly basis; these are plotted in Fig. 5.

Evidently, there did not appear to be any seasonal trends; i.e. the EUI was overestimated in all month of the year.

Therefore, we proceeded considering the heat demand on an annual basis.

2) Differences in Heat Demand: In order to account for possible differences in the individual contributions, we considered each factor contributing to the heat balance (i.e. individual heat losses and heat gains) separately.

TABLE IV
CALCULATED HEAT DEMANDS (EUI) IN [KWH/M^2] OF THE INDIVIDUAL BUILDING MODEL (AREA-WEIGHTED MEAN VALUE) AND THE ARCHETYPE MODEL

Model	**Individual building model**				**Archetype model**			
Period/Building type	FARM	SFH	ROW	MFH	FARM	SFH	ROW	MFH
P1	210.4	178.3	173.0	138.4	219.6	186.8	186.2	144.8
P2	198.7	188.5	183.1	149.0	210.7	200.2	196.9	154.8
P3	180.4	189.9	179.3	151.7	191.8	202.2	194.3	156.4
P4	188.8	195.9	186.9	139.9	194.2	207.9	203.1	145.7
P5	168.5	168.1	161.3	119.2	177.3	177.7	188.9	124.4
P6	148.1	146.0	141.9	106.6	157.9	154.8	151.8	107.5
P7	113.0	118.4	112.5	90.7	110.8	124.6	120.9	92.7
P8	114.5	92.5	90.7	75.7	114.6	96.2	96.3	76.9
P9	59.8	54.9	62.2	55.3	60.7	60.3	66.4	56.3

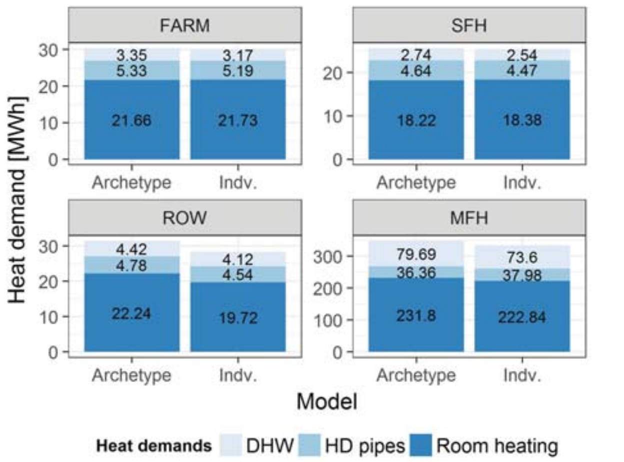

Fig. 6 Heat losses contributing to the total heat demand in the four building types built in period P5

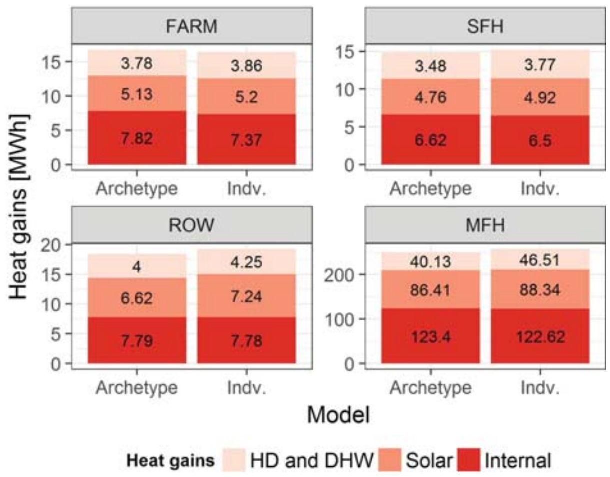

Fig. 7 Heat gains from three different sources in the two models

As in the previous section, we only considered construction period P5, due to the varying degree of difference between the archetype-based and the individual building model. Row houses were particularly interesting in this context, as they displayed the largest difference between the two models.

Heat losses from heating distribution (HD) pipes, domestic hot water (DHW) pipes, DHW tanks and DHW preparation as well as room heating are depicted in Fig. 6.

In all four building types, the heat demand for DHW was slightly higher in the archetype model than in the individual building model.´However, heat losses from HD pipes as well as for room heating was not consistently higher in one model compared to the other. This indicated that individual differences could pose a thread to the archetype model, despite it being accurate at the whole building level.

Similarly, individual heat gains, in terms of heat losses from HD- and DHW pipes, solar heat gains and internal heat gains varied among the two models. However, the internal heat gain, which was a typical value (see Table I), was almost identical in the two models. Each individual heat gain is depicted in Fig. 7.

The similarity in solar heat gains should be noted. Despite the assumed distribution of the windows and weighting shadows, the solar heat gains in the two models are remarkably similar.

Table V lists the differences in total heat demand, as well as individual heat losses and heat gains, across all archetypes in the study.

TABLE V
DIFFERENCE IN HEAT DEMANDS, INCLUDING RELEVANT HEAT LOSSES AND HEAT GAINS, BETWEEN THE COMPREHENSIVE ARCHETYPE MODEL AND THE (AVERAGE OF) THE INDIVIDUAL BUILDING MODEL

Name	**Min**	**Avg**	**Max**
EUI	-6.2 %	1.6 %	10.8 %
Room heating	-10.1 %	0.6 %	11.3 %
HD pipes	-29.9 %	-0.7 %	29.7 %
DHW pipes	-3.5 %	6.7 %	18.5 %
DHW tanks	11.5 %	46.4 %	80.7 %
DHW preparation	-0.7 %	0.1 %	1.7 %
Solar heat gains	-9.4 %	-2.6 %	3.4 %
Internal heat gains	-0.1 %	-2.6 %	3.4 %
Heat gains (HD and DHW)	-39.7 %	-11.4 %	11.2 %

Evidently, the comprehensive archetype model was capable of emulating the average EUI of the individual building model fairly accurately. However, considerable individual differences could also be detected, which could compromise the validity an energy-saving potential calculated in an archetype setting, if only specific energy-conservation measures are considered (e.g. replacement of DHW tanks). Therefore, individual contributions should be considered when evaluating the uncertainty/accuracy of an archetype-based BSEM.

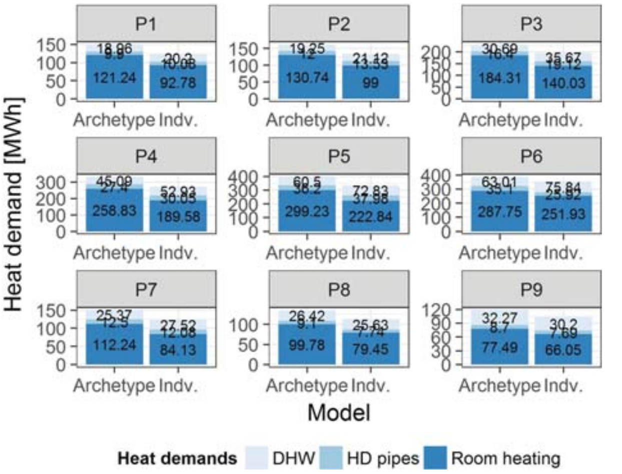

Fig. 8 Heat losses from three different sources in multi-family houeses in the simple archetype model and the individual building model respectively

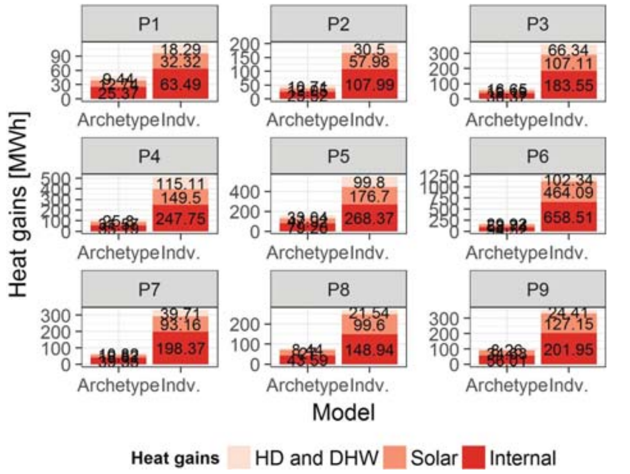

Fig. 9 Heat gains from three different sources in multi-family houeses in the simple archetype model and the individual building model respectively

B. Simplified Archetype Model

In order to simplify the comprehensive archetype model, a simple heating season based model was employed (i.e. ignoring the quasi-steady state properties of the monthly mean method). This entailed that the heat demand could only be studied at an annual basis.

Differences between the annual heat demand in the simple archetype model and the individual building model are listed in Table VI.

TABLE VI
DIFFERENCES (e) IN CALCULATED HEAT DEMAND (EUI) BETWEEN THE INDIVIDUAL BUILDING MODEL AND THE SIMPLIFIED ARCHETYPE MODEL ACROSS CONSTRUCTION PERIODS

Building type	e_{min}	e_{mean}	e_{max}
FARM	3.3 %	5.7 %	17.9 %
SFH	7.2 %	9.8 %	21.1 %
ROW	8.8 %	18.0 %	26.4 %
MFH	-0.2 %	10.0 %	13.2 %

In terms of the area-weighted mean error, the simple archetype model did not perform as good as the comprehensive archetype model. Moreover, the spread on the errors (i.e. the minimum- and maximum errors) within the individual construction periods was considerably larger.

Considering the area-weighted heat losses and heat gains in the individual building model with the corresponding heat losses and heat gains in the simple calculation model in all MFH's (Figs. 8 and 9), the observed discrepancies arose due to a combination of heat losses that were overestimated and heat gains that were underestimated in the simple calculation model. Especially the room heat demand was badly overestimated in the simple archetype model.

A potential cause of the observed discrepancies using the simplified calculation method was the assumed length of the heating season. Assuming a too short heating season would cause the heat gains to be too low, because only useful heat gains were considered. This would also explain the overestimation of the room heat demand (because useful heat gains were subtracted from the heat losses).

V. DISCUSSION AND CONCLUSION

Building archetypes offer a simple way of representing a complex building stock, whether input values are based on available data (average buildings) or educated guesses (e.g. example buildings). However, a simplified representation is associated with loss of accuracy.

Using archetypes that were constructed on the basis of more than 150.000 Danish residential buildings, it was possible to emulated the average heat demand of each building stock segment with a difference that was within 5 % in most cases. However, this was only made possible in a comprehensive setting, where vast amounts of data was available and the comprehensive archetype model could be tuned to match the individual building model as much as possible.

Furthermore, considering individual heat losses and heat gains, significantly larger differences emerged. This indicated that individual contributions should be considered when evaluating the accuracy/uncertainty of an archetype based model, as differences could even out.

It should be noted that the observed errors in the comprehensive archetype model could be ascribed to the archetype representation alone as the same input data and the same calculation method was used in both models. This implies that additional errors could be expected in cases where all input values are not available for all buildings, e.g. in example based models. Hence, the present study represents a best-case scenario in terms of the accuracy of archetype models.

Moreover, the simplicity of the comprehensive archetype model in this study suffered from defining values sufficiently accurately (e.g. in terms of the share of buildings with mechanical ventilation as well as the properties relating specifically to those buildings), in order to ensure that the calculation procedures in the two models were comparable. In a normal setting, a much less comprehensive archetype model would probably have been used (in order to benefit from the simplicity of this type of model), which could also compromise the accuracy of an archetype model.

Using a seasonal calculation method produced errors above

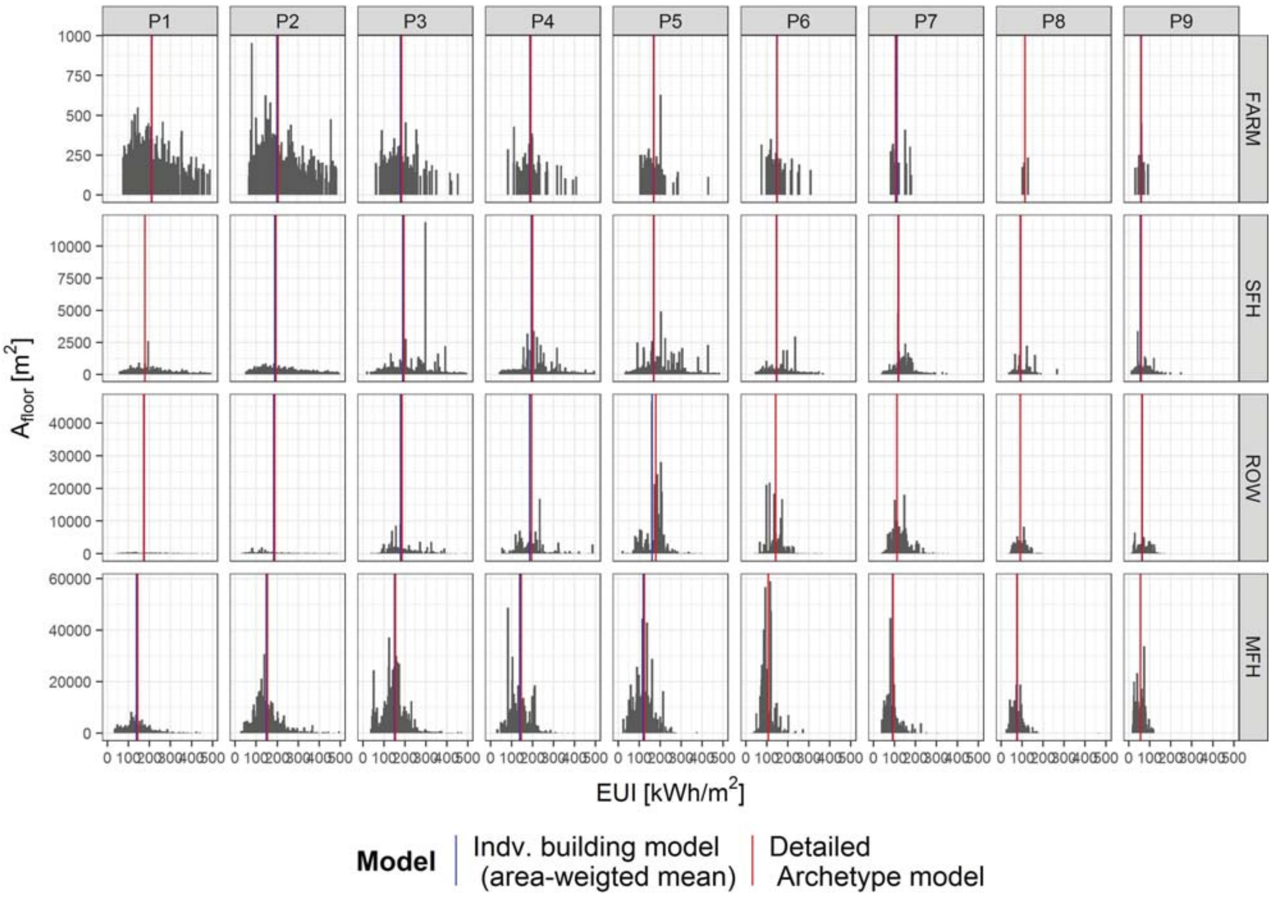

Fig. 10 Calculated heat demands of all buildings, comparing the mean heat demand within each archetype with the heat demand calculated using the archetype model

20 %, presumably due to a faulty assumptions regarding the length of the heating season.

Lastly, it should be noted that the present study only focused on the accuracy on an aggregate level (in terms of the average heat demand). Therefore, differences on the individual building level could be significantly larger due to the large spread on the heat demands within each archetype group; a natural point for further investigation.

A. Pitfalls

Care should be taken when constructing representative buildings in terms of area-weighted input values. Missing values, e.g. values that have not been registered, could cause weightings to be wrong. However, missing values also pose a potential thread to the individual building model, as they could be difficult to detect as there are many values to consider.

Finally, it should be considered whether building archetypes should be constructed on the basis of all buildings in a sample/building stock. Often, interest is in estimating the energy-saving potential in energy inefficient buildings. Therefore, archetypes should perhaps be constructed on the basis of data on the most energy-inefficient buildings in a sample. However, detecting the most energy-inefficient building in a sample could be difficult without access to individual building models.

NOMENCLATURE

e	Difference between model results
EUI	Energy-use intensity
SFH	Single-family house
MFH	Multi-family house

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All plots in the present study were made in R [14] using the 'ggplot2' package [15] from the tidyverse package [16].

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