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Published in:
Proceedings of the 15th IBPSA Conference San Francisco, CA, USA, Aug. 7-9, 2017

DOI (link to publication from Publisher):
10.26868/25222708.2017.272

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Flexible building stock modelling with array-programming

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Abstract

Many building stock models employ archetype-buildings in order to capture the essential characteristics of a diverse building stock. However, these models often require multiple archetypes, which make them inflexible.

This paper proposes an array-programming based model, which calculates the heat demand of each building separately. This approach makes it possible to study any subset of the building stock without loss of information. Moreover, the calculated heat demand can readily be compared to a registered consumption in individual buildings to account for discrepancies. Results show, that we tend to overestimate potential energy-savings, if we do not consider these discrepancies.

The proposed model makes it possible to compute and visualize potential energy-savings in a flexible and transparent way.

Introduction

Motivation

With a goal of becoming CO_2 neutral by 2050, Denmark's ambitions are high. This implies employing renewable energy sources, increasing energy efficiency and a shift in energy supply towards electricity as well as expanding the district heating network.

Increasing energy efficiency requires not only a lower demand in new buildings, but also energy savings in the existing building stock.

In order to determine the share of renewable energy to the amount of energy savings, it is necessary to be able to determine the potential for energy-savings in different subsets of the building stock (e.g. with different heat supply) as well as in the entire building stock as a whole.

In order to identify potential energy-savings in this context, a good building stock model must

- give reliable estimates of the heat demand
- be flexible in terms of modelling different building types
- be able to identify and display potential energy-savings in a transparent manner

The purpose of this model is to be able to investigate the potential for energy-savings in the entire Danish building stock; however, only a few examples are considered in this paper, for the purpose of illustration.

State-of-the-art

Several bottom-up building stock models exist, many of which use building archetypes to encapsulate the diversity of the building stock, e.g. (Sandberg et al. 2016). Some studies assign each building to a category and calculate the heat demand for each building, e.g. (Cerezo Davila, Reinhart, and Bemis 2016). Others use general characteristics of each archetype to consider the building stock as a whole (Kragh and Wittchen 2014).

One drawback of this type of building stock models is the lack of flexibility associated with the need for defining reference buildings prior to modelling. This naturally imposes some constraints, since the number calculations scales proportionally with the number of reference buildings defined (hence there's a trade-off between workload and accuracy).

Moreover, since calculated energy demands of these reference buildings cannot be compared directly to the registered consumption, extensive analyses are required prior modelling, for these to be representative in terms of reliable energy demand estimates.

Lastly, the archetype approach entails aggregating input data, which causes a loss of transparency, since individual buildings cannot be identified in the output.

Many different aspects can be taken into account when setting up a building stock model; for instance, a model can be either static, i.e. analysing only the current energy demand (Österbring et al. 2016), or dynamic, i.e. considering future energy demands (Sartori, Holck, and Brattebø 2016). Therefore, a building stock model should be flexible, so that it can be adapted to study different aspects, as desired.

This paper introduces a building stock model, based on array programming (i.e. a vectorized calculation approach), which calculates the heat demand for each building separately. This makes it possible to calibrate the calculated heat demand against registered consumption, as these can be compared building by building. This property makes it possible to account for differences in consumption in different building types as well as general trends such as rebound effects.

Moreover, this way of modelling provides the flexibility to study any subsets of the building stock, without subdividing prior to modelling. Likewise, no input parameters are aggregated which implies that each

https://doi.org/10.26868/25222708.2017.272

building is represented in the output. This makes it possible to identify which building that are affected by each energy-saving measure, thereby ensuring transparency.

Lastly, potential energy-savings may be identified either in terms of specific measures to employ or in term of a specific subset of special interest. This makes the model a powerful tool for calculating energy-demands as well as potential energy-savings due to its flexibility and transparency. With the model, politicians and other stakeholders can identify potential energy-savings and promote relevant energy-saving measures.

Data description

The present model relies on data from two databases, namely the Danish Building- and Dwelling stock Register (BBR) and the Danish Energy Performance Certificate (EPC) database.

Only heat demands in residential buildings are modelled in the present paper, though the work is to be extended to include all types of buildings in the Danish building stock later. Residential buildings, in this context, include farmhouses, detached Single-Family Houses (SFH), terraced houses and apartment blocks.

The content of the two databases is briefly described in the subsequent sections.

BBR data

The Danish Building- and Dwelling stock Register contains information on every building in Denmark down to a single unit[1] level. This includes information on heated floor areas and heat supply characteristics among many other things.

In addition, the enactment of a consolidation act in 2012, requires all energy supply companies to report registered energy consumption back to the BBR register. However, the registered consumption may be reported back in several ways, which causes some loss of information when linking the databases.

Table 1 holds the number of buildings together with the total heated floor area of each unit in the BBR.

Table 1: Residential buildings registered in the BBR

Use	**No. of buildings/units**	**Total heated floor area**	**Share[2]**
Farmhouse	115 467	21 995 294	7.16%
Detached houses	1 105 004	162 241 097	52.8%
Terraced house	412 866	38 093 403	12.4%
Apartment	1 092 315	85 006 994	27.7%
Total	2 725 652	307 336 788	100 %

[1] A unit being either a dwelling unit or a commercial unit within a building (e.g. a single apartment)
[2] Share of total floor area

EPC data

With the introduction of the Energy Performance in Buildings Directive (EPBD) (European Commision 2010), EU member states must issue Energy Performance Certifications (EPCs) at sale or rental of buildings. In Denmark, 480 342 residential buildings have been certified, since the introduction of the current certification scheme in 2006. Information in the EPC includes technical specifications of building envelope components as well as of building services. This information is collected by an energy auditor that inspects the building visually.

Due to faulty data in the database, it was necessary to implement a number of criteria to disregard these incorrect registrations. For more information, see "Removing faulty data".

After removing faulty registrations, 403 415 buildings were included in the analyses. The distribution of these buildings, across use, are listed in Table 2.

Table 2: Residential buildings registered in the EPC database

Use	**No. of buildings/units**	**Total heated floor area**	**Share[2]**
Farmhouses	14 603	2 271 526	2.5%
Detached houses	253 897	32 445 668	35.1%
Terraced house	96 382	12 361 846	13.4%
Apartment	38 533	45 294 416	49.0%
Sum	403 415	92 373 456	100 %

It is evident that farmhouses and detached SFH's are underrepresented in the EPC database (compared to the BBR database), whereas the share of apartments is larger in the EPC database than in the BBR database. However, due to the large amount of buildings in each category, this makes no difference in practice.

All calculations described in the present paper are based on data from the EPC database. Data from the BBR database is only used for extrapolation of results (since the EPC database does not cover all buildings in Denmark), as well as for supplying registrations on heat consumption in individual buildings.

Method – array-based programming

The model is set up to calculate the heat demand in each building, by means of vectorized calculations. However, before proceeding immediately to calculating heat demands, faulty data must first be removed, and data must be arranged in an appropriate array structure. The modelling process consists of five steps:

- Removing faulty data
- Arranging data in an array structure
- Calculating heat demands
- Comparing calculated heat demands and registered heat consumption
- Visualizing potential energy-savings

Removing faulty data

Critical inspection of data in the EPC database revealed several physically non-meaningful registrations such as building components with U-values larger than 7.0 W/m^{2}K, buildings with zero heat capacity or zero area and buildings with working hours longer than the operation hours of the building.

Moreover, some registrations included buildings with no building envelope, no internal heat load or no Domestic Hot Water (DHW) demand.

Therefore, ‘essential information’ was defined for selecting data such that each building contains:

- A building envelope
- At least one window
- Ventilation (in term of natural ventilation, mechanical ventilation, infiltration or a combination of these)
- A DHW demand
- An internal heat load

Furthermore, each building was required to have at least one heating system.

In case of faulty registrations regarding all other information than that mentioned above (i.e. non-‘essential information’), that particular registration was disregarded, whereas the all other data on the particular building was included in the analyses.

Registered energy consumption in the BBR database were only kept, if these were above 785 kWh (which is equivalent to the expected average heat demand for DHW for one person), above 20 kWh/m^2 per year and below 500 kWh/m^2 per year. The latter criterion was necessary to ensure correspondance between the registered consumption and the registered heated floor area, since some registrations cover more than one building without information about the corresponding heated floor area.

Arranging data in an array structure

Once data has been extracted from the database, these are organised in an array structure (i.e. a table), which holds a unique ID for each building component as well as an ID that identifies which building a given component belongs to.

Each building component type is kept in a separate table/vector, such that one vector contains all building envelope elements of all buildings (except for windows), one vector contains all windows, etc. This way of organizing data ensures that heat losses from all components are calculated separately, such that these can be retrieved later, when analysing the results of the calculation. Figure 1 shows an example of an array table:

	Identid	BuildingId	Component	Area	UValue	TempFactor
1	5114290	736669	Ceiling	23	0,6	1
2	5114291	736669	Ext.wall	10	2,1	1
3	5114292	736669	Ceiling	44	1,2	1
4	5114293	736669	Floor	50	0,3	1
5	5114294	736671	Ext.wall	200	1,8	1
6	5114295	736671	Ceiling	100	0,6	1
7	5114296	736671	Floor	100	1,2	1
8	5114297	736672	Floor	88	0,52	1
9	5114298	736672	Floor	10	0,34	0,7
10	5114299	736672	Floor	5	0,34	1,2

Figure 1: Example of an array table

Storing data this way, facilitates easy and computationally inexpensive computations of heat losses and heat gains (in cases of windows and heating installations), by means of vector calculations.

Calculating heat demands

Heat demands are calculated for each building separately, by means of a quasi-stationary calculation procedure in accordance with (EN/ISO 13790 2008). Transmission- and ventilation losses are included in the calculation procedure; and so is the heat demand for DHW. Moreover, heat losses from building services are accounted for. These are calculated in accordance with Danish national standards (DS 452 2013). Likewise, solar heat gains are calculated for each window separately, taking the physical properties of each window (i.e. the glazing area, and g-value) into account. In the calculation of solar heat gains, the orientation of each window and shades from surrounding obstacles are also accounted for.

Transmission losses are calculated for each building envelope element, based on their thermal characteristics. Likewise, ventilation losses are calculated for each part of the building, as specified by the energy auditor (i.e. each building can be specified as one or more zones with individual ventilation characteristics). In the calculation of ventilation losses, ventilation- and infiltration rates are accounted for, inside as well as outside the operating hours of the building. Moreover, heat recovery in mechanical ventilation systems are taken into account.

Each of these contributions (to the total heat demand, author) are kept in separate tables until the heat balance for each building is set up.

In the calculations, a fixed indoor temperature of 20°C is assumed, because dwellings are assumed to be in use all 24 hours of the day. Meteorological data for a typical Danish year, in terms of the Danish Design Reference Year (DRY) (Kern-hansen 2013), is used in the calculations. The meteorological data used in the calculations is the same for all buildings, due to the similarity of the climate in all parts of Denmark. However, the meteorological data may easily be replaced, should interest be on studying effects of climate changes, for instance.

Once the heat balance has been computed for each building, for each month of the year, these are aggregated on a yearly basis. This way, contributions may be studied separately or aggregately, as desired. This also facilitates specification of individual enery-saving measures, which can be used for studying the potential for energy-savings of each building, or specific groups of buildings as desired.

Neither renewable energy sources in the individual buildings, nor the efficiency of the heating system is included in these calculations. However, the nature of this calculation procedure allows for doing so.

Comparing calculated heat demands and registered heat consumption

Calculating heat demands at an individual-building level makes it possible to compare the calculated heat demands to registrations of energy consumption. This way, discrepancies can be accounted for and appropriate precautions can be taken, to ensure that potential energy-savings are not overestimated. However, establishing the relationship between the calculated heat demand and the registered heat consumption requires a comprehensive statistical analysis, which is beyond the scope of this paper. The model does provide the basis for such an analysis, however. In the present paper, the relationship is studied by means of simple linear regression.

Before comparing the calculated heat demands with the registered heat consumption, both these are heating degree day corrected in order to ensure similar boundary conditions.

Linking databases

Due to different ways of reporting data in the two databases, a number of criteria had to be imposed, to avoid mismatches. A 'one unit-to-one unit' criterion was imposed together with a threshold of a maximum difference in heated floor area of 200 % between the two databases. This may seem like a lot at first, but different conditions in the Danish legislation justify this threshold limit.

The two databases were linked by the physical address at which the registration was made, i.e. municipality code, street code, house number and building number was required to match.

Investigating the potential for energy-savings

Potential energy-savings can be studied in one of two ways in the model, namely:

- Specifying a subset of the building stock of particular interest
- Specifying an energy-saving measure of interest

Specifying a subset of the building stock allows for targeting specific subsets, e.g. buildings with individual boilers. This allows for studying energy performance as well as effects of adopting energy-saving measures in these buildings. This could imply studying whether it is technically possible, as well as economically feasible, to convert to low temperature district heating.

Specifying a particular energy-saving measure makes it possible to study effects of imposing new energy efficiency policies; for instance, imposing minimum requirements in connection with renovation projects, such as replacement of windows or roof coverings.

Alternatively, it could be studied, which measures to employ to achieve CO_2-neutrallity by 2050 in a cost-optimal way.

Both approaches allow for assessing and visualizing potential energy-savings, while correcting for discrepancies between calculated heat demands and registered heat consumption.

Results

In the following, we first consider the calculated heat demand. Next, we compare this demand to the registered heat consumption in these buildings that can be located in both databases. Lastly, we consider two approaches to modelling and visualizing potential energy-savings.

Calculated heat demands

The distribution of calculated heat demands per floor area (i.e. the energy demand intensities) is depicted for each individual building in Figure 2.

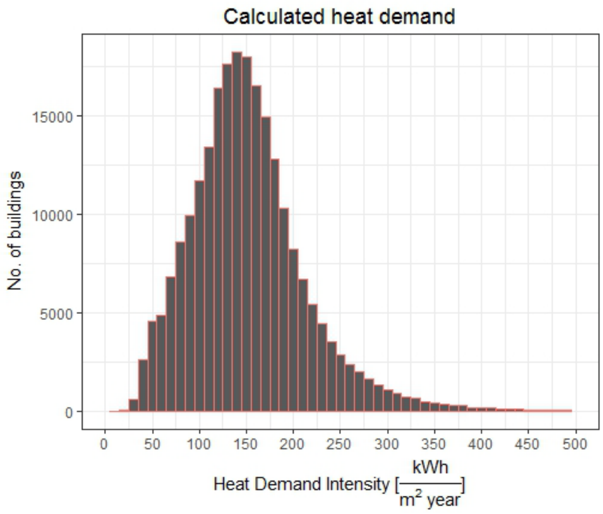

Figure 2: Distribution of calculated energy demand intensities

To test the accuracy of the model, we first extrapolate the calculated heat demand, separated by building use, to investigate whether it matches the registered energy consumption data in the national statistics:

Table 3: Model accuracy

	Heat demand
Model (extrapolated)	161.7 PJ
National statistics	155.0 PJ
Difference	6.7 PJ
Difference [%]	4.6 %

This indicates that our model does a reasonable job predicting the heat demand, when scaled up to a national level. However, the heat demand may very well differ from one subset of the building stock to another; which is obviously very important to take into account when estimating potential energy-savings.

For instance, the Danish national statistics distinguishes between single-family houses (i.e. farmhouses, detached single-family houses and terraced houses) and multi-family buildings (i.e. apartment blocks); these are compared to the calculated heat demands in Table 4.

Table 4: Heat demand in SFHs and apartments

	Heat demand in SFHs	Heat demand in apartments
Model (extrapolated)	117.4 PJ	44.4 PJ
National statistics	113.4 PJ	41.6 PJ
Difference	4.0 PJ	2.8 PJ
Difference [%]	3.5 %	6.7 %

This illustratates the fact that simple extrapolation may turn out to be different, when comparing results at a less aggregated level.

To account for these differences, we need to compare the calculated heat demand to registered heat consumption at a less aggregated level. Fortunately, the array-programming based allows for comparing calculated heat demands to registered heat consumption down to an individual building level (see 'Calculated demands vs. registered consumption').

Another pitfall of simply extrapolating the calculated heat demands by the heated floor area (as done above) is that the heat demand may not scale linearly with the heated floor area. To test this assumption, we plot the calculated heat demand against the heated floor area, see Figure 3.

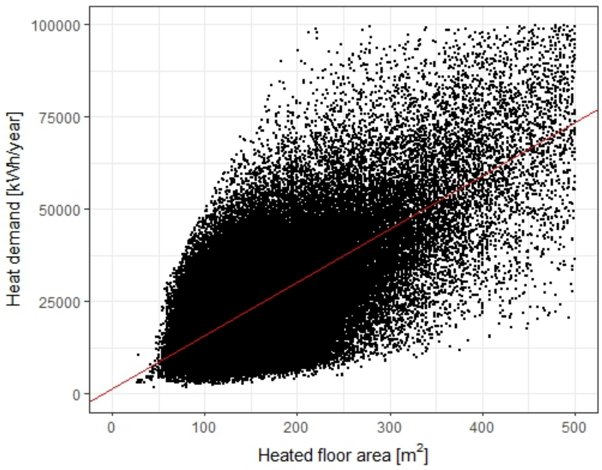

Figure 3: Calculated heat demand vs. heated floor area

Data seem to suggest, that the calculated heat demand scales approximately linearly with the heated floor area (i.e. the linear model fits the data nicely, capturing about 90 % of the variation in the data, i.e. $R^2 = 0.90$), which we would also expect intuitively.

However, different building types may scale differently with the heated floor area, e.g. the ratio of the building envelope area to the heated floor area is considerably different for single family houses and apartment blocks.

Considering the equation of the simple linear regression, we see that the intercept does not make sense physically, see equation (1) below

$$\Phi calc = 1337\frac{kWh}{yr} + 144\frac{kWh}{m^2 * yr} * A \qquad (1)$$

Where A is the heated floor area in m^2.

Obviously, the intercept should be at zero, since a building with no area should have no energy demand.

Moreover, in order for the fitted linear model to be valid, the residuals must follow a normal distribution. However, such analyses are left for future research. For now, our best estimate is to use simple linear regression.

Another way of verifying the validity of the model is by means of cross validation against other programs. The present model was verified by random checks in which the calculated heat demands were compared to heat demands calculated in the Danish national calculation program Be15 (Aggerholm and Grau 2014). This program is used for energy performance calculations of new and existing buildings in Denmark. In all random checks, there was a fine agreement between the calculated heat demands.

Calculated demands vs. registered consumption

Before estimating potential energy-savings, we must first ensure that our model is sufficiently accurate. We do so by fitting the calculated heat demands to registrations of heat consumption in individual buildings.

Sample data

As the BBR register does not hold registrations of energy consumption in all the buildings in the EPC register, we cannot include all buildings from the previous analyses in this analysis. Moreover, registrations in the BBR register that cover the consumption of more than one building unit were left out of the analysis.

232 594 buildings with a registered energy consumption are present in both databases. Table 5 summarizes the characteristics of the building sample used for the proceeding analysis.

Table 5: Sample buildings

Use	No. of buildings/units	Total heated floor area	Share
Farmhouse	1 545	323 286	0.6%
Detached houses	168 405	26 308 445	46.3%
Terraced house	41 225	5 075 407	8.9%
Apartment	21 419	25 155 301	44.2%
Sum	232 594	56 862 441	100 %

It is apparent, that both farmhouses and terraced houses are underrepresented in the sample data, whereas detached single-family houses and apartment blocks constitute a large fraction of the total heated floor area in the sample. Depending on the analyses to be made, this need not to be a problem, but should of course be borne in mind. For the sake of demonstrating the potential of the model, it makes no difference, for which reason it will not be considered further.

Calculated heat demands vs. registered consumption

The calculated heat demand is plotted against the registered heat consumption for the each building in the sample in Figure 4. Individual regression lines are fitted to the data for each type of building in the sample.

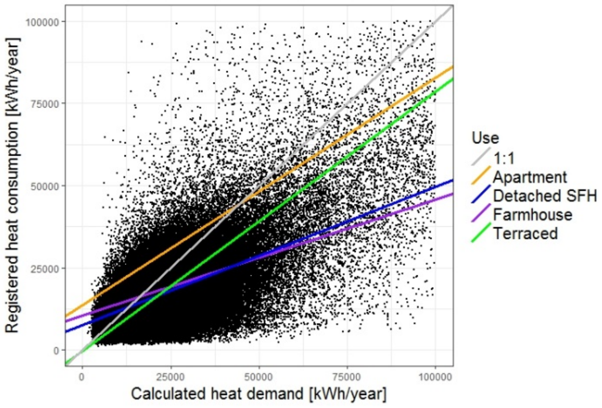

Figure 4: Registered heat consumption vs. calculated heat demand with individual regression lines

Had the calculated heat demand matched the registered heat consumption on average, the points would be equally dispersed around the grey line, which gives the 1:1 relationship; i.e. a straight line with intercept equal to 0 and slope equal to 1. However, this seems not to be the case for any of the four types of buildings in the given sample.

The intercept and slope of each regression line is given in Table 6.

Table 6: Relating the calculated heat demand to the registered heat consumption

Use	Intercept	Slope
Farmhouses	10 589	0.35
Detached houses	7 528	0.42
Terraced houses	-304	0.79
Apartments	13 756	0.69

In all building types, except for the terraced houses, we see that we underestimate the heat consumption at low calculated heat demands. The slope is less than one in all four cases which indicates that we gradually go towards overestimating the heat consumption. The break-even point for each building type is given by the intersection between each of the coloured lines and the grey line. To sum up, we underestimate the heat consumption at low calculated heat demands, while we overestimate the heat consumption where we calculate large heat demands. Moreover, the degree to which this is happening appears to depend on the building type in question.

Several things may cause this systematic discrepancy. The fact that the efficiency of the heating system as well as renewable energy sources have not been included in the model, may explain some of the discrepancy.

Another potential cause may be the assumed indoor temperature, which could be different (on average) in different types of buildings; e.g. buildings of different thermal quality, as suggested by (Itard, Majcen, and Visscher 2012). This would mean that energy savings will thus be traded for a better thermal indoor climate in many cases, resulting in lower energy savings than expected. This effect is often denoted ‘the rebound effect’.

The observed discrepancy may also be caused by incorrect estimation of the building’s thermal characteristics. However, if this is done systematically, it is a serious matter, that should be addressed.

In other possible errors, fuels that have not been reported, such as wood for fireplaces, should be mentioned. Likewise, the operating hours may be different from those assumed. The many possible explanations renders it troublesome to determine which factors that causes the discrepancy, when considering only these data.

Naturally, occupant behaviour causes the heat demand to vary in individual buildings. The current calculation method does not account for this user behaviour; however, this is not the intention either. However, the calculation method should be accurate on average, given that the input parameters and model assumptions are correct of course.

When scaling up to a national level, we found the calculated heat demand to be in good agreement with the national statistics. This is important because it means that we are either missing something, e.g. a parameter whose regression line would even things out, or there is simply a difference between the individual consumption data and the national statistics.

The relationship between the input variables and the output is most likely complex and may even contain dependencies between input variables. Therefore, it should be emphasized that the exact cause of the observed discrepancy cannot be determined from the present analysis; additional statistical analysis is required to establish these relationships. The model is perfectly suited for this task, but this kind of analysis is beyond the scope of this paper, as mentioned previously.

Regardless of the relationship between input and output variables, we must account for the observed discrepancy, whenever we estimate potential energy-savings in a subset of the building stock. We will do so by means of simple linear regression in the following, despite the fact that this is probably too simple to yield correct results. However, for illustrating the general idea, this should serve the purpose.

Scenario analysis: Potential energy-savings

The array based calculation model offers two approaches to studying potential energy-savings:

- Specify an energy-saving measure to be studied
- Specify a subset of the building stock to be studied

Here, we will consider two scenarios related to estimation of potential energy-savings.

- Replacement of windows before 2050
- Potential energy-savings in buildings with individual boilers

The purpose of the model is to study potential energy-savings in all buildings in the Danish building stock in the future studies, but now we will focus only on these two examples.

Replacement of window before 2050

The idea to study potential energy-savings related to replacement of windows immediately arises when we look at the distribution of window U-values in the raw data; these are depicted in Figure 5:

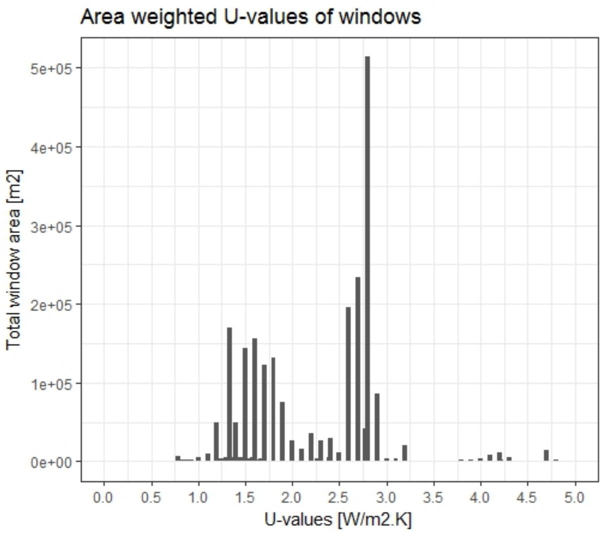

Figure 5: Distribution of U-values in the EPC database

Evidently, there are large areas of glazed facades, whose energy performance could be improved substantially, if these were replaced by windows of today's standard.

Due to the relatively short life span of windows, it seems fair to assume that all windows have been replaced at least once before 2050. Assuming that all windows with a U-value above 1.2 W/m^{2}K will be replaced by windows with a U-value of 0.9 W/m^{2}K, we can estimate the potential energy-savings based on these data. The total energy demand, as calculated before and after such a replacement, is given in Table 7.

Table 7: Calculated potential for energy-savings of window replacement before correction

	Before	After	Difference
Total heat demand	161.7 PJ	138.0 PJ	23.7 PJ (14.7%)

However, this is under the assumption that the calculated heat demand matches the registered heat consumption, which we found previously not to be true in all cases. To correct for this, we need to know the relationship between the calculated demand and the registered consumption.

For convenience, we here assume that this relationship can be described satisfactorily by a simple linear regression without regards to any subsets; see Figure 6.

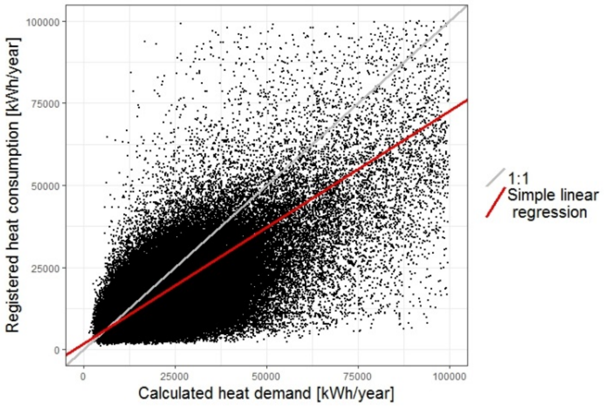

Figure 6: Simple linear regression of the registered heat consumption vs. calculated heat demand

Based on this regression, we can correct the calculated heat demand of each building in our sample individually.

The corrected heat demand before and after window replacement is shown in Table 8.

Table 8: Potential energy-savings after correction

	Before	After	Difference
Total heat demand	105.6 PJ	92.8 PJ	12.8 PJ (12.1%)

We see that the absolute energy-saving potential is substantially smaller when we correct the calculated heat demands.

We also see that the calculated heat demand before window replacement (i.e. the calculated demand, calibrated against the simple linear regression in Figure 6) does not match the national energy statistics. This may indicate that the statistical model is not sufficiently accurate, but it may also be that individually registered heat consumption, used for calibrating our estimate of the consumption, does not match the national statistics. However, we shall not consider this further here.

In any case, this emphasizes the point that discrepancies must be taken into account, when estimating potential energy-savings.

Potential energy-savings in building with individual boilers

The second approach to studying potential energy-savings, is by considering a subset of the building stock. In a Danish context, buildings with individual boilers are of particular interest, as the government wishes to expand the district heating network, as well as shifting the heat supply to be covered by electrically driven heat pumps to a further extend. However, in order to convert from a traditional heating system, to a low-temperature (e.g. floor heating) system, the thermal condition of the building plays a vital role. Therefore, we wish to consider the thermal state of these buildings, as well as the potential for energy-savings in these.

The EPC database contains 157 863 buildings which are registered with a 'Boiler' as their primary heat supply. Some general characteristics about these buildings are given in Table 9.

Table 9: Buildings w. individual boilers

Use	No. of units	Heated floor area [m2]
Farmhouse	11 519	2 307 585
Detached SFH	117 042	18 726 081
Terraced house	24 570	3 832 588
Apartments	4 732	3 963 504
Total	157 863	28 829 758

We see that these are mostly single-family houses, which may be important when considering costs as well as possible subsidisation schemes.

The general state of these buildings, in terms of energy use intensity is depicted in Figure 7.

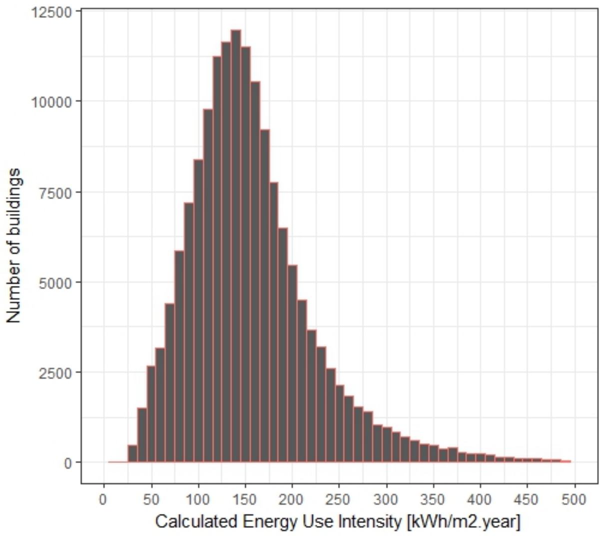

Figure 7: Energy use intensity in buildings with individual boilers

In order to propose reasonable energy-saving measures, we consider the individual contributions (i.e. transmission losses and ventilation losses); these are listed in Figure 8. The array approach to storing and calculating demands makes it possible to access this information, as it is stored in separate vectors.

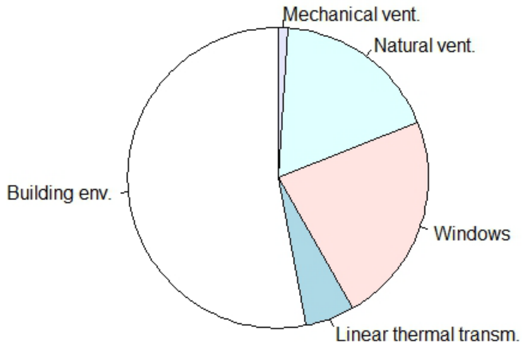

Figure 8: Distribution of the total heat losses from building envelope elements and ventilation

We see that transmission losses through the building envelope account for roughly half of the total heat loss while transmission losses through windows and natural ventilation account for approximately a fifth of the total heat loss each. The individual shares are listed in Table 10.

Table 10: Shares of the total heat losses among the building envelope elements and ventilation in buildings with boilers

	Share
Building envelope	52 %
Linear thermal transmittances	5 %
Windows	22 %
Natural ventilation	20 %
Mechanical ventilation	1 %

In order to reduce the heat demand in these buildings, we therefore propose the following energy-saving measures:

- Re-insulating the building envelope
- Replacing windows
- Installing mechanical ventilation with heat recovery

Table 11 lists the replacement criteria for the four building envelope elements. Given that a U-value is above (or equal to) the value listed in the '$U_{replace}$' column, it is assumed that this will be upgraded to meet the U-values listed in the 'U_{new}' column.

Table 11: U-values of building envelope components subject to energy efficiency upgrades

Envelope component	$U_{replace} \geq$	U_{new}
Roofs	0.4 W/m^{2}K	0.10 W/m^{2}K
Floors	0.8 W/m^{2}K	0.10 W/m^{2}K
Ext. walls	0.6 W/m^{2}K	0.18 W/m^{2}K
Windows	1.4 W/m^{2}K	0.9 W/m^{2}K

Assuming that half of all homeowner choose to install a mechanical ventilation system (e.g. due to some subsidisation scheme), we assume an efficiency of the heat recovery unit in the new ventilation system of 0.85.

Figure 9 illustrates the heat demand before and after employing the proposed energy-saving measures.

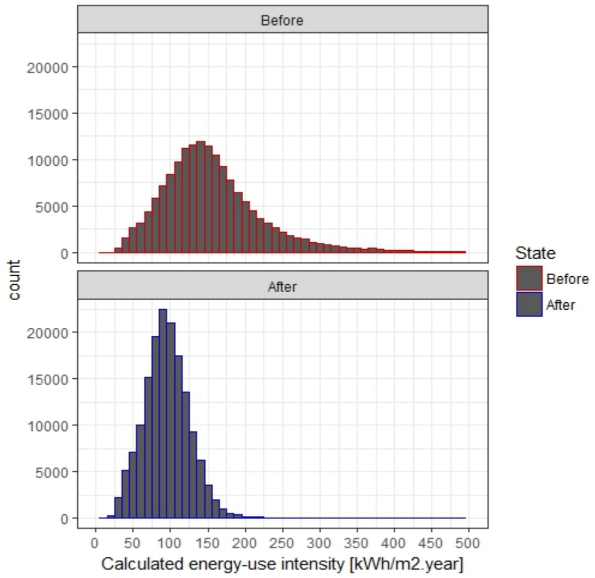

Figure 9: Reduction in heat demand

We see that the heat demand has been lowered substantially in many buildings; however, additional analyses are required to determine whether the reduction is sufficient to employ low temperature heating system in these buildings.

In order to address the buildings which still have a high heat demand, these may be identified in the dataset, in order to promote energy-saving measures, which target these buildings explicitly.

Discussion

The proposed model enables researchers to study heat demands – and related potential energy-savings – in the building stock, without loss of information and in a flexible way. This includes the possibility to relate the calculated heat demand to registrations of heat consumption in individual buildings.

A systematic discrepancy between the calculated heat demand and the registered heat consumption was observed. This discrepancy may arise several places, many of which was discussed in the'Calculated demands vs. registred consumption' section. However, it is important to make it clear that these are only potential explanations; to address this issue, a more comprehensive statistical analysis must first be performed.

Moreover, the quality of the data is questionable, since these data are collected through visual inspections, which entails assuming default values in many cases. With this said, the large amount of data available hopefully ensures a fair data quality on average.

Finally, the adjustment of potential energy savings could be improved, had the statistical analysis been more comprehensive.

Conclusion

In this paper, we have proposed an array-based building stock model, for calculating heat demands and studying related potential energy-savings.

One advantage of this model is its flexibility in terms of modelling all buildings in the data sample individually as this eliminates the need for defining specific building types prior to modelling.

Secondly, calculating heat losses for each building component in each building separately makes it possible to retrieve this information for any building in the sample. This makes it possible to highlight specific energy-saving measures in any subgroup of the building stock, which makes it possible to promote specific energy-savings measures by means of political incentives.

Lastly, the model allows for comparison of calculated energy demands and registered heat consumption on an individual building level. This makes it possible to account for discrepancies as well as correct these for any subset of the building stock individually. However, the latter requires a comprehensive statistical analysis of data, which was not addressed in the present paper.

One drawback of the proposed model is the difficulty to comprehend amounts of data this large; i.e. it may be difficult to detect erroneous input data in a dataset this large. However, this applies in general, when deling with large amounts of data.

Pros and cons of the proposed model are listed below.

Pros:

- Any subgroup of buildings can be identified in both the input and the output of the model.
- Subsets need not to be specified prior to modelling.
- The model is computationally inexpensive.
- Calculated heat demands can be compared directly to a registered heat consumption on an individual building level.

Cons:

- Requires a fair amount of data, collected on a disaggregted level
- Not all observations can be inspected individually, manually.
- Data must be collected in a consistent way to avoid linking information incorrectly.

Future work

In order to improve the proposed model, a comprehensive statistical analysis should be conducted, to determining the relationship between the calculated heat demand and the registered heat consumption. This could improve the model substantially, as potential energy-savings could be determined much more accurately.

Secondly, electricity demands should be included, to account for possible interactions.

Finally, more building types could be included, so that not only dwellings are considered. Likewise, potential energy-savings should be determined for more subsets, to cover all buildings in the building stock. This requires delving deeper into different energy-saving measures, including how they interact.

Acknowledgements

This research was funded by the Danish Innovation Fund.

Nomenclature/abbreviations

EPC: Energy Performance Certificate

BBR: Building and Dwelling Register (in Danish: *Bygnings- og Boligregister*)

SFH: Single-Family House

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