Development of reference building models based on statistical data for the analysis of the building heat demand

M Barton, L Schwan, J Hahn, R Anders and C Schweigler
CENERGIE - Research Center Energy-efficient Buildings and Districts,
Munich University of Applied Sciences,
Department 05: Building Services Engineering,
Lothstr. 34, D-80335 Munich, Germany
michael.barton@hm.edu

Abstract. For the transition of the energy system from the status quo to a point where the political targets are achieved, the largest potentials for energy and CO\textsubscript{2} savings are in the building sector, especially due to older unrenovated buildings. For the state of Bavaria, preliminary investigations have shown that approximately 27\% of the total final energy demand is provided for space heating and domestic hot water preparation of the residential building stock. Extensive measures must be taken in this sector for a successful energy transition. To make the best use of available resources, investigations with realistic reference building models are essential. Previous studies have shown that a significant classification of the building stock can be performed and large parts of it can be represented with a limited number of reference building models. In this study, it is shown that the representativity can be further increased by selective grouping of the categories while keeping the number of necessary models as small as possible. In addition, a method is presented to model reference buildings using statistical data. The methods of grouping and modelling as well as possible applications and outputs of the generated models are shown for a realistic example.

1. Introduction
The building sector offers the largest potential for energy and CO\textsubscript{2} savings. Especially older buildings exhibit a high energy demand and are therefore accountable for notably higher CO\textsubscript{2} emissions. After analyzing the residential building stock of the state of Bavaria, preliminary investigations have shown that approximately 27.4\% of the final energy demand is used for space heating and domestic hot water preparation in the residential sector. Around 73.6\% of this demand is covered by conventional heat sources. This is equivalent to 23.4\% of Bavaria's total CO\textsubscript{2} emissions. Approximately 70\% of this final energy and related CO\textsubscript{2} emissions could be saved by fully renovating the residential building stock. Further CO\textsubscript{2} savings could be achieved by heat supply based on renewable energy sources. [1]

For the identification of specific measures for energy savings and for the analysis of innovative supply systems, realistic reference building models are essential. Different energy systems can be analysed systematically using these models to identify the most effective solutions for the future heat supply to buildings. In a preceding publication, the building stock of Bavaria has been divided into 720 categories [1]. It has been demonstrated that a limited number of building models allows for representation of the entire building stock and its energy consumption with sufficient accuracy [2].
2. Methodology
In this publication, a method to generate reference building models from selected statistical data is described. As an example of this method, a reference building model is developed which represents a relevant share of the building stock of Bavaria on the basis of given statistical data.

First, the decisive criteria for the modelling of the reference building are defined. This step shows how individual building categories can be grouped together to achieve more accurate representation with a reduced number of building models.

Then, the process for gathering the required building data is explained. This includes literature data, calculated data, and statistical data of the portion of the building stock under investigation. Some of the necessary statistical data has been generated in previous investigations.

Finally, the actual modelling process of the building is presented, accompanied by a discussion of potential applications of the model. A comparison of the calculated energy demand with the statistical data serves as indicator for the quality of the building model.

3. Systemic development of reference building models
With the presented method it is possible to develop models of reference buildings from statistical data of various kinds, which can be used to investigate a particular group of buildings. For best results, the selection and aggregation process should strongly depend on the research topic under investigation.

3.1. Selection of the building stock to be represented
The building stock of a region is very diverse, as the buildings differ in many aspects such as type and year of construction. In statistical data, the stock is typically divided into building categories. These categories are defined by criteria such as building type, floor area, energy demand, age of construction, building condition, etc. For each of the categories a reference building model can be developed. It can be useful to combine building categories into groups. For one thing, the building stock becomes more transparent and the number of reference buildings to be modelled decreases with the number of categories. In addition, the categories become more meaningful and can be adapted to requirements of the specific investigation.

In a previous project, the Bavarian building stock has been divided into 720 categories [1]. Table 1 shows the classification of the buildings that led to this number of categories. The division is very fine, resulting in a large number of categories.

| Table 1. Bavarian building stock: 720 categories, characterized by four criteria [1] |
| --- | --- | --- | --- | --- |
| **Criterion** | **Classes** | **Detached house** | **Semi-detached house** | **Terraced house** | **Other building type** |
| Building type | 4 classes | | | | |
| Number of apartments | 5 classes | 1 | 2 | 3 to 6 | 7 to 12 | 13 or more |
| Degree of refurbishment | 3 classes | Not renovated | Partially renovated | Fully renovated | |
| Age class | 12 classes | Before 1919, 1919 – 1948, 1949 – 1978, 9 classes between 1979 - 2016 |

In order to obtain robust categories which represent a significant share of the building stock, a clustering of building categories has been performed. Hereby, the building age is an important factor. While up to the 1970s, buildings constructed during a longer period of time can be grouped together, from the 1980s onward a finer division is necessary due to regulations on construction standards and environmental care [3,4,5], as has been shown earlier [2]. In order to cope with ambiguities of the
statistical data and for improved significance for the current topic of research, the classification criteria were adjusted as shown in Table 2. Buildings with more than three apartments were grouped together and the age classes were merged in order to obtain time periods of similar length.

Table 2. Bavarian building stock: 108 categories, based on refined criteria [1]

| Criterion                  | Classes                  | Detached house | Semi-detached house | Terraced house | Other building type |
|----------------------------|--------------------------|----------------|---------------------|----------------|---------------------|
| Building type              | 4 classes                | 1              | 2                   | 3 or more      |                     |
| Number of apartments       | 3 classes                |                |                     |                |                     |
| Degree of refurbishment    | 3 classes                | Not renovated  | Partially renovated| Fully renovated|                     |
| Age class                  | 3 classes                | Before 1949    | 1949 – 1978         | 1979 – 2016    |                     |

The results of the new classification are shown in Figure 1. Despite extensive grouping, the classification is strongly fragmented with numerous categories that are irrelevant regarding their share in the total energy demand and quantity. The figure confirms statements in preliminary investigations: Resorting to a limited number of building categories, a significant percentage of the building stock can be represented in terms of its energy demand and total number of buildings. This effect is further increased by combining building categories.

For both criteria, the largest shares shown in Figure 1 are assigned to the category of unrenovated, freestanding, detached houses with one apartment of the period 1979 - 2016. 13 % of the final energy demand are allotted to this category, representing 18 % of the total number of buildings. This combined category has been created from nine individual categories of the previous study [1] with different age classes.

![Figure 1. Bavarian building in 108 categories – final energy demand and number of buildings [1]](image-url)
The individual types within this combined category had previously been of little significance in terms of the criteria under consideration. The new category now has significantly higher coverage and is therefore more relevant. Yet, as a result of the formation of a larger category, the detailed values of the individual categories deviate from the averaged values representing the combined class. The extent of these deviations is shown in Figure 2.

It is not necessary to combine all nine categories of the different age classes from 1979 onwards. Depending on the purpose of investigation and the tolerated deviation between detailed and averaged data, other groupings of age classes are possible. Figure 2 shows an example of some alternatives. In principle, buildings with similar characteristics should be pooled in one category. With regard to the topic of investigation, the definition of building categories may be modified accordingly.

In the following section, an example for the definition of a reference building model will be given. For this purpose, one of the options for the grouping of building ages has been chosen. The period 1996 - 2004 has been selected (orange frame in Figure 2), comprising two detailed building age classes (1996 - 2000 and 2001 - 2004). In terms of average apartment size, this category shows only a small deviation from the original data of the individual categories. In contrast, the individual data for the final energy demand deviate significantly from the average value for the entire period.

### Unrenovated freestanding detached houses with one apartment

| Scenario | 1979 - 1984 | 1985 - 1990 | 1991 - 1995 | 1996 - 2000 | 2001 - 2004 | 2005 - 2008 | 2009 - 2011 | 2012 - 2015 | 2016 |
|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------|
| Number of buildings / apartments | 561,555 | 121,194 | 54,800 | 77,386 | 99,003 | 66,233 | 57,552 | 32,641 | 42,334 | 10,412 |
| Buildings per year | - | 15,149 | 13,700 | 15,477 | 19,801 | 16,558 | 14,388 | 10,880 | 10,584 | 10,412 |
| Average per apartment [m²] | 138 | 137 | 140 | 141 | 143 | 146 | 144 | 155 | 152 |
| Specific final energy demand [kWh/a/m²] | - | 208 | 217 | 206 | 162 | 135 | 127 | 119 | 115 | 98 |
| Absolute final energy demand [MWh/a] | 13,409,222 | 3,471,311 | 1,626,416 | 2,233,033 | 2,259,670 | 1,286,984 | 1,063,874 | 557,731 | 754,364 | 155,839 |

| Number of buildings / apartments | 561,555 | 253,380 | 165,236 | 90,193 | 52,746 |
| Buildings per year | - | 14,905 | 18,360 | 12,885 | 10,349 |
| Average per apartment [m²] | 138 | 142 | 145 | 154 |
| Deviation area | 0,4% | 1,0% | -1,3% | 0,8% | -1,2% | -0,6% | 1,0% | -0,4% | 1,6% |
| Specific final energy demand [kWh/a/m²] | 209 | 215 | 124 | 112 |
| Deviation demand | 1% | 4% | 2% | -7% | 12% | -2% | 4% | -3% | 13% |
| Absolute final energy demand [MWh/a] | 13,409,222 | 7,330,760 | 3,546,655 | 1,621,605 | 910,203 |

| Number of buildings / apartments | 561,555 | 253,380 | 222,788 | 85,387 |
| Buildings per year | - | 14,905 | 17,138 | 10,673 |
| Average per apartment [m²] | 138 | 143 | 150 |
| Deviation area | 0,4% | 1,0% | -1,3% | 1,6% | -0,4% | -2,2% | 4,5% | -3,0% | -1,1% |
| Specific final energy demand [kWh/a/m²] | 209 | 111 | 114 |
| Deviation demand | 1% | -4% | 2% | -31% | -18% | -12% | -4% | -19% | 16% |
| Absolute final energy demand [MWh/a] | 13,409,222 | 7,330,760 | 4,610,528 | 1,467,934 |

| Number of buildings / apartments | 561,555 | 352,383 | 209,172 |
| Buildings per year | - | 16,017 | 13,073 |
| Average per apartment [m²] | 139 | 147 |
| Deviation area | 0,9% | 1,5% | -0,9% | -1,2% | 2,5% | 0,6% | 2,2% | -5,2% | -3,3% |
| Specific final energy demand [kWh/a/m²] | 196 | 124 |
| Deviation demand | -6% | -10% | -5% | 21% | -8% | -2% | 5% | 8% | 26% |
| Absolute final energy demand [MWh/a] | 13,409,222 | 9,590,430 | 3,818,792 |

| Number of buildings / apartments | 561,555 | 561,555 |
| Buildings per year | - | 14,778 |
| Average per apartment [m²] | 142 |
| Deviation area | 3,0% | 3,7% | 1,3% | 1,0% | -1,0% | -2,9% | -1,3% | -8,4% | -6,6% |
| Specific final energy demand [kWh/a/m²] | 168 |
| Deviation demand | -19,1% | -22,4% | -18,3% | 3,6% | 24,2% | 33,0% | 41,6% | 46,3% | 70,8% |

**Figure 2.** Summary of categories with the deviations from the individual categories [1]
3.2. Input data and calculation model

After selecting a building category which represents a significant share of the building stock, the data collection for modelling the according reference building is initiated. Since different sources are used, it should be considered that the classification of the individual criteria taken from different sources may differ. In order to cope with these discrepancies, a weighted average of the statistical data of the involved categories can be used to obtain increased accuracy.

The reference building model should have the average living area given by the statistical data. The other geometric parameters are obtained from literature sources and calculations. In addition, the ratio of the outer surface area of the building ($S_{\text{area}}$) and the building volume ($V_{\text{build}}$) serves as decisive geometric parameter. For the selected category, the target value of this ratio ($S_{\text{area}}/V_{\text{build}}$) is given by statistical data. For the example presented in this publication, the characteristic building data is taken from the tabula statistics of the “Institut Wohnen und Umwelt” (IWU) [6]. For the selected period from 1996 to 2004, the data of the statistical category “Single family house 09” (SFH90) are applied.

Figure 3 shows further geometric parameters which are taken into account for modelling a reference building. A large portion of this data can be determined from norms and typical regional building characteristics. Values that cannot be obtained from theoretic or statistical sources, are determined by a set of equations [formulas (1) to (10)]. This procedure provides data for all unknown values, if sufficient geometric parameters are given as input. Table 3 gives an overview of the geometric parameters that have been researched, set or calculated for the modeling of the example building.

![Figure 3. Typical geometric parameters of buildings](image)

\[
S_{\text{area}} = 2(h_1 + k + e) \cdot [(b + 2w) + (l + 2w)] + (b + 2w) \cdot [(l + 2w) + (h_2 + v)] + 2 \cdot f \cdot (l + 2w) \quad (1)
\]

\[
V_{\text{build}} = (b + 2 \cdot w) \cdot (l + 2 \cdot w) \cdot [(h_1 + k + e) + 0.5 \cdot (h_2 + v)]
\]

\[
A_{\text{living}} = l \cdot (b + c + d) / i \quad (3)
\]

\[
h_2 = \tan(\alpha) \cdot (0.5 \cdot (b + 2 \cdot w) - u)
\]

\[
u = o/\sin(\alpha)
\]

\[
v = o/\cos(\alpha)
\]

\[
a = x/\tan(\alpha)
\]

\[
c = (y - x)/\tan(\alpha)
\]

\[
d = 2 \cdot ((h_2 - y)/\tan(\alpha))
\]

\[
f = 0.5 \cdot (b + 2 \cdot w)/\cos(\alpha)
\]
With regard to the purpose of research, in the system of equations an acceptable and realistic range for the $S_{\text{area}}/V_{\text{build}}$ ratio is defined, allowing a variation around its statistical value. In order to find an appropriate setting of all other geometric parameters the $S_{\text{area}}/V_{\text{build}}$ ratio is varied within the specified range. Depending on the chosen $S_{\text{area}}/V_{\text{build}}$ ratio, different sets of results for the geometric parameters are obtained. Finally, the most suitable setting with regard to the objective of investigation is selected as solution. For the example building model the results from Table 3 were selected.

An important aspect is the characterization of the windows in terms of thermal properties and orientation. These values can be taken from statistical data. For the model of the example building, data for the building type SFH09 of the tabula statistics of the IWU [6] have been used. For the thermal properties, i.e. heat transfer coefficient and transmissivity, an average value for the time period under consideration is applied. Orientation and size of the windows are set in order to obtain identical window size per living area for both buildings, reference building and statistical building. The values for the example building are summarized in Table 4.

Finally, the U-values for the building elements are determined. These can be obtained from literature. Values from statistical data or values of regionally typical materials can be used. When a reference building model for an existing building is to be developed, the U-values of the actual building construction can be applied, if available. For the current example, again the statistical data from building SFH09 of the IWU statistic are used [6] (Table 5).

**Table 3.** Geometric parameters for modelling the example building

| Parameter                          | Symbol | Value | Origin   | Source |
|-----------------------------------|--------|-------|----------|--------|
| Floors and attic type             | -      | One floor + occupied attic | Researched | [6]    |
| Living area                       | $A_{\text{living}}$ | 142 m² | Statistics | [1]    |
| Roof inclination                  | $\alpha$ | 25°   | Researched/Set | [7]    |
| Wall thickness                    | $w$    | 0,25 m | Set      | -      |
| Ceiling thickness                 | $e$    | 0,25 m | Set      | -      |
| Roof thickness                    | $o$    | 0,25 m | Set      | -      |
| Room height                       | $h_1$  | 2,5 m  | Researched | [6]    |
| Height till living area not counts| $x$    | 1 m    | Researched | [8]    |
| Height till living area counts half| $y$   | 2 m    | Researched | [8]    |
| Inner walls factor                | $i$    | 1,1    | Set      | -      |
| Surface to volume ratio           | $S_{\text{area}}/V_{\text{build}}$ | 0,8212 | Researched/Set | [6]    |
| Building length                   | $l$    | 12,5 m | Calculated | -      |
| Building width                    | $b$    | 9,8 m  | Calculated | -      |

**Table 4.** Values of windows for modelling the example building based on [6]

| Orientation | Area (in % of total) | g-value |
|-------------|----------------------|---------|
| East        | 4,2 m² (11,1%)       | 0,6     |
| South       | 23,6 m² (62,4%)      | 0,6     |
| West        | 4,2 m² (11,1%)       | 0,6     |
| North       | 5,8 m² (15,4%)       | 0,6     |

**Table 5.** U-values for modelling the example building based on [6]

| Element       | Value              |
|---------------|--------------------|
| Roof          | 0,35 W/(m²·K)     |
| External wall | 0,30 W/(m²·K)     |
| Ground        | 0,45 W/(m²·K)     |
| Windows       | 1,90 W/(m²·K)     |
4. Building model and results of the calculations

Using the collected data, the reference building for the selected building category can be modelled and further calculations for energy studies can be performed. The procedure is not bound to a specific software. The following example is used to demonstrate the practical application of the method and to provide insight into the quality of the results.

4.1. Modelling of the reference building

The example building has been modelled with the software DesignBuilder. The previously generated data have been used as input for the software. The building model is shown in Figure 4. For illustrative purposes, the structure of the example building has been kept simple. However, it can be further detailed if required.

![Figure 4. Example reference building modeled with the Software DesignBuilder](image)

4.2. Modelling result: Annual heat demand

For energy studies, the reference building model can be applied to determine the annual heat demand for a specific building type under distinct conditions. Some general conditions used for the current example are listed in Table 6. For the presented reference building and typical weather conditions for the Bavarian region, a value of 19.168 kWh for the annual heat demand has been obtained, equivalent to a specific final energy demand of 135 kWh/m² a. Compared to the statistical value 151 kWh/m² a, as given in Figure 2, a deviation of 10.6 % is found.

For the calculations, default settings of the DesignBuilder software were used, except for the values listed in Table 6. Better matching with the statistical data is accomplished when parameters of operation and use are set individually. Decisive figures for the annual heat demand of the building are the number of people living in the household, the user profile and heat gains from electric appliances.

Figure 5 shows representative results for the course of the heat demand using the example reference building model. The results can be used to analyze and evaluate the thermal behavior of buildings and the operation of related energy supply systems. The possibilities of further and more extensive investigations and studies are numerous and cross-functional.

![Figure 5. Results of calculations generated by the example reference building model](image)

| Parameter              | Value                  | Origin         | Source |
|------------------------|------------------------|----------------|--------|
| Building orientation   | North-South roof       | Set            | -      |
| Person/m²              | 0.0143 p/m²            | Researched/Set | [9]    |
| Domestic hot water     | 0.67 l/(m²·d)          | Researched/Set | [10]   |
| Inner set temperature  | 16 - 21 °C             | Set            | -      |
5. Conclusion and Outlook

A method for developing reference building models from statistical data has been developed. Application of the modelling procedure has been presented for the case of an example building for the region Bavaria, Germany. In order to represent the entire building stock, buildings are classified in terms of different categories. On basis of a detailed classification, 720 building categories are distinguished with regard to different criteria, like building size and age class.

It has been demonstrated that the validity and significance of building categories can be increased by reducing the degree of detail of the classification. As a result, building categories are formed which represent an increased number of buildings and a higher share of the final energy demand of the building stock. It was found that the number of reference building models required to represent a variety of buildings depends on the desired accuracy and intended degree of coverage. The building stock can be represented by the proposed method with a moderate number of reference building models. The models can be used to conduct extensive investigations of both building energy demand and energy supply.

Due to the influence of occupant behavior, a large variation of the specific net-energy consumption (electricity, heating, domestic hot water) up to a factor five can occur for identical building units [11]. Given the use of statistical consumption data obtained from field data, results generated by the described procedure represent average occupant behavior as well as average building physics. This is appropriate for studies in the context of the energy transition, when trends for the entire building stock are of interest. Nevertheless, the underlying building models also offer full flexibility for analyzing individual situations of use and particular occupant behavior.

The proposed method can be used to develop and aggregate a variety of reference building models from statistical data in order to carry out necessary and influential investigations. A powerful tool is provided, that that may be applied for coordination and implementation of extensive measures to accomplish a successful transition of the energy system.

References

[1] Barton M, Schweigler C, Bayerischer Wohngebäudebestand und Energiebedarf für die Wärmeversorgung – aktueller Stand und Prognose für das Jahr 2050, CENERGIE München Germany, Conference INUAS, Munich, Germany, 2020 (in publishing process).
[2] Schwan L, Hahn J, Barton M, Anders R, Schweigler C, Analysis and development of reference buildings for the energy transition in the thermal sector, CENERGIE München Germany, 2019.
[3] Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden, Energieeinsparverordnung (EnEV), Germany, July 26, 2007.
[4] Verordnung zur Änderung der Energieeinsparverordnung, EnEV, Germany, 2009.
[5] Bigalke U, Armbruster A, Lukas F, Krieger O, Schuch C, Kunde J, Statistiken und Analysen zur Energieeffizienz im Gebäudebestand, Germany, 2016
[6] Institut Wohnen und Umwelt (IWU), Deutsche Wohngebäudetypologie: Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden, Darmstadt Germany, 2015
[7] Corradini R, Regional differenzierte Solarthermie-Potenziale für Gebäude mit einer Wohneinheit, Dissertation, Ruhr-Universität Bochum Germany, 2013.
[8] Verordnung zur Berechnung der Wohnfläche, Wohnflächenverordnung (WoFlV), Germany, January 1, 2004.
[9] Bayerisches Landesamt für Statistik und Datenverarbeitung, Bestand an Wohngebäuden und Wohnungen in Bayern: Endergebnisse der Gebäude- und Wohnungszählung 2011, Germany, 2012.
[10] Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden, Energieeinsparverordnung (EnEV), Germany, latest update October 2014.
[11] Hahn J, Schumacher P, Lang W, Jensch W, Performance Gap and Occupant Behavior – Review and Analysis of German high-efficient residential buildings. Conference ECOS, Osaka, Japan, 2020 (in publishing process).