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A comparative benchmarking study of multi-storey residential buildings in two periods of energy saving efforts: the 1980s and the 2010s.

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Abstract. In 1990, Technological Institute (TI) in Denmark made a benchmarking study of 92 typical multi-storey buildings covering 23 000 dwellings. The study included measurement data from the 1970s and the years after the energy crises. This study showed that over a period of less than 20 years a significant reduction in energy consumption took place. In a new similar study, TI and Aalborg University have analysed 62 buildings covering 18 000 dwellings including measurement data from the last 20 years. This time, the data covers a period with an increasing focus on the carbon-emission impacts of energy consumption. As opposed to the first benchmarking study, the new 20-years study shows that the heat consumption has been almost constant over the last 20 years. This paper presents a comparative study of the two sets of measurements and evaluates energy saving efforts and individual building energy performance. Furthermore, the paper compares two different ways of deriving benchmarks from the data and demonstrates how utilizing change-point models/energy signature as opposed to the more traditional mean annual values per heated area, significantly increases the usability.

1. Introduction

Worldwide, the buildings and construction sector accounts for 36% of final energy use and 39% of energy and process-related carbon dioxide emissions (1). Currently in EU, building energy use accounts for over 40% of the total primary energy consumption (2).

Therefore, massive investments are made in these years in energy renovation of the older building stock, but the effect related to lowering the energy consumption is still quite modest. Typical figures of heat consumption are indeed accessible from national energy statistics. These figures, however, can easily be misrepresented by impact of new buildings and extensions of existing buildings. The figures can also be misrepresented by different user intensity. In Denmark, for example, the number of square meters per dweller in single family houses and in blocks of flats have steadily increased over the years (3). Finally, the figures can be misrepresented by the fact that indoor climate ideals change over time. Thus, it is well known that areas with higher income typically have higher demands for a comfortable indoor climate with higher ventilation rates and higher indoor temperature (4).

An overall problem with monitoring and benchmarking is the lack of verification of the effect of energy retrofitting measures. This has elicited doubts about their effects and the impact on carbon emission reduction. This is confirmed by studies that have examined the depths of energy retrofits on municipal, regional, or national levels. Commonly, they call attention to the difficulty to distinguish between energy savings and carbon reductions and the energy performance of the building (5).

Some studies have found that energy retrofitting can reduce energy consumption more than the efficiency improvement might indicate (6). Other studies have found that energy retrofitting usually cannot reach the magnitude of energy savings estimated by technical calculations (7). Moreover, it is widely acknowledged that a gap arises between the technical estimation and the actual energy consumption after retrofitting, which is recognised as rebound and pre-bound effects (8,9).

The purpose of this paper is to make a comparative analysis of the development in the heat consumption of older multi-storey dwellings over the past five decades. The analysis is based on two different datasets; one dataset compiled in 1990 covering the heating consumption of 92 typical multi-storey buildings during the period from 1971-1988 and one dataset compiled in 2021 covering the heating consumption of 62 buildings during the period from 2003-2020. The buildings in the two datasets are similar but not the same, however 7 buildings are present in both time-series.

Half a century ago, there was a worldwide energy crisis that led to huge savings in relatively few years. However, since then the development is modest, especially when considering recent years' focus on energy savings in building renovation. This paper pinpoints the most interesting aspects that can be derived from looking at the development in the heating energy consumption during the last 50 years.

For building owners, it is often difficult to assess whether a building is performing sufficiently in regards to energy efficiency. In this respect, benchmarking is a valuable tool, however the traditional methods, e.g. stating a mean annual heat consumption per person or m^2 is lacking in versatility and this study demonstrates how utilizing change-point models/energy signature to determine key performance indicators (KPIs) instead, significantly increases usability. The consumption measurements collected in the project will therefore also be used for the development of a new benchmarking tool aimed at multi-storey building owners and the derived KPIs will feed into a web-based benchmarking tool.

2. Materials

This study includes two time-series of heat consumption in multi-storey residential buildings: An early period from 1971-1988 and a late period from 2003-2020, both periods are based on meter reading during approximately 18 years of consumption.

The early time-series count 23 000 dwellings and a total heated area of 1 766 000 m². The buildings were erected throughout the time span of six decades, i.e., between 1920 and 1980, one third of the buildings were erected in the 1940s.

The late time-series counts 18 000 dwellings and a total heated area of 1 085 000 m². The buildings in this time-series were erected throughout a time span of 90 years, see figure 1.
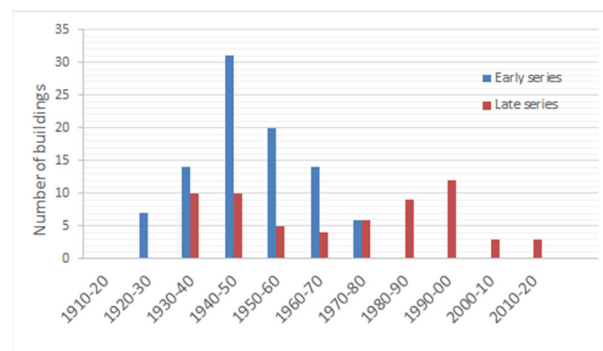
Figure 1. The two time-series distributed on decades of erection.

At present, the datasets do not include any information on additions of new buildings, extension of existing buildings, renovations carried out, number of tenants, indoor temperature etc. and therefore the comparison is made solely based on the registered raw heating energy consumption data.

2.1. The early time-series

The early time-series was established by Mikael Grimmig (10) and it represents the energy accounts of five different housing associations located in the greater Copenhagen area. The data was collected retrospective since the heating season 1970/71 and extend until the heating season 1987/88. The series covers the seasonal energy consumption for heating in 92 multi-storey residential buildings. The data consisted of energy consumption for degree day adjusted heating and hot water production/use/distribution. The unit is kWh/m^2, thus representing the annual energy efficiency of each of the 92 buildings for 18 years in total.

Measurements originate from aggregated and converted meter readings. Out of the time-series, 55 consumption statements have direct meter readings of district heating. Concerning degree adjustment, the degree independent energy consumption, i.e. domestic hot water use, was set to a standard fixed 25%. Two buildings, one built in 1930 and one built in 1941 were not equipped with hot water installations at the time.

2.2. The late time-series

The second time-series originates from a green account concept set up by the administrative unit of the housing association fsb. The fsb green account was set up in 2003 and has been running since then.

The buildings in this time-series were erected from 1933 onwards. One half of the buildings were built before the energy crises in the 1970s, the other half after. Six of the multi-storey buildings are relatively new, e.g. built after 2000. According to the building regulations these buildings' total need for energy for heating, ventilation, cooling and domestic hot water must not exceed 70 kWh/m².

All the buildings of the second time-series are heated by the greater Copenhagen district heating system (HOFOR). Concerning degree adjustment, the degree independent energy consumption, i.e. hot water use, was set to a standard fixed 30%.

2.3. Seven recurring buildings

Comparing the two sets of data seven buildings are present in both time-series, see Figure 2.

Damstokkene		**Munkevangen**	
Built [year]: 1943		Built [year]: 1944	
Dwellings [-]: 91		Dwellings [-]: 425	
Heated area: [m^2]: 6 197		Heated area: [m^2]: 30 420	
Skolevangen		**Birkebo**	
Built [year]: 1945		Built [year]: 1950	
Dwellings [-]: 345		Dwellings [-]: 65	
Heated area: [m^2]: 27 785		Heated area: [m^2]: 5 441	
Præstevænget		**Stakhaven**	
Built [year]: 1949		Built [year]: 1956	
Dwellings [-]: 122		Dwellings [-]: 144	
Heated area: [m^2]: 8 941		Heated area: [m^2]: 11 264	
Rymarksvænget			
Built [year]: 1970			
Dwellings [-]: 443			
Heated area: [m^2]: 47 562			

Figure 2. The seven multi-story apartment buildings present in both time-series.

These buildings represent 1 635 dwellings and a total heated area of 137 610 m^2. The seven recurring buildings make it possible to better analyse the general development in consumption and connecting the two time-series and stipulating the changes in heat consumption during the time between the two series.

3. Methods

In this study, two different benchmarking approaches are used: The traditional method of benchmarking energy performance, i.e. developing average values of KPIs, e.g. total heating consumption in kWh/m^2, sometimes enhanced by additional values for fractals or via scatterplots (11,12) and an alternative method for determining multiple KPIs, the so-called energy signature (ES).

The first method recognises the benchmarking approach defined by Pérez-Lombard (13). In this approach, raw measured data is used to determine benchmark figures. Benchmarking figures, however, are not easy to establish. First of all, a cleaning process is needed, i.e. careful identification and exclusion of outliers (lost meter readings, incorrect loggings etc.). After cleaning, the data are degree-day corrected and credible benchmark figures can be established, e.g. typically annual energy consumption for heating in well-defined units like kWh per heated square meters (kWh/m^2 per year). Similarly, benchmarks for electricity consumption and carbon emission related to heat and electricity consumption can be derived.

The second method uses so-called change-point models or more specifically the ES method, which produces much more versatile benchmarking KPIs. This method requires more data, e.g. monthly readings, however in return it can produce multiple KPIs such as the actual base load (heating used for domestic hot water production/circulation/use), the specific heat losses and the balance point temperature. Furthermore, the higher level of detail in data can also help to exclude outliers, a process which can be operationalized and automated. Therefore, the ES is a more detailed benchmark, and the ES can even be used to e.g., calibrate building performance simulation programs (BES) (14), or as simple models themselves in e.g., district-scale modelling (15).

The overall method used to understand the benchmarking statistics in the two time-series, is a simple case oriented qualitative comparative analysis: What differences and similarities are present and how does the historic context of the studies influence the focus points and the results of the studies (16).

4. Analysis

The early and late time-series are from quite different time periods regarding scope and context. The early data set covers the 1970s, this series is to a great extent affected by the double energy supply crisis in 1973 and 1979. During this period energy prices increased significantly which resulted in a societal requirement of massive energy savings. An almost panic-stricken situation in the beginning, was - replaced by stable energy prices and growing wealth towards the end of the time-series. The late series, covering the first two decades of this century, can be characterised by falling energy prices and growing wealth, but surprisingly not notably effected by the economic crisis in 2008. In the 2010s, the focus on energy saving was replaced by an increasing interests in carbon emission reductions. This, however, does not seem to affect the level of energy savings either. The difference between the two sets of data is very clear when compared, see Figure 3.
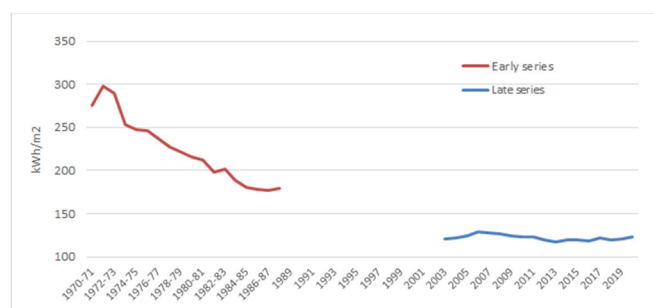
Figure 3. Average annual degree-day corrected energy consumption for heating for the two time-series.

In the early time-series a reduction of 40% was attained, in the late time-series no reduction is observed. During the period from 1987 to 2003, i.e. between the two time-series, a 35% reduction is

observed. These reductions are explained primarily by replacement of windows (16%), the introduction of individual metering (12%) and the use of building management systems (BMS) (5%).

4.1. The early time-series

In the original report of the early time-series Grimmig found that the average consumption of the 92 multi storey residential buildings was reduced by 35-40 % between 1970 and 1988.

Remarkable for this series of data is that a large reduction of the energy consumption throughout the years can be observed, most significant in the beginning of the series, i.e., the heating season between1971-72 and 1973-74. Whereas the first drop represents a reduction of 15%, the next decline between 1973-74 and 1984-85 accounts for 29%. Grimmig noticed that the buildings with the highest heat consumption were the ones to achieve the largest energy savings over the years. See figure 4, showing the development depending on the start heat consumption of 400-450, 300-350, 300-250 and less than 250 kWh/m^2 respectively.
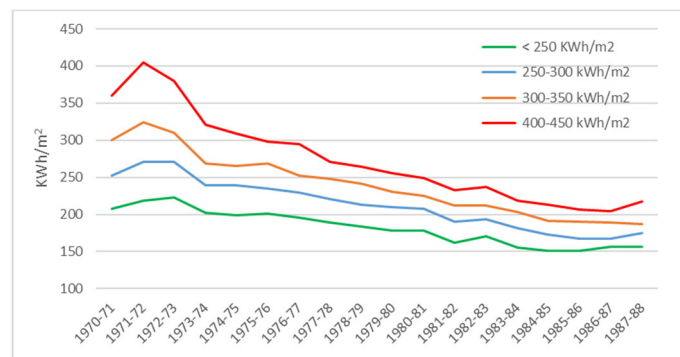
Figure 4. Average annual degree-day corrected energy consumption for heating. Reduction in relation to 1971-72 consumption. (Grimmig, 1990, p.31).

A number of energy efficiency measures were carried out during the period, and Grimmig listed roof insulation, cavity wall insulation and sealing of window joints. Concerning change of energy supply, Grimmig underlines the impact of change from boilers to natural gas and change from boilers to district heating. Concerning improved operation management Grimmig listed the most employed measures of the time. These were thermostat valves, night-time drop and automatic control by use of BMS.

4.2. The late time-series

In the late time-series heating and hot water consumption is more or less constant, see Figure 5.
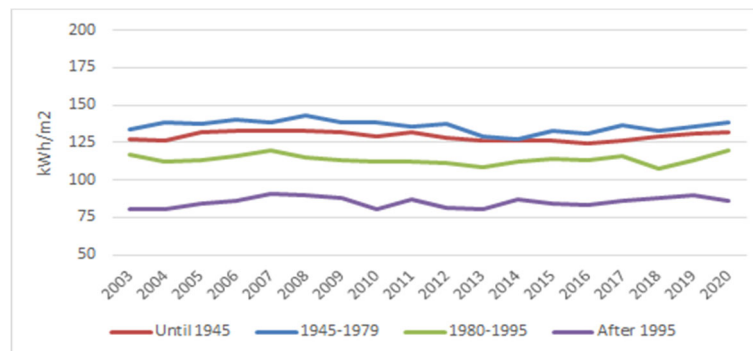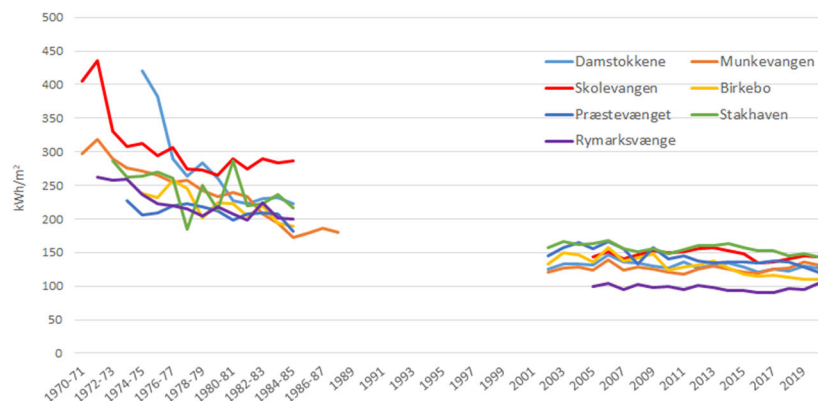

Figure 5. Average annual degree-day corrected energy consumption for heating for the late time-series, divided into period of erection.

As in the early time-series, small deviations can be seen over the years. However, if the early and the late time-series are represented by use of the same y-axis, it becomes clear that almost no changes occur in the late time-series. The average heat consumption of the 62 buildings is within general uncertainty at the same level of 100 kWh/m^2 for the entire 20 years, and the individual variations can be ascribed to inaccurate meter reading, outliers, imprecise climate adjustment and changing user behaviour.

As a bit of a surprise, the oldest buildings erected before 1945 performs better than the second oldest buildings erected in the period after the Second World War. This can be interpreted as proper retrofitting of the oldest buildings but also that a potential for energy retrofitting of the second oldest buildings still exists. The youngest buildings have by far the best performance i.e. of approx. 80 kWh/m² annually.

4.3. Comparative study

Figure 6 shows the development in the measured heat consumption for the seven recurring buildings identified in both the early and late time-series. As can be seen, the development in the energy performance of the individual buildings follow the general development shown in Figure 3. Variations for individual buildings might indicate measuring uncertainty, changes of tenants' behavior and other kinds of fluctuations, these however, are most notable during the early series.


Figure 6. Average degree-day corrected annual energy consumption for heating for seven buildings present in both time-series.

Based on the abovementioned experiences, we have recognized a need for a more versatile benchmarking methodology. The methodology must be able to differentiate and make individual assessments of buildings like the seven recurring buildings in the late time-series condition. Therefore, in order to establish more versatile and exact benchmarks we have decided to use three-point change-point models, also termed energy signatures (ESs). By use of this method, exclusion of outliers can be operationalized and automated. Moreover, it can be interpreted as a simple model for the buildings and as a way to to determine multiple KPIs for each individual building.

The ES can be used to determine the expected monthly or even (with some approximation) daily heat consumption for the building, and furthermore it can be used as a very simple model for the building. Another important feature of the ES is, that if long data series are available then it is possible to analyze the development in the ES over time, e.g., to investigate effects of energy efficiency measures, socio-economic developments in society etc.

Figure 7 shows an example of the ES plot for Skolevangen with presumed outliers in red.
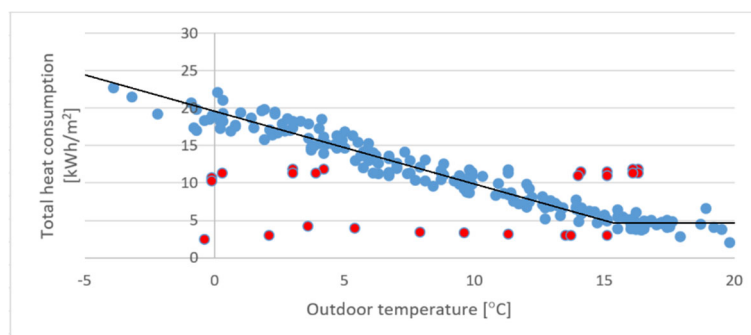
Figure 7. ES for Skolevangen. The baseload is 4.89 kWh/m^2, the balance point is 15.72 °C and the specific heat loss is 0.91 kWh/m^2/°C. Outliers marked with red.

The benchmarking KPIs for the seven recurring buildings can be summed up as shown in table 1.

Table 1. Benchmarking KPIs for seven different buildings.

	Base load [kWh/m^2]	Specific heat loss [kWh/m^2/°C]	Balance temperature [°C]
Damstokkene	3.49	0.97	15.28
Munkevangen	3.81	0.87	15.32
Skolevangen	4.89	0.91	15.72
Birkebo	3.49	0.91	16.03
Præstevænget	4.21	1.02	15.59
Stakhaven	4.10	1.12	15.70
Rymarksvænget	3.18	0.60	15.98

Even though the seven buildings seem to have very similar consumption patterns, table 1 clearly shows that there are quite distinctive differences in base loads, specific heat loss and balance temperature, and therefore this method of determining KPIs significantly increases the possibilities and versatility of a benchmarking tool. Furthermore, the temporal development of the benchmarking KPIs can be analyzed in order to determine effects of different types of energy efficiency improvements taking into account e.g. pre- and rebound effects. This, in turn will make it possible to extrapolate the effects of such improvements/changes in other buildings to determine expected energy savings.

5. Conclusion

The heat consumption in multi-storey residential buildings can vary significantly from building to building, just as the consumption in a building varies from year to year. The purpose of this study was to identify reasons for variations in building energy performance. Two time-series demonstrating the temporal development of the annual heating consumption of multi-storey residential buildings were investigated. Reductions of approximately 40% was seen through the 1970s and this period was followed by 20 years with savings of almost 35%, but since 2000 no identifiable savings have occurred.

In the early time-series, savings were achieved by building envelope measures, i.e. roof insulation, cavity wall insulation and sealing of window joints and through changes in heating systems from boilers to natural and gas district heating. A huge part of savings were also achieved through thermostat valves, night-time drop and automatic control by use of building management systems (BMS). During the period from 1987-2003, i.e. between the two time-series, reductions are explained primarily by replacement of windows (16%), introduction of individual metering (12%) and BMS (5%). This means, that for most of the buildings, the "low-hanging fruits" were already picked and therefore the late time-series has only little or no reduction in heating energy use. This also means that the saving potential in these buildings, will be limited and further reductions will be more costly.

A closer study, however, reveals that the efforts to obtain energy savings were still existing in the late series, however this was overshadowed by re-bound effects, a favourable trend of the economic situation, and tenants' change of behaviour. This was also concluded for the seven recurring buildings, i.e., one relatively new building and six older buildings already energy optimised.

On this background we found that, buildings that are already to some extent energy optimised a refined method for benchmarking is needed. Therefore, in the second time-series we decided to implement a more advanced benchmarking method based on the energy signature. This way buildings with similar energy performance according to classic benchmarking became distinguishable and moreover show significant variations for instance concerning base load and specific heat loss.

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