Data-driven Methods to Characterize the Dynamics of Buildings

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Overarching Hypothesis for WP3: Intelligent Energy Systems Integration

- **Demand-side perspective:** We cannot achieve a non-fossil society only by optimizing the individual buildings.
- **Supply-side:** We need to analyse buildings in a community/society context looking to how energy is:
  - **Produced,**
  - **Transmitted,**
  - **Stored**
  - **Converted**
  (PTSC)
This has leads to

• Energy flexibility
• Aggregation
• Measuring and logging
• Data – and its smart use
Flexibility –
Peak Load Reduction for District Heating

How much can peak load be reduced?
How Long Can Buildings Offer Thermal Comfort Without Heat Supply?

Old house
1851-1930

Old house
1961-1972

Source: Rongling Li, DTU Civil Engineering
How Long Can Buildings Offer Thermal Comfort Without Heat Supply?

Renovated 1851-1930 house

New house 2007-2010

Source: Rongling Li, DTU Civil Engineering
16 Houses in Sønderborg

Source: Peder Bacher & Panagota Gianicolou
16 Houses in Sønderborg
Aggregation

Heating Power, kW

Source: Peder Bacher & Panagota Glaniou
This points to

- Potential for virtual storage
- Possible need for Model Predictive Control (MPC)

... for this we need to know the building performance and characteristics better
European Commission:


By way of example, in a district heating network where metering data are transmitted/collected automatically on an hourly or daily basis, such data will represent a significantly higher value for optimising system services, etc., than metering data collected on a monthly basis with walk-by/drive-by technologies.


(29) Targeted incentives should be provided to promote smart-ready systems and digital solutions in the built environment. This offers new opportunities for energy savings, by providing consumers with more accurate information about their consumption patterns, and by enabling the system operator to manage the grid more effectively.

(37) Building automation and electronic monitoring of technical building systems have proven to be an effective replacement for inspections, in particular for large systems, and hold great potential to provide cost-effective and significant energy savings for both consumers and businesses. The installation of such equipment should be considered to be the most cost-effective alternative to inspections in large non-residential and multi-... residential buildings...

Article 14 (4) ... non-residential buildings...

building automation and control systems shall be capable of:
(a) continuously monitoring, logging, analysing and allowing for adjusting energy use;
Measuring and Logging

- Heat meter
- Indoor Climate meter
- Wireless tags – motion sensors
- 3 phase current clamps
Gee, this can be extensive....!

Comprehensive logging with integrated measurement systems:
- Temperature
- CO₂
- RH%
- Energy meters
- Electricity consumption
- Open/close sensors (doors & windows)
- Occupancy sensors
- Outdoor climate
- Thermography
- Blower door (air tightness)

It can be expensive (for building owners) and bothersome (for occupants) with all these sensors. We have developed a concept, whereby we use mathematics/statistics, so we can manage with:

**Few sensors, but data collection with high frequency**
Data-driven Methods to Characterize the Dynamics of Buildings – Part 2

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RE+BUS

CITIES
Centre for IT Intelligent Energy Systems
EXAMPLE OF GREY-BOX MODEL
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS
EXAMPLE OF GREY-BOX MODEL

\[
dT_i = \left( \frac{T_w - T_i}{R_{w1}C_i} + \frac{\Phi_h}{C_i} + \frac{T_e - T_i}{R_{ie}(\cdot)C_i} \right) dt + \sigma_i dW_i
\]

\[
dT_w = \left( \frac{T_i - T_w}{R_{w1}C_w} + \frac{T_e - T_w}{R_{w2}C_w} + \frac{\Phi_s}{C_w}gA(\cdot) \right) dt + \sigma_w dW_w
\]

\[\gamma_k = T_{i,k} + \epsilon_k\]
 IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS
EXAMPLE OF GREY-BOX MODEL – PARAMETERS AND FUNCTIONS

Figure 13: RC-diagram of wall.

\[
\begin{align*}
\frac{dT_i}{dt} &= \left( \frac{T_w - T_i}{R_{w1}C_i} + \frac{\Phi_h}{C_i} + \frac{Te - T_i}{R_{ie}(\cdot)C_i} \right) dt + \sigma_i dW_i \\
\frac{dT_w}{dt} &= \left( \frac{T_i - T_w}{R_{w1}C_w} + \frac{T_e - T_w}{R_{w2}C_w} + \frac{\Phi_s}{C_w} gA(\cdot) \right) dt + \sigma_w dW_w \\
\gamma_k &= T_{i,k} + \epsilon_k
\end{align*}
\]
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS
EXAMPLE OF GREY-BOX MODEL – PHYSICAL INTERPRETATION

HEAT LOSS COEFFICIENT

\[
UA = \frac{1}{R_{w1} + R_{w2}}
\]

HEAT CAPACITIES

\[
C_i \\
C_w
\]

TIME CONSTANTS

\[
\tau_i = R_{w1} \cdot C_i \\
\tau_w = R_{w2} \cdot C_w
\]
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS
EXAMPLE OF GREY-BOX MODEL – HIDDEN FUNCTIONAL RELATIONS

SOLAR TRANSMITTANCE (DIFFUSE RADIATION)
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS
EXAMPLE OF GREY-BOX MODEL – HIDDEN FUNCTIONAL RELATIONS

SOLAR TRANSMITTANCE (DIRECT RADIATION)
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS
EXAMPLE OF GREY-BOX MODEL – HIDDEN FUNCTIONAL RELATIONS

SOLAR TRANSMITTANCE (DIRECT RADIATION)
Semi-parametric modelling of sun position dependent solar gain using B-splines in grey-box models

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\textbf{A B S T R A C T}

Modelling the effects of solar irradiation plays an important role in various applications. This paper describes a semi-parametric (combined grey-box and spline-based), data-driven technique that can be used to model systems in which the solar gain depends on the sun position. The solar gain factor is introduced, i.e. the absorbed fraction of measured solar irradiation, and estimated as a continuous non-parametric function of the sun position. The implementation of the spline-based solar gain factor in a grey-box model framework is described. The method is tested in two case studies—in a model of the internal temperature of a dwelling in Aalborg, Denmark, and a model of the return temperature of a solar collector field in Solrød, Denmark. It is shown that the solar gain factor as a function of sun position is able to account for structural variations in solar gain that may occur due to factors such as shading obstacles and window or absorber orientation. In both test cases, the spline-based solar gain function improved the model accuracy significantly, and largely reduced structural errors in prediction residuals. In addition, the shape of the estimated function provided insight into the dynamics of the system and the effect of solar irradiation.
REBUS CONNECT
ENERGY LABELLING
IN LARGE SCALE
Height-to-height variation
Unoccupied test house

Room-to-room variation
Occupied apartment
Height-to-height variation
Unoccupied test house

UP TO 5 °C TEMPERATURE DIFFERENCE

Room-to-room variation
Occupied apartment
UP TO 10 °C TEMPERATURE DIFFERENCE

UP TO 5 °C TEMPERATURE DIFFERENCE
\[ \Phi_h = \begin{cases} UA(T_b - T_a) & \text{for } T_a < T_b, \\ \Phi_0 & \text{otherwise} \end{cases} \]

\[
\text{LSE}(f(x), g(x)) = \log \left[ \exp(f(x)k) + \exp(g(x)k) \right] k^{-1}
\]

Smooth approximation of \(\max[f(x), g(x)]\)
THE MODEL

HEAT CONSUMPTION

WEATHER DEPENDENT HEAT CONSUMPTION

WEATHER INDEPENDENT HEAT CONSUMPTION

NOISE

SMOOTH MAXIMUM FUNCTION

\[ \Phi_{\text{heat}} = \text{LSE}[(UA_0 + W_s UA_W) (T_{b_0} - T_a) - gA I_g, \Phi_0] + e \]

WEATHER DEPENDENT HEAT CONSUMPTION (DEPENDS ON OUTDOOR TEMPERATURE, WIND SPEED AND SOLAR RADIATION)
THE MODEL

Graph showing the relationship between outdoor temperature [°C] and heating power [kW].

- Prediction (grey dots)
- Smoothed prediction (black line)
- Observations (white dots)
# MAPPING OF THERMAL PROPERTIES OF 16 DANISH DWELLINGS

<table>
<thead>
<tr>
<th>House</th>
<th>Year</th>
<th>Floor area [m²]</th>
<th>$U_0$ [W/(K m²)]</th>
<th>$UA_0$ [W/K]</th>
<th>$UA_W$ [W/K per m/s]</th>
<th>$gA$ [m²]</th>
<th>$\Phi_0$ [W]</th>
<th>$T_b$ [°C]</th>
<th>$T_{transition}$ [°C]</th>
<th>$\Phi_{x,i} / T_i = 20$ °C</th>
<th>$\sigma_{\Phi_{x,i}}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1970</td>
<td>151</td>
<td>1.25 (0.03) *</td>
<td>189 (4) *</td>
<td>5.8 (0.7) *</td>
<td>2.5 (0.3) *</td>
<td>676 (84) *</td>
<td>16.5 (0.5)</td>
<td>12.1 – 21.0</td>
<td>702</td>
<td>157</td>
</tr>
<tr>
<td>2</td>
<td>1969</td>
<td>163</td>
<td>1.25 (0.02) *</td>
<td>204 (4) *</td>
<td>3.9 (0.8) *</td>
<td>3.7 (0.3) *</td>
<td>340 (47) *</td>
<td>14.2 (0.4)</td>
<td>9.5 – 18.9</td>
<td>1246</td>
<td>194</td>
</tr>
<tr>
<td>3</td>
<td>1963</td>
<td>140</td>
<td>1.28 (0.02) *</td>
<td>179 (2) *</td>
<td>3.2 (0.5) *</td>
<td>2.5 (0.1) *</td>
<td>141 (30) *</td>
<td>15.7 (0.2)</td>
<td>11.9 – 19.5</td>
<td>810</td>
<td>103</td>
</tr>
<tr>
<td>4</td>
<td>1952</td>
<td>86</td>
<td>1.45 (0.03) *</td>
<td>125 (2) *</td>
<td>4.1 (0.5) *</td>
<td>1.5 (0.2) *</td>
<td>215 (19) *</td>
<td>12.8 (0.3)</td>
<td>10.2 – 15.4</td>
<td>971</td>
<td>118</td>
</tr>
<tr>
<td>5</td>
<td>1966</td>
<td>111</td>
<td>1.54 (0.03) *</td>
<td>171 (3) *</td>
<td>6.1 (0.7) *</td>
<td>1.6 (0.2) *</td>
<td>110 (63)</td>
<td>16.6 (0.3)</td>
<td>9.6 – 23.6</td>
<td>643</td>
<td>155</td>
</tr>
<tr>
<td>6</td>
<td>1969</td>
<td>119</td>
<td>0.97 (0.02) *</td>
<td>115 (2) *</td>
<td>6.5 (0.6) *</td>
<td>2.8 (0.2) *</td>
<td>47 (19)</td>
<td>13.3 (0.3)</td>
<td>10.2 – 16.4</td>
<td>880</td>
<td>129</td>
</tr>
<tr>
<td>7</td>
<td>1947</td>
<td>119</td>
<td>2.17 (0.04) *</td>
<td>258 (5) *</td>
<td>7.2 (1.3) *</td>
<td>1.2 (0.4) *</td>
<td>6 (50)</td>
<td>13.5 (0.3)</td>
<td>6.9 – 20.0</td>
<td>1810</td>
<td>243</td>
</tr>
<tr>
<td>8</td>
<td>1965</td>
<td>160</td>
<td>1.24 (0.04) *</td>
<td>199 (6) *</td>
<td>5.7 (1.4) *</td>
<td>2.2 (0.4) *</td>
<td>376 (45)</td>
<td>12.6 (0.5)</td>
<td>8.9 – 16.4</td>
<td>1569</td>
<td>258</td>
</tr>
<tr>
<td>9</td>
<td>1965</td>
<td>173</td>
<td>1.21 (0.02) *</td>
<td>210 (3) *</td>
<td>4.2 (0.6) *</td>
<td>1.2 (0.2) *</td>
<td>523 (62)</td>
<td>18.2 (0.3)</td>
<td>15.8 – 20.6</td>
<td>389</td>
<td>275</td>
</tr>
<tr>
<td>10</td>
<td>1996</td>
<td>135</td>
<td>0.90 (0.02) *</td>
<td>121 (2) *</td>
<td>5.1 (0.6) *</td>
<td>2.5 (0.2) *</td>
<td>106 (25)</td>
<td>14.1 (0.4)</td>
<td>10.2 – 18.0</td>
<td>786</td>
<td>193</td>
</tr>
<tr>
<td>11</td>
<td>1966</td>
<td>122</td>
<td>1.09 (0.04) *</td>
<td>133 (4) *</td>
<td>3.1 (1.1) *</td>
<td>1.2 (0.3) *</td>
<td>108 (46)</td>
<td>14.7 (0.5)</td>
<td>10.5 – 18.9</td>
<td>751</td>
<td>96</td>
</tr>
<tr>
<td>12</td>
<td>1975</td>
<td>136</td>
<td>1.05 (0.02) *</td>
<td>143 (2) *</td>
<td>3.1 (0.4) *</td>
<td>1.9 (0.1) *</td>
<td>644 (17)</td>
<td>13.4 (0.3)</td>
<td>11.3 – 15.4</td>
<td>1001</td>
<td>94</td>
</tr>
<tr>
<td>13</td>
<td>1937</td>
<td>86</td>
<td>2.67 (0.06) *</td>
<td>229 (5) *</td>
<td>9.2 (1.4) *</td>
<td>4.4 (0.4) *</td>
<td>45 (31)</td>
<td>11.2 (0.3)</td>
<td>7.6 – 14.8</td>
<td>2227</td>
<td>431</td>
</tr>
<tr>
<td>14</td>
<td>1965</td>
<td>123</td>
<td>1.36 (0.02) *</td>
<td>167 (2) *</td>
<td>5.7 (0.6) *</td>
<td>2.4 (0.2) *</td>
<td>356 (22)</td>
<td>14.1 (0.3)</td>
<td>11.8 – 16.4</td>
<td>1068</td>
<td>203</td>
</tr>
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<td>7.0 – 19.1</td>
<td>1593</td>
<td>210</td>
</tr>
<tr>
<td>16</td>
<td>1967</td>
<td>137</td>
<td>1.22 (0.02) *</td>
<td>167 (3) *</td>
<td>3.4 (0.7) *</td>
<td>1.3 (0.2) *</td>
<td>193 (26)</td>
<td>13.5 (0.3)</td>
<td>8.1 – 18.9</td>
<td>1137</td>
<td>143</td>
</tr>
</tbody>
</table>

$H_0$: $U_0 = 0$, $UA_0 = 0$, $UA_W = 0$, $gA = 0$, $\Phi_0 = 0$, $T_b = 17$

Significance code **: $p$-value < 0.05
Article

Method for Scalable and Automatised Thermal Building Performance Documentation and Screening

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Abstract: In Europe, more and more data on building energy use will be collected in the future as a result of the energy performance of buildings directive (EPBD), issued by the European Union. Moreover, both at European level and globally it became evident that the real energy performance of new buildings and the existing building stock needs to be documented better. Such documentation can, for example, be done with data-driven methods based on mathematical and statistical approaches. Even though the methods to extract energy performance characteristics of buildings are numerous, they are of varying reliability and often associated with a significant amount of human labour, making them hard to apply on a large scale. A classical approach to identify certain thermal performance parameters is the energy signature method. In this study, an automatised, nonlinear and smooth approach to the well-known energy signature is proposed, to quantify key thermal building performance parameters. The research specifically aims at describing the linear and nonlinear heat usage dependency on outdoor temperature, wind and solar irradiation. To make the model scalable, we realised it so that it only needs the daily average heat use of buildings, the outdoor temperature, the wind speed and the global solar irradiation. The results of applying the proposed method on heat consumption data from 16 different and randomly selected Danish occupied houses are analysed.

Keywords: thermal building performance; data-driven energy performance documentation and screening; energy signature; occupants effect on heat consumption

1. Introduction

Today, the building stock suffers from low energy efficiency and significant discrepancies between anticipated and actual heat consumption known as the performance gap. The performance gap has been documented in several studies, see, e.g., in [1, 2]. In [3], it is stated that only 3% of the building stock in the EU has energy label A, which corresponds to the level of new buildings. Additionally, the reliability of the energy labels has been proven to be limited. In a report from 2018 by the Danish Energy Agency it was stated that 20 to 30% of the Danish building energy labels were wrong. This corresponds to between 12,000 and 18,000 energy labels that specific year.

The energy efficiency directive (EED) of the European Union (EU) [4] states that all member states are responsible for the installation of individual energy meters, including heat meters, on all buildings to the extent that it is technically possible and economically feasible. Furthermore, the new energy performance of buildings directive (EPBD) lists several requirements to boost the national renovation strategies [5]. These initiatives are established in order to increase the energy efficiency of the EU building stock. With the current data collection requirements and the new EPBD, the relevancy of...