Data-driven Methods to Characterize the Dynamics of Buildings

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Overarching Hypothesis for WP3: *Intelligent Energy Systems Integration*

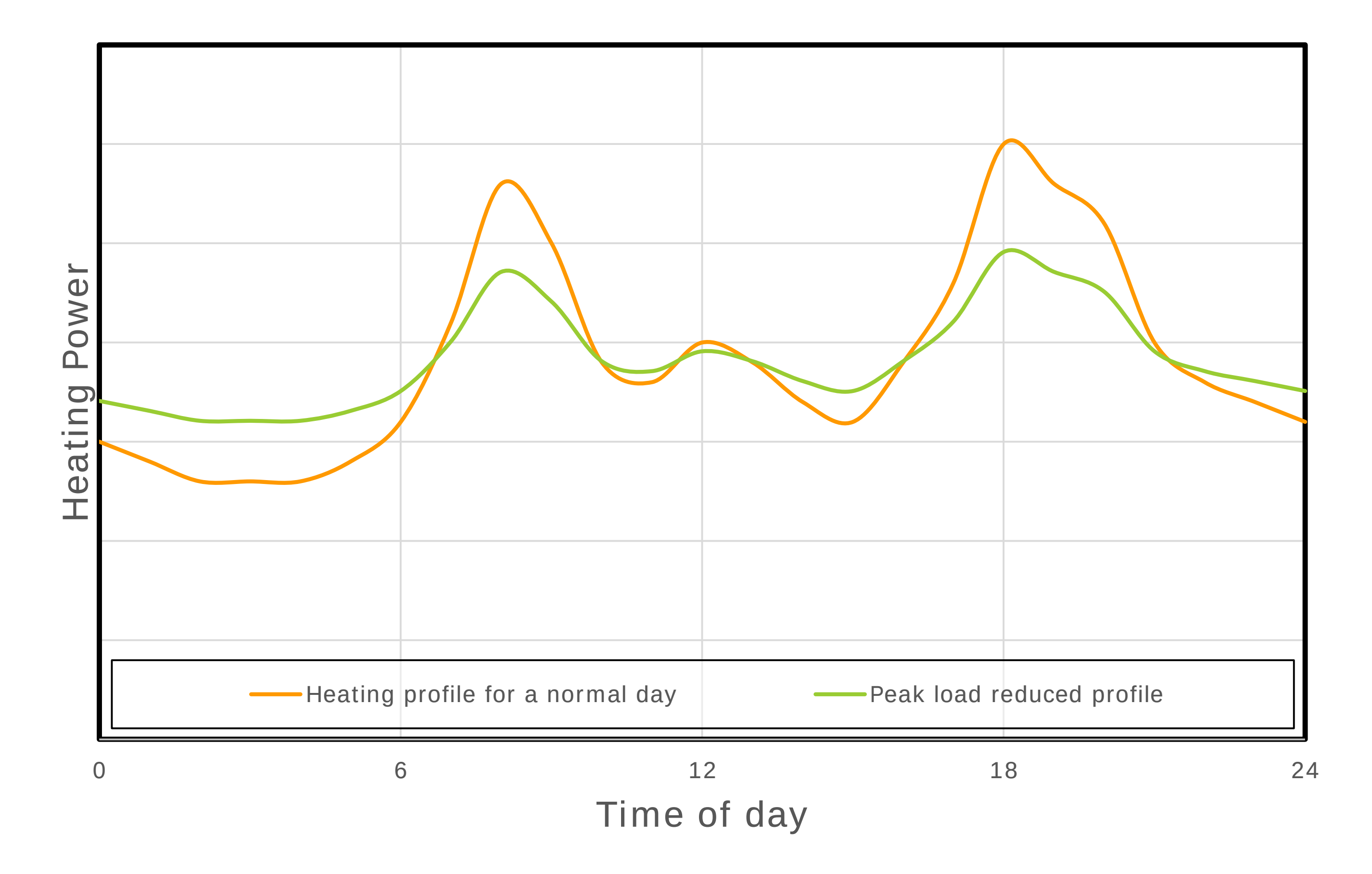
- Demand-side perspective: We cannot achieve a non-fossil society only by optimizing the individual buildings
- Supply-side: We need to analyse buildings in a community/society context looking to how energy is:
  - **P**roduced,
  - **T**ransmitted,
  - **S**tored
  - **C**onverted

  (PTSC)

This has leads to

- Energy flexibility
- Aggregation
- Measuring and logging
- Data – and its smart use

Flexibility –
Peak Load Reduction for District Heating

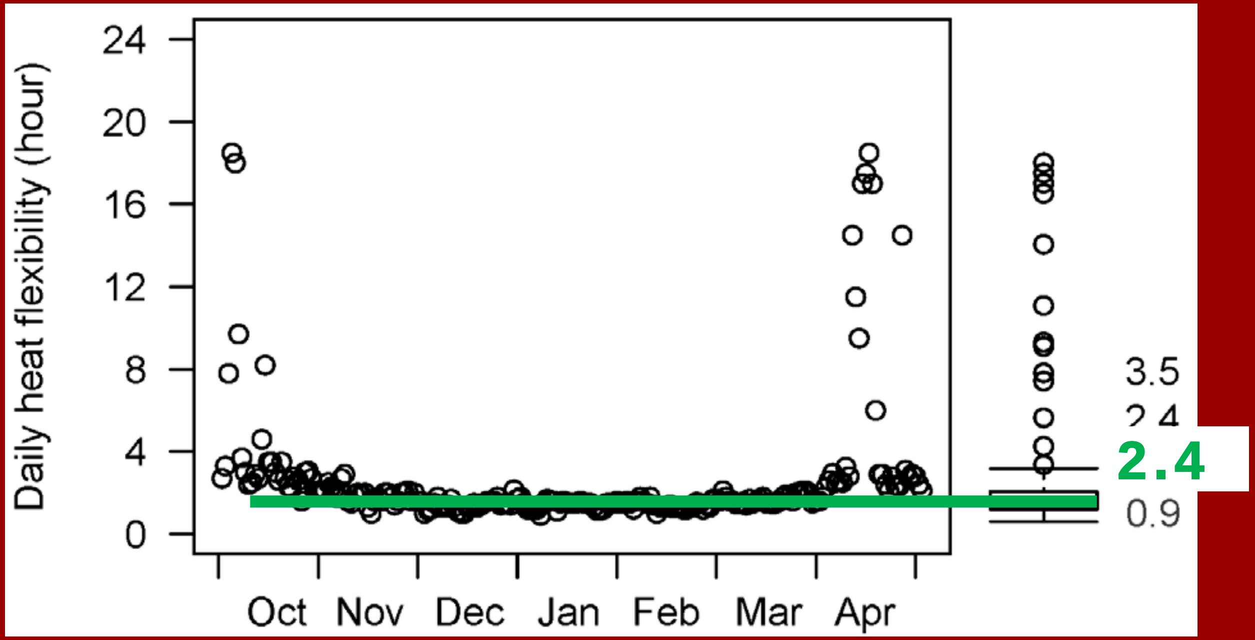


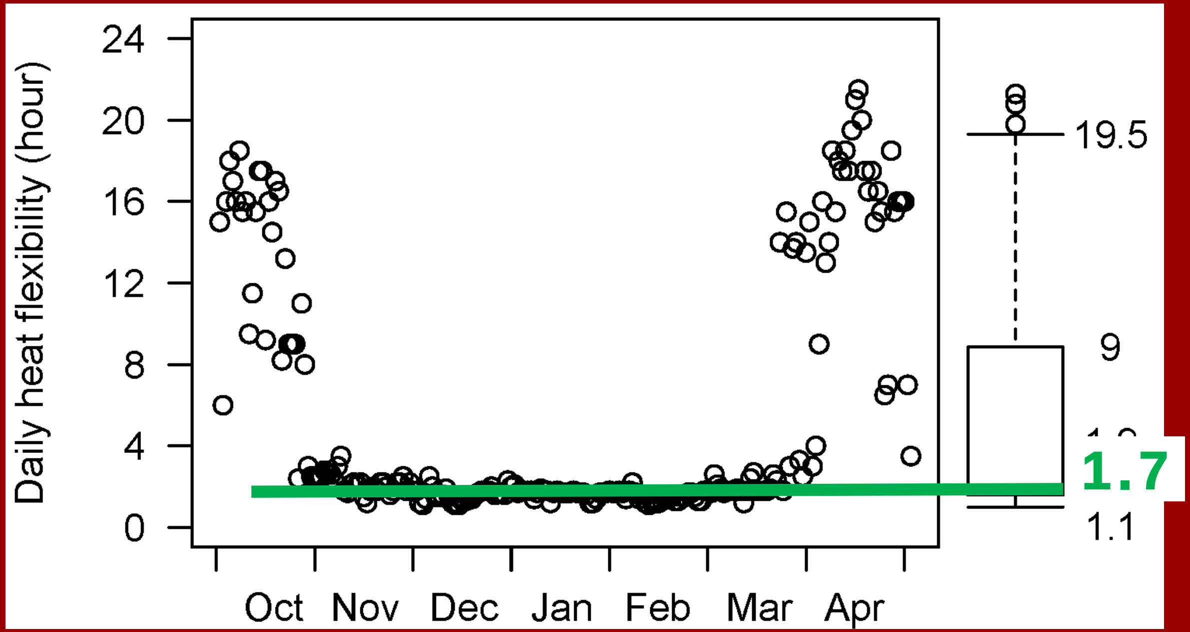
How much can peak load be reduced?

How Long Can Buildings Offer Thermal Comfort Without Heat Supply?

Old house
1851-1930

Old house
1961-1972





Source: Rongling Li, DTU Civil Engineering

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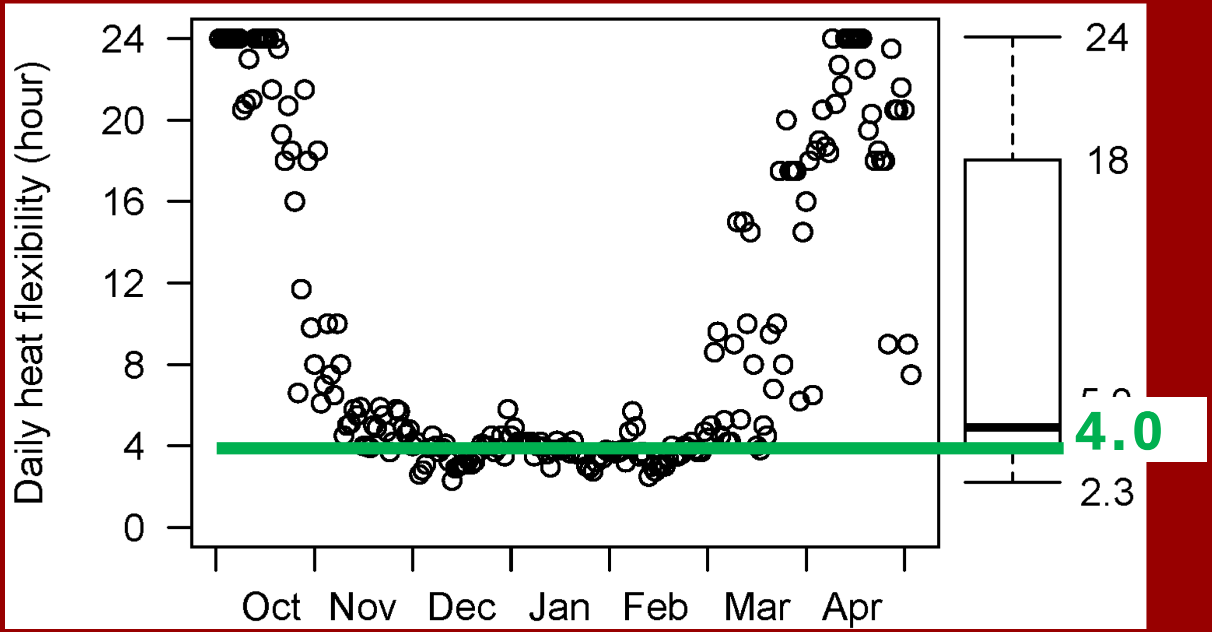
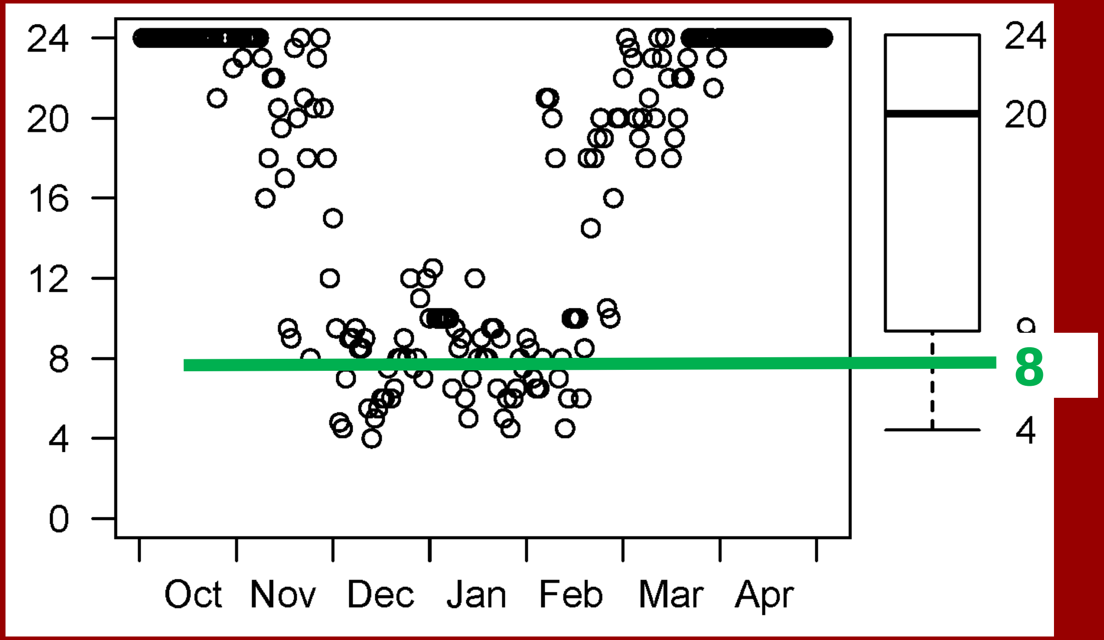
How Long Can Buildings Offer Thermal Comfort Without Heat Supply?

Renovated
1851-1930 house

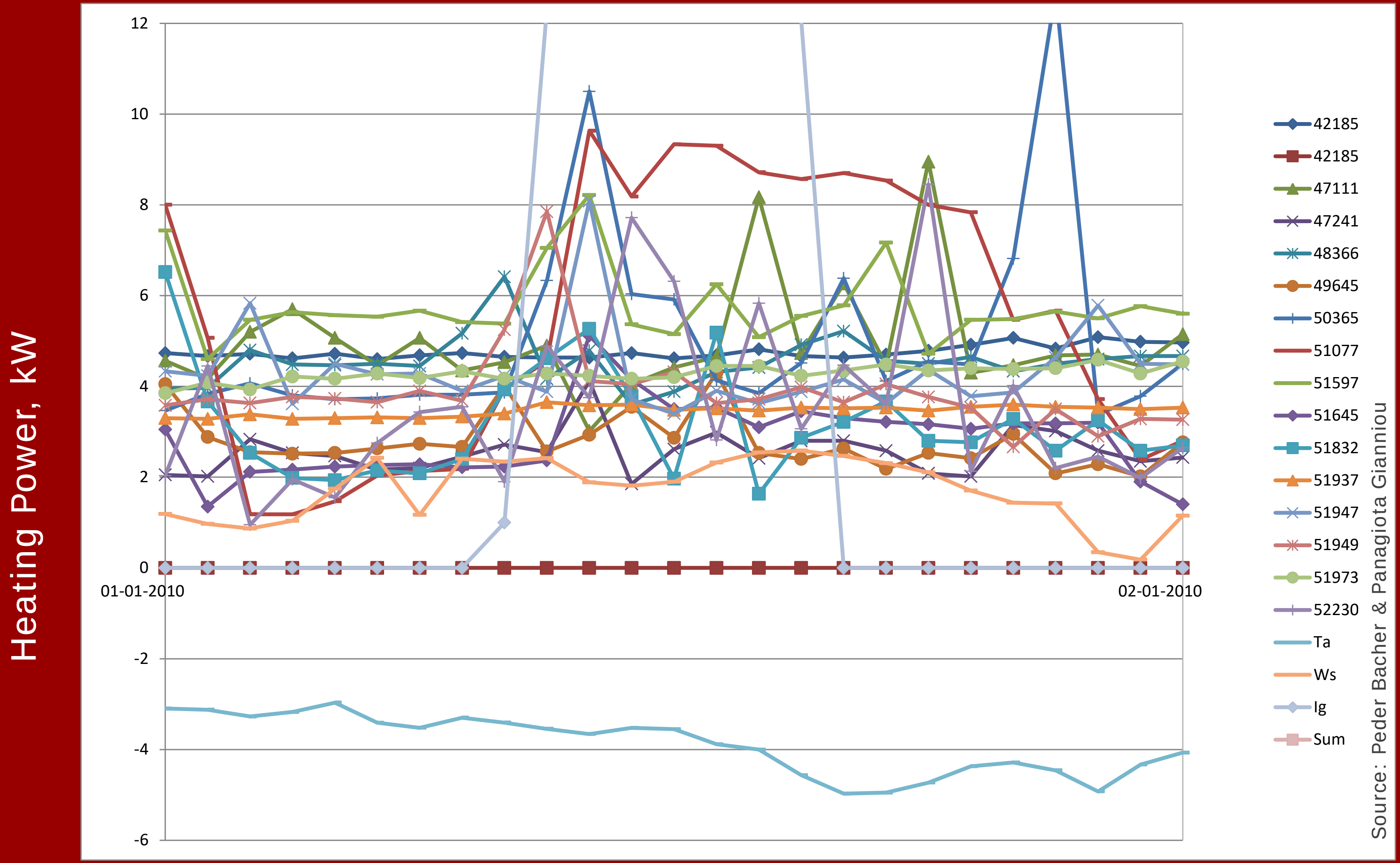
New house
2007-2010



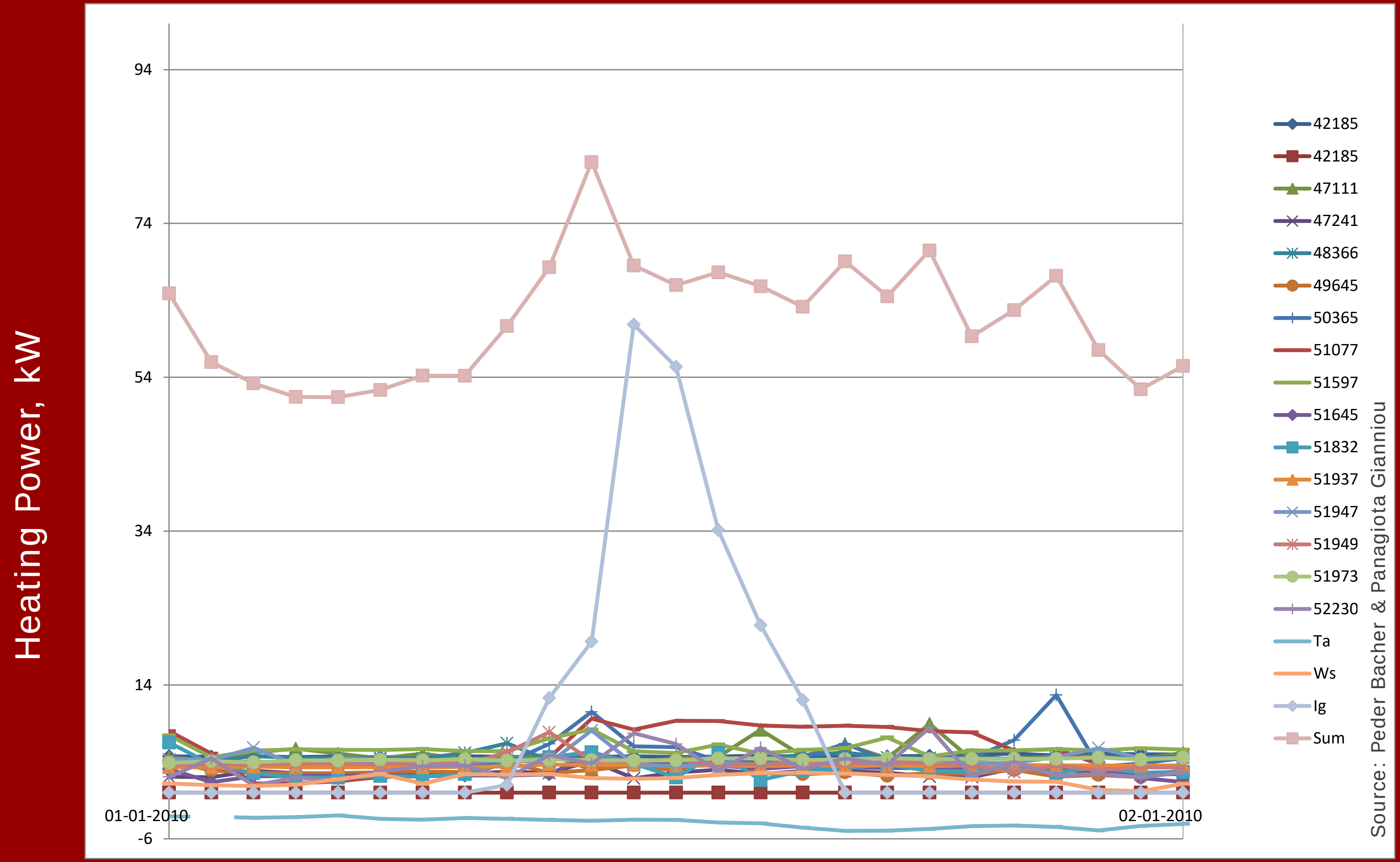


Source: Rongling Li, DTU Civil Engineering

16 Houses in Sønderborg



16 Houses in Sønderborg
Aggregation



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:

Energy Efficiency Directive (EED - 2019)

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

Energy Performance of Buildings Directive (EPBD - 2018 amendment)

(29) Targeted incentives should be provided to <u>promote</u> smart-ready systems and <u>digital solutions</u> 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 <u>electronic monitoring</u> of technical building systems have proven to be an effective replacement for inspections, in particular for large systems, and hold great <u>potential to provide cost-effective and significant energy savings</u> 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-apartment buildings of a sufficient size ...

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

building automation and control systems shall be capable of:

(a) <u>continuously monitoring, logging, analysing and allowing for adjusting</u> energy use;

Source: Danish Energy Agency

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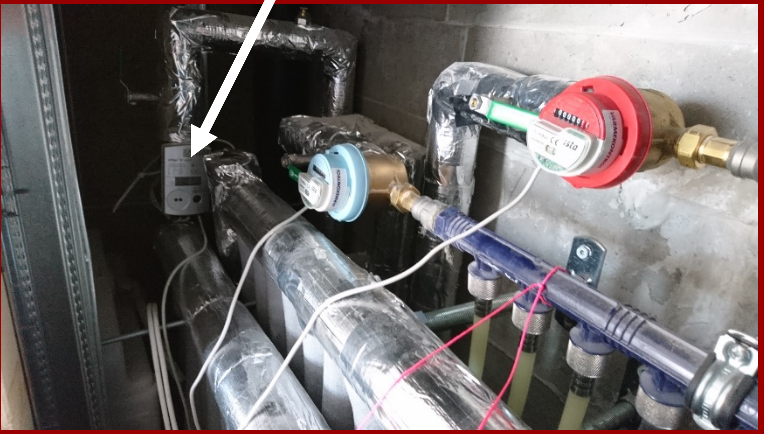
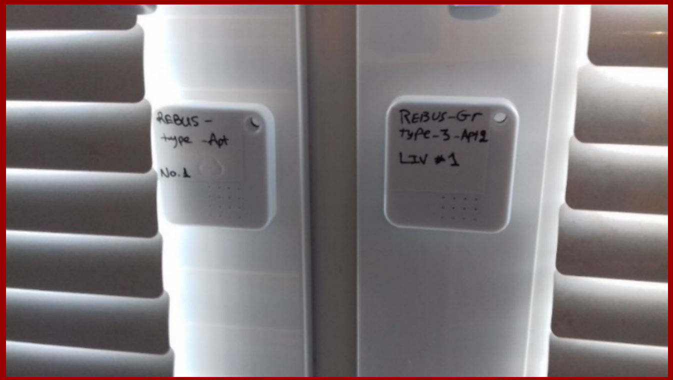
Measuring and Logging

Heat meter

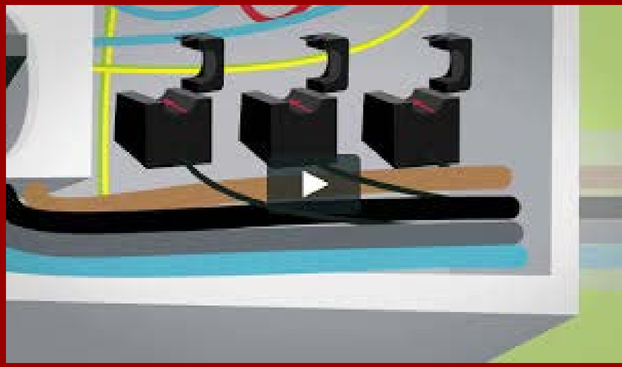


Indoor Climate meter

Wireless tags – motion sensors



3 phase current clamps



Gee, this can be extensive….!

Comprehensive logging with integrated measurement systems:

- Temperature
- CO_2
- 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

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Data-driven Methods to Characterize the Dynamics of Buildings – Part 2

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Christoffer Rasmussen, PhD-candidate, DTU Compute

REBUS

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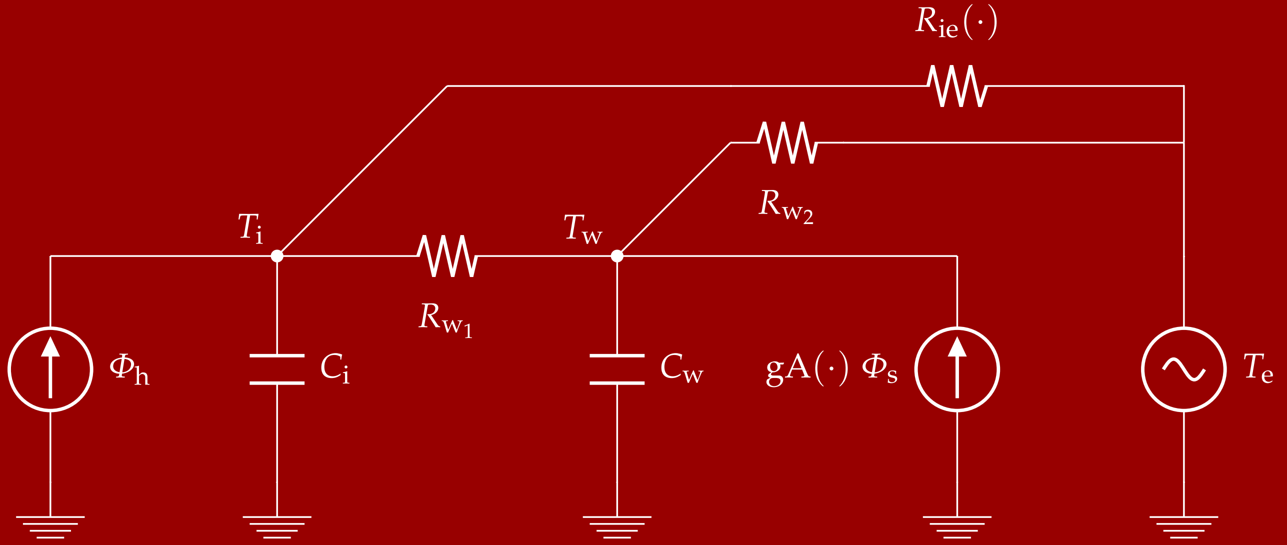
EXAMPLE OF GREY-BOX MODEL

IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS

IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS

EXAMPLE OF GREY-BOX MODEL



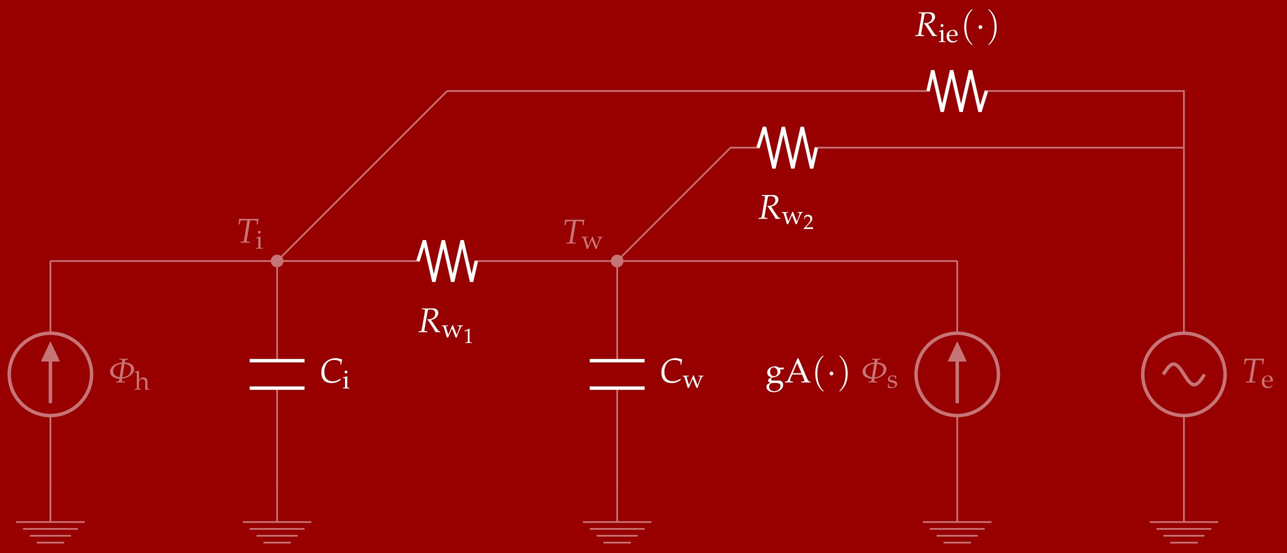
$$\mathrm{d}T_{\mathrm{i}} = \left(\frac{T_{\mathrm{w}} - T_{\mathrm{i}}}{R_{\mathrm{w}_1} C_{\mathrm{i}}} + \frac{\Phi_{\mathrm{h}}}{C_{\mathrm{i}}} + \frac{T_{\mathrm{e}} - T_{\mathrm{i}}}{R_{\mathrm{ie}}(\cdot) C_{\mathrm{i}}} \right) \mathrm{d}t + \sigma_{\mathrm{i}} \mathrm{d}W_{\mathrm{i}}$$

$$\mathrm{d}T_{\mathrm{w}} = \left(\frac{T_{\mathrm{i}} - T_{\mathrm{w}}}{R_{\mathrm{w}_1} C_{\mathrm{w}}} + \frac{T_{\mathrm{e}} - T_{\mathrm{w}}}{R_{\mathrm{w}_2} C_{\mathrm{w}}} + \frac{\Phi_{\mathrm{s}}}{C_{\mathrm{w}}} \mathrm{gA}(\cdot) \right) \mathrm{d}t + \sigma_{\mathrm{w}} \mathrm{d}W_{\mathrm{w}}$$

$$Y_k = T_{\mathrm{i},k} + \epsilon_k$$

IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS

EXAMPLE OF GREY-BOX MODEL – PARAMETERS AND FUNCTIONS



$$\mathrm{d}T_{\mathrm{i}} = \left(\frac{T_{\mathrm{w}} - T_{\mathrm{i}}}{R_{\mathrm{w}_1} C_{\mathrm{i}}} + \frac{\Phi_{\mathrm{h}}}{C_{\mathrm{i}}} + \frac{T_{\mathrm{e}} - T_{\mathrm{i}}}{R_{\mathrm{ie}}(\cdot) C_{\mathrm{i}}} \right) \mathrm{d}t + \sigma_{\mathrm{i}} \mathrm{d}W_{\mathrm{i}}$$

$$\mathrm{d}T_{\mathrm{w}} = \left(\frac{T_{\mathrm{i}} - T_{\mathrm{w}}}{R_{\mathrm{w}_1} C_{\mathrm{w}}} + \frac{T_{\mathrm{e}} - T_{\mathrm{w}}}{R_{\mathrm{w}_2} C_{\mathrm{w}}} + \frac{\Phi_{\mathrm{s}}}{C_{\mathrm{w}}} \mathrm{gA}(\cdot) \right) \mathrm{d}t + \sigma_{\mathrm{w}} \mathrm{d}W_{\mathrm{w}}$$

$$Y_k = T_{\mathrm{i},k} + \epsilon_k$$

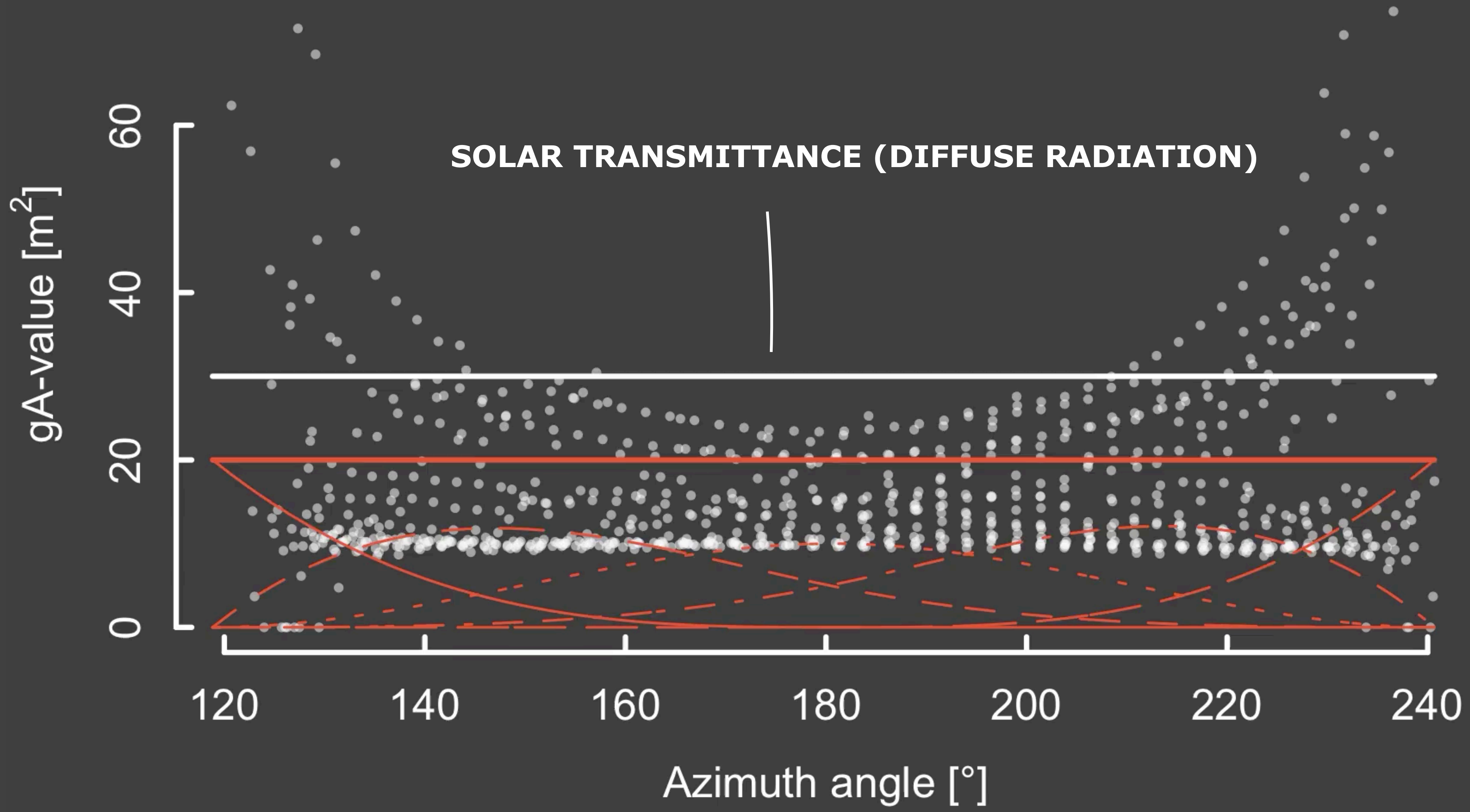
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS

EXAMPLE OF GREY-BOX MODEL – PHYSICAL INTERPRETATION

HEAT LOSS COEFFICIENT	$\mathrm{UA} = \frac{1}{R_{\mathrm{w}_1} + R_{\mathrm{w}_2}}$
HEAT CAPACITIES	C_{i} C_{w}
TIME CONSTANTS	$\tau_{\mathrm{i}} = R_{\mathrm{w}_1} \cdot C_{\mathrm{i}}$ $\tau_{\mathrm{w}} = R_{\mathrm{w}_2} \cdot C_{\mathrm{w}}$

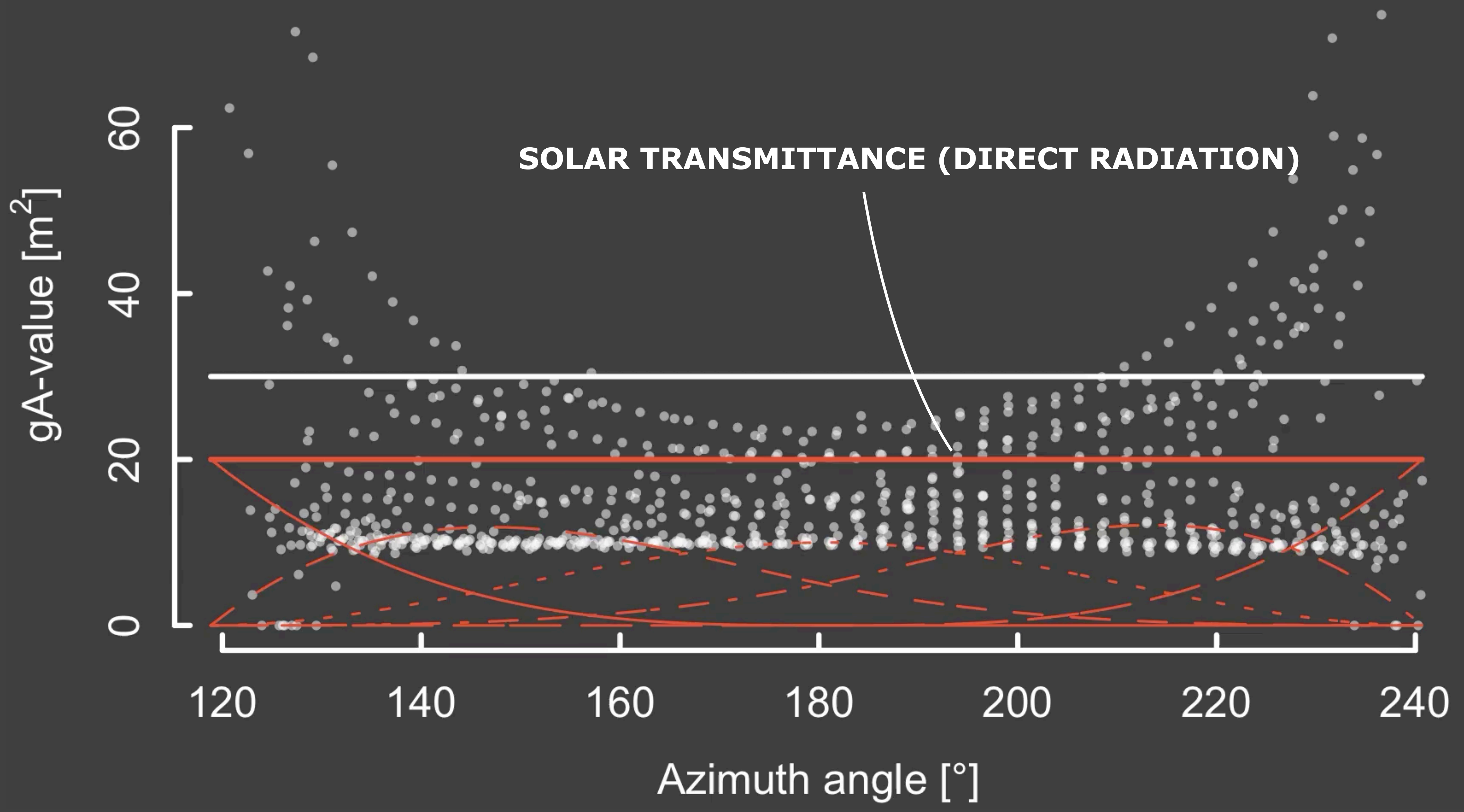
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS

EXAMPLE OF GREY-BOX MODEL – HIDDEN FUNCTIONAL RELATIONS



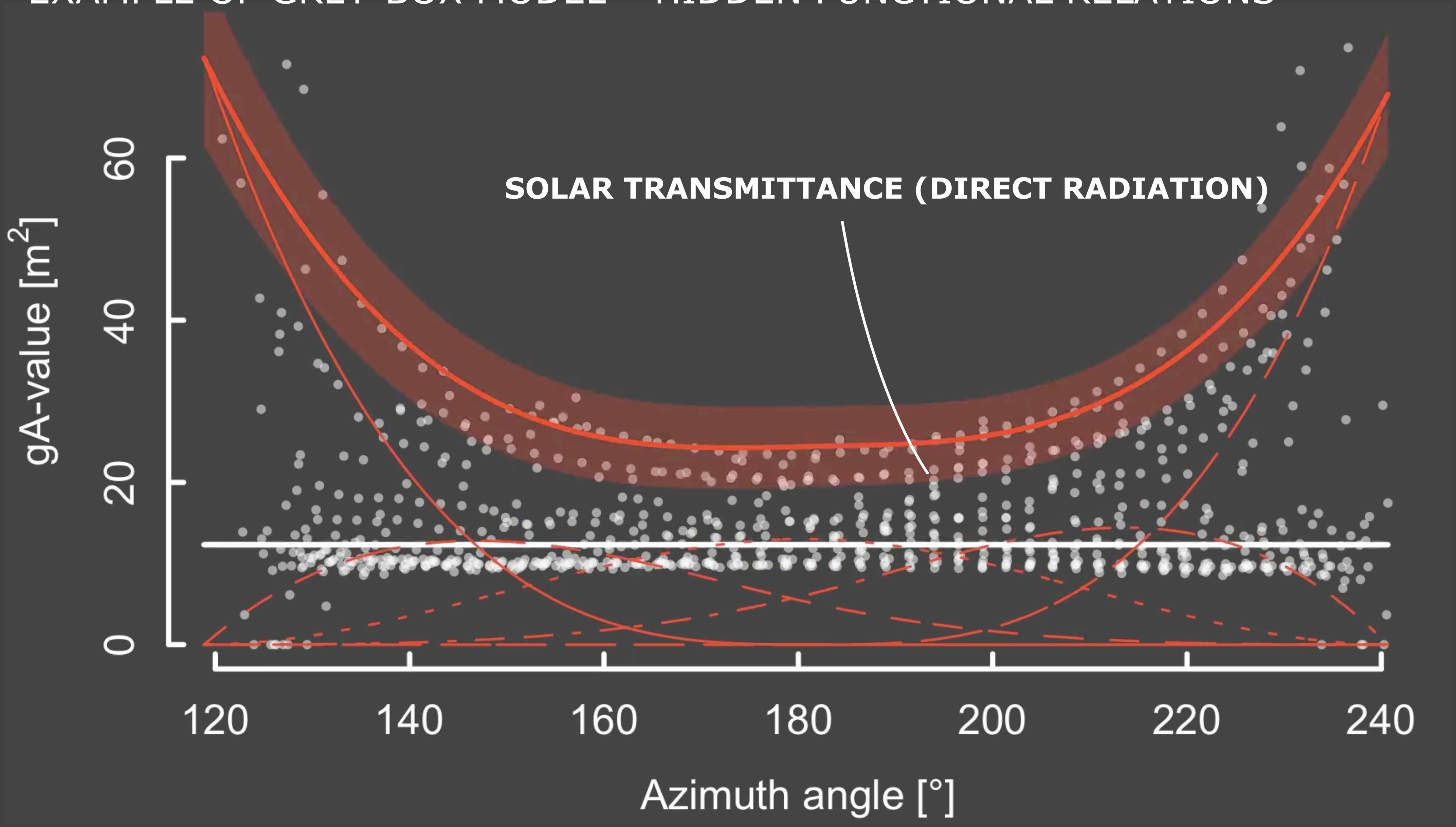
IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS

EXAMPLE OF GREY-BOX MODEL – HIDDEN FUNCTIONAL RELATIONS



IDENTIFICATION OF THERMAL PROPERTIES OF BUILDINGS

EXAMPLE OF GREY-BOX MODEL – HIDDEN FUNCTIONAL RELATIONS



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Solar Energy 195 (2020) 249–258

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

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Semi-parametric modelling of sun position dependent solar gain using B-splines in grey-box models

Check for updates

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ARTICLE INFO

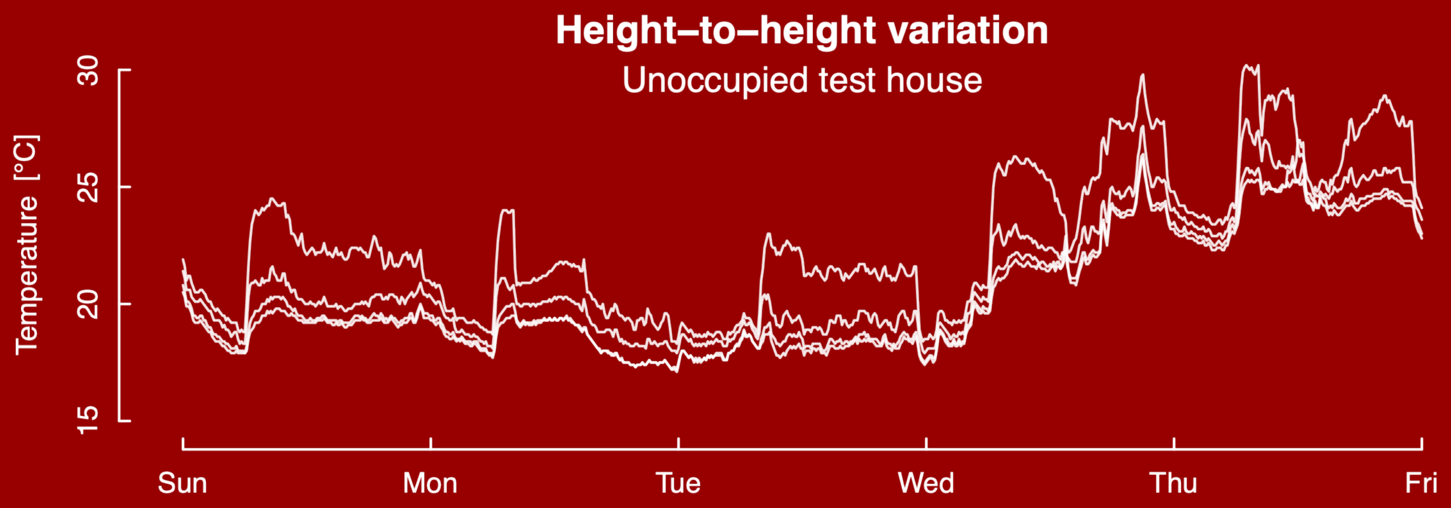
Keywords:
Solar gain modelling
Grey-box modelling
Splines
Thermal dynamics
Building energy
Solar heat collectors

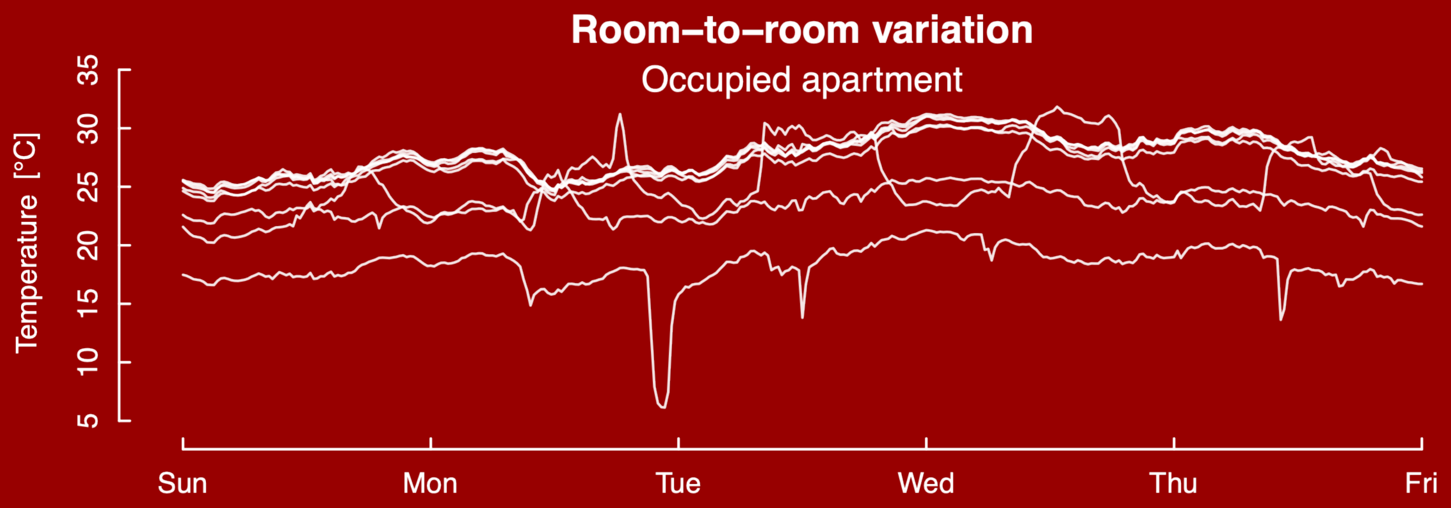
ABSTRACT

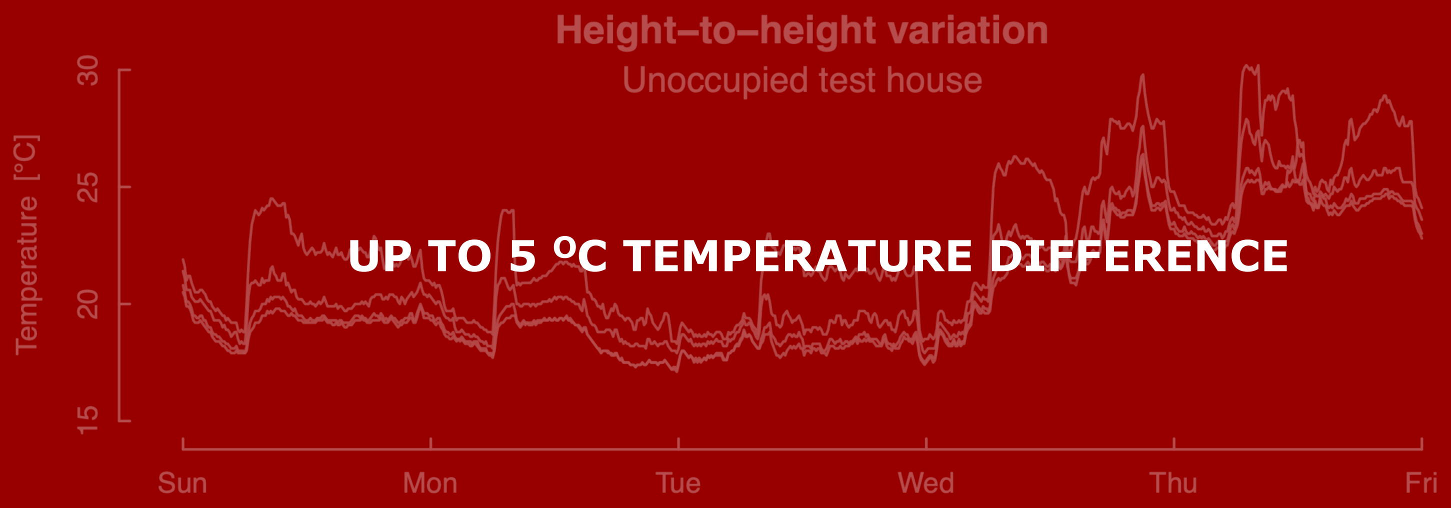
Modelling the effects of solar irradiation plays an important role in various applications. This paper describes a semi-parametric (combined grey-box and spline-based), data-driven technique that can be used to model systems in which the solar gain depends on the sun position. The *solar gain factor* 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 local solar input characteristics. Accurate representation of such site characteristics was not possible with

REBUS CONNECT

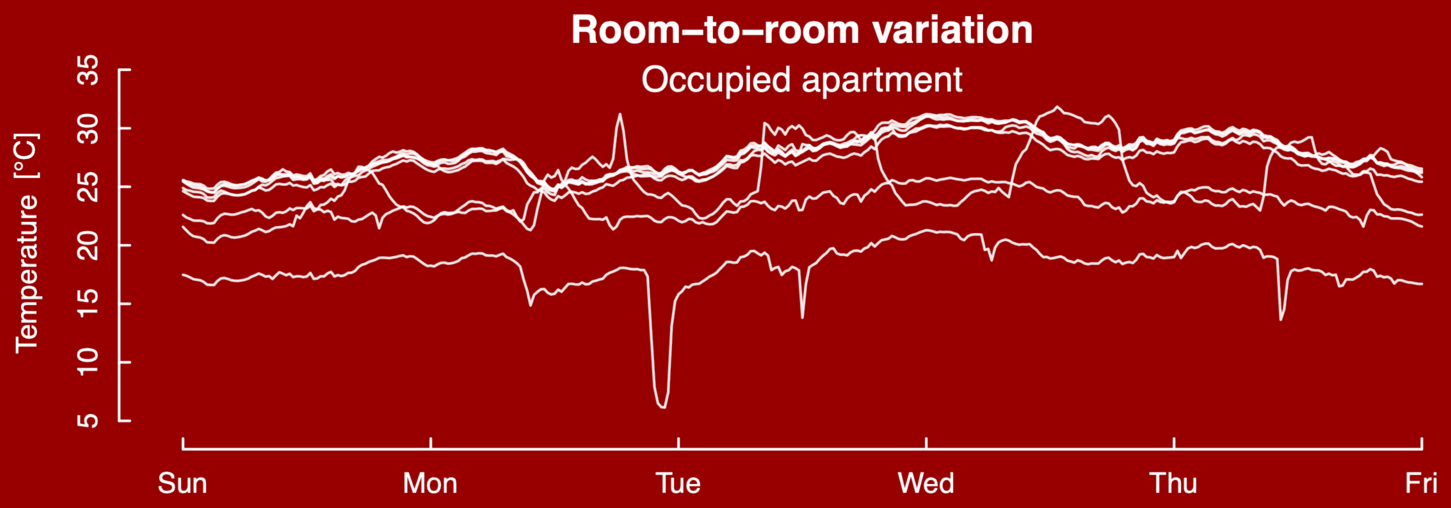
ENERGY LABELLING IN LARGE SCALE

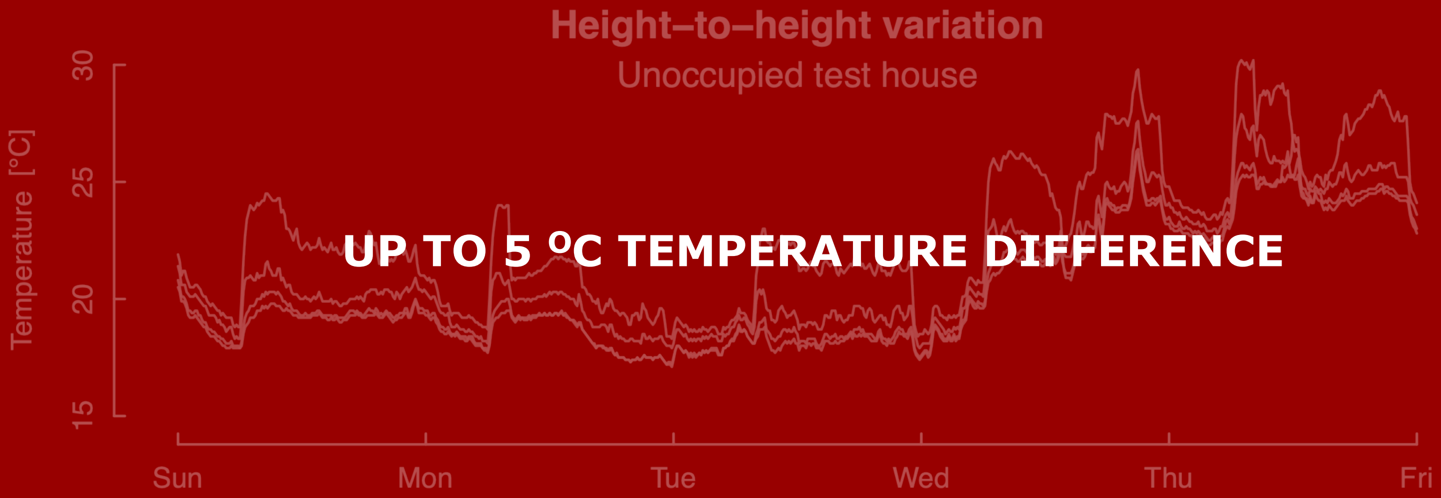

Height–to–height variation
Unoccupied test house
Temperature [°C]
15
20
25
30
Sun
Mon
Tue
Wed
Thu
Fri


Room–to–room variation
Occupied apartment
Temperature [°C]
5
10
15
20
25
30
35
Sun
Mon
Tue
Wed
Thu
Fri

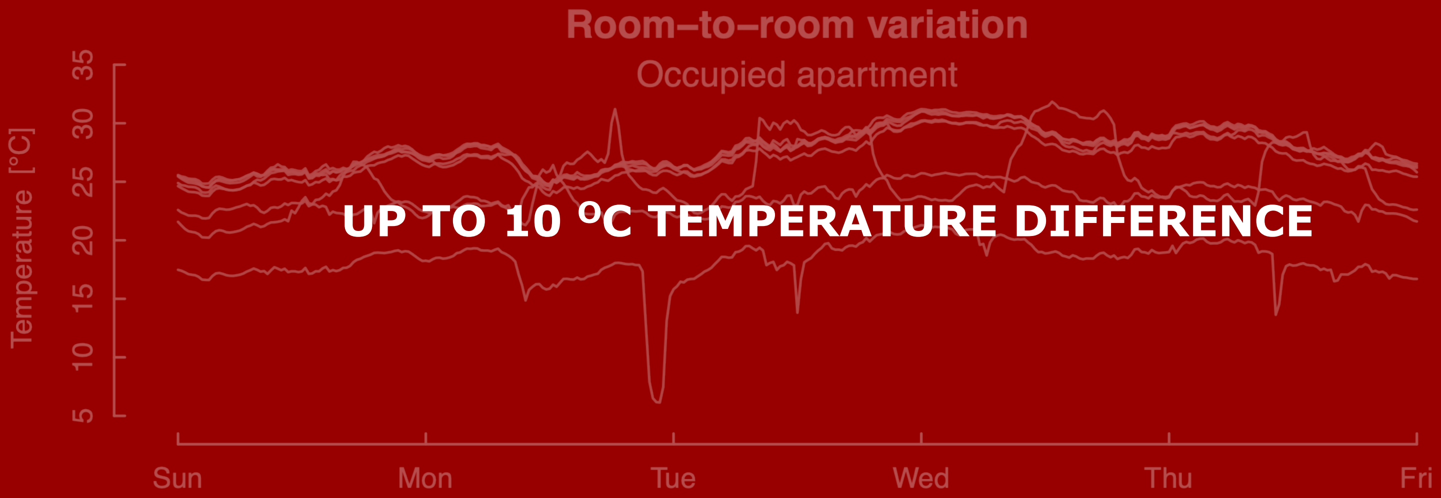


UP TO 5 ^{O}C TEMPERATURE DIFFERENCE





UP TO 5 ^{o}C TEMPERATURE DIFFERENCE



UP TO 10 ^{o}C TEMPERATURE DIFFERENCE

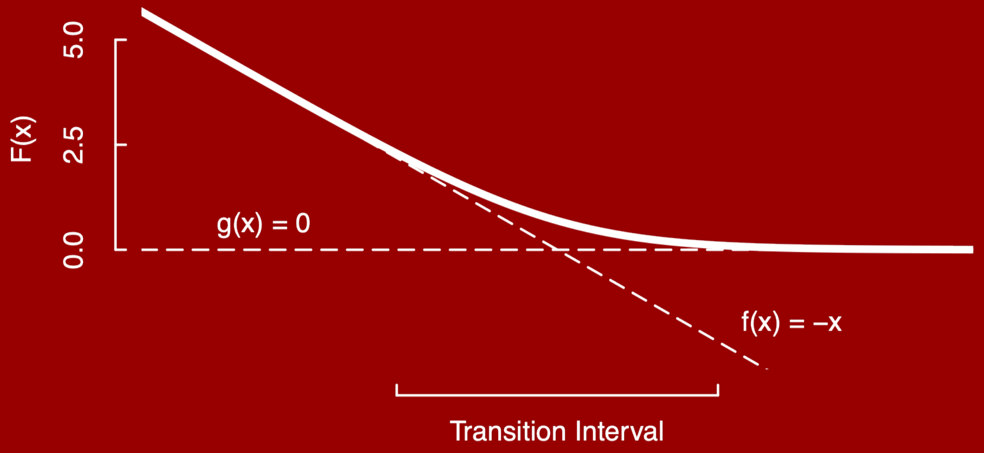
ENERGY SIGNATURE

$$\Phi_\mathrm{h} = \begin{cases} \mathrm{UA}(T_{\mathrm{b}_0} - T_\mathrm{a}) & \text{for} \quad T_\mathrm{a} < T_\mathrm{b} \\ \Phi_0 & \text{otherwise} \end{cases}$$

+

SMOOTH MAXIMUM FUNCTION

$$\mathrm{LSE}(f(x), g(x)) = \underbrace{\log\left[\exp(f(x)\,k) + \exp(g(x)\,k)\right] k^{-1}}_{\text{Smooth approximation of } \max[f(x),\, g(x)]}$$



THE MODEL

HEAT CONSUMPTION

WEATHER INDEPENDENT HEAT CONSUMPTION

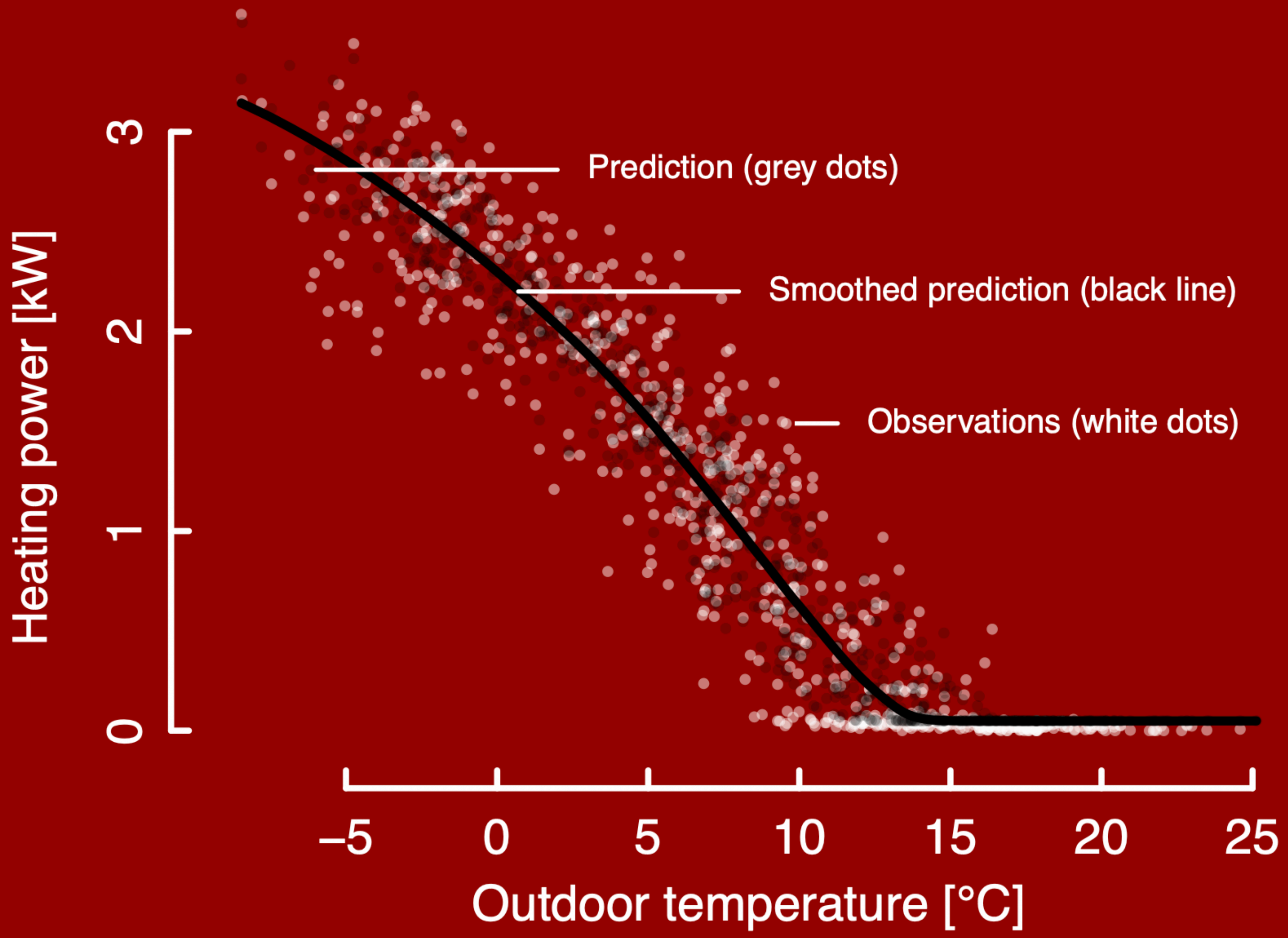
$$\Phi_{\mathrm{heat}} = \mathrm{LSE}\left[\left(\mathrm{UA}_0 + W_{\mathrm{s}}\,\mathrm{UA}_{\mathrm{W}}\right)\left(T_{\mathrm{b}_0} - T_{\mathrm{a}}\right) - \mathrm{gA}\,I_{\mathrm{g}},\;\; \Phi_0\right] + e$$

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

NOISE

SMOOTH MAXIMUM FUNCTION

THE MODEL



Prediction (grey dots)
Smoothed prediction (black line)
Observations (white dots)
Heating power [kW]
0
1
2
3
–5
0
5
10
15
20
25
Outdoor temperature [°C]

MAPPING OF THERMAL PROEPRTIES OF 16 DANISH DWELLINGS

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House	Year	Floor area [m^2]	U_0 [$W/(K\,m^2)$]	UA_0 [W/K]	UA_W [W/K per m/s]	gA [m^2]	Φ_0 [W]	T_b [°C]	$T_{transition}$ [°C]	$\overline{\Phi}_{x,t} \mid T_i = 20\,°C$ [W]	$\sigma_{\Phi_{x,t}}$ [W]
1	1970	151	1.25 (0.03) *	189 (4) *	5.8 (0.7) *	2.5 (0.3) *	676 (84) *	16.5 (0.5)	12.1 – 21.0	702	157
2	1969	163	1.25 (0.02) *	204 (4) *	3.9 (0.8) *	3.7 (0.3) *	340 (47) *	14.2 (0.4) *	9.5 – 18.9	1246	194
3	1963	140	1.28 (0.02) *	179 (2) *	3.2 (0.5) *	2.5 (0.1) *	141 (30) *	15.7 (0.2) *	11.9 – 19.5	810	103
4	1952	86	1.45 (0.03) *	125 (2) *	4.1 (0.5) *	1.5 (0.2) *	215 (19) *	12.8 (0.3) *	10.2 – 15.4	971	118
5	1966	111	1.54 (0.03) *	171 (3) *	6.1 (0.7) *	1.6 (0.2) *	110 (63)	16.6 (0.3)	9.6 – 23.6	643	155
6	1963	119	0.97 (0.02) *	115 (2) *	6.5 (0.6) *	2.8 (0.2) *	47 (19) *	13.3 (0.3) *	10.2 – 16.4	880	129
7	1947	119	2.17 (0.04) *	258 (5) *	7.2 (1.3) *	1.2 (0.4) *	6 (50)	13.5 (0.3) *	6.9 – 20.0	1810	243
8	1965	160	1.24 (0.04) *	199 (6) *	5.7 (1.4) *	2.2 (0.4) *	376 (45) *	12.6 (0.5) *	8.9 – 16.4	1569	258
9	1965	173	1.21 (0.02) *	210 (3) *	4.2 (0.6) *	1.2 (0.2) *	523 (62) *	18.2 (0.3) *	15.8 – 20.6	389	275
10	1996	135	0.90 (0.02) *	121 (2) *	5.1 (0.6) *	2.5 (0.2) *	106 (25) *	14.1 (0.4) *	10.2 – 18.0	786	193
11	1966	122	1.09 (0.04) *	133 (4) *	3.1 (1.1) *	1.2 (0.3) *	108 (46) *	14.7 (0.5) *	10.5 – 18.9	751	96
12	1975	136	1.05 (0.02) *	143 (2) *	3.1 (0.4) *	1.9 (0.1) *	644 (17) *	13.4 (0.3) *	11.3 – 15.4	1001	94
13	1937	86	2.67 (0.06) *	229 (5) *	9.2 (1.4) *	4.4 (0.4) *	45 (31)	11.2 (0.3) *	7.6 – 14.8	2227	431
14	1965	123	1.36 (0.02) *	167 (2) *	5.7 (0.6) *	2.4 (0.2) *	356 (22) *	14.1 (0.3) *	11.8 – 16.4	1068	203
15	1953	127	1.65 (0.03) *	209 (4) *	8.0 (1.0) *	3.1 (0.3) *	166 (35) *	13.0 (0.3) *	7.0 – 19.1	1593	210
16	1967	137	1.22 (0.02) *	167 (3) *	3.4 (0.7) *	1.3 (0.2) *	193 (26) *	13.5 (0.3) *	8.1 – 18.9	1137	143
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

energies

MDPI

Article

Method for Scalable and Automatised Thermal Building Performance Documentation and Screening

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Received: 29 May 2020; Accepted: 20 July 2020; Published: 28 July 2020

check for updates

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

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THANK YOU

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