Grey-box modelling; Bridging the gap between physical and statistical modelling

ZEN Workshop, Energy Flexibility in Zero-Emission Neighborhoods, Oslo, November 2017

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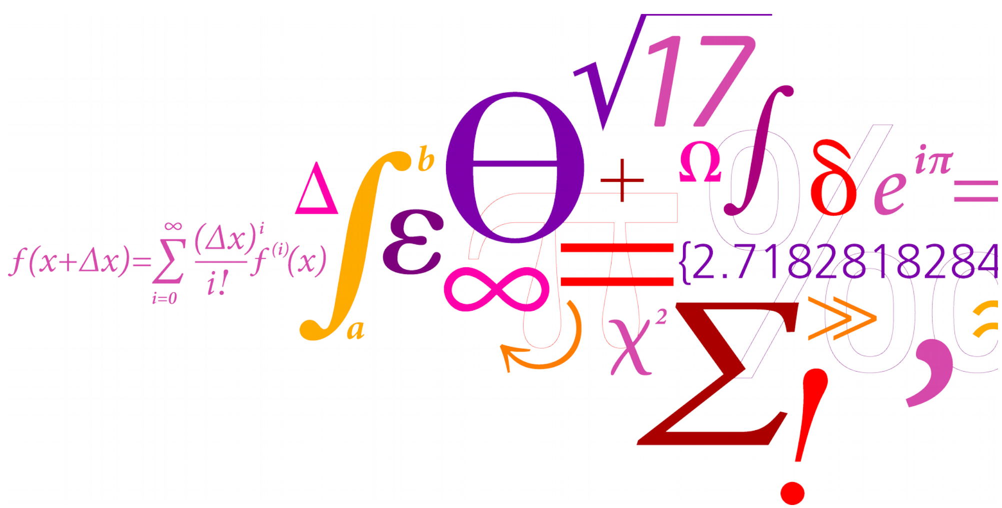

DTU Compute
Department of Applied Mathematics and Computer Science

Thermal performance characterization using time series data - statistical guidelines

IEA EBC Annex 58

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November 28, 2016

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Guidelines from Annex 58

Static and dynamic conditions: estimate the Heat Loss Coefficient (HLC) and gA-value from 'simple' data:

- Constant indoor temperature
- *Model input*: ambient temperature and global radiation (wind not included in guideline models)
- *Model output*: heat load

Grey-box models for detailed building behavior characterization:

- Varying indoor temperature (turn the heating on/off)
- *Model input*: ambient temperature, global radiation, wind
- *Model output*: indoor air temperature

Procedures (recipes) for model selection and validation, with examples in R

Introduction to Grey-Box modelling

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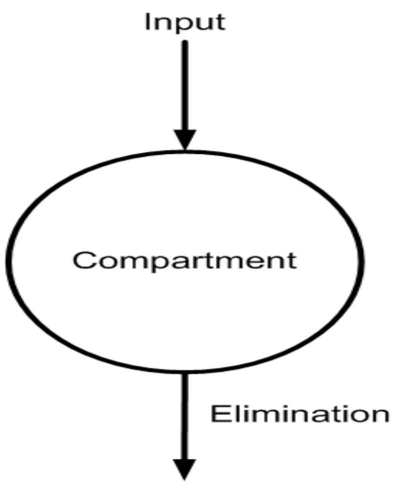
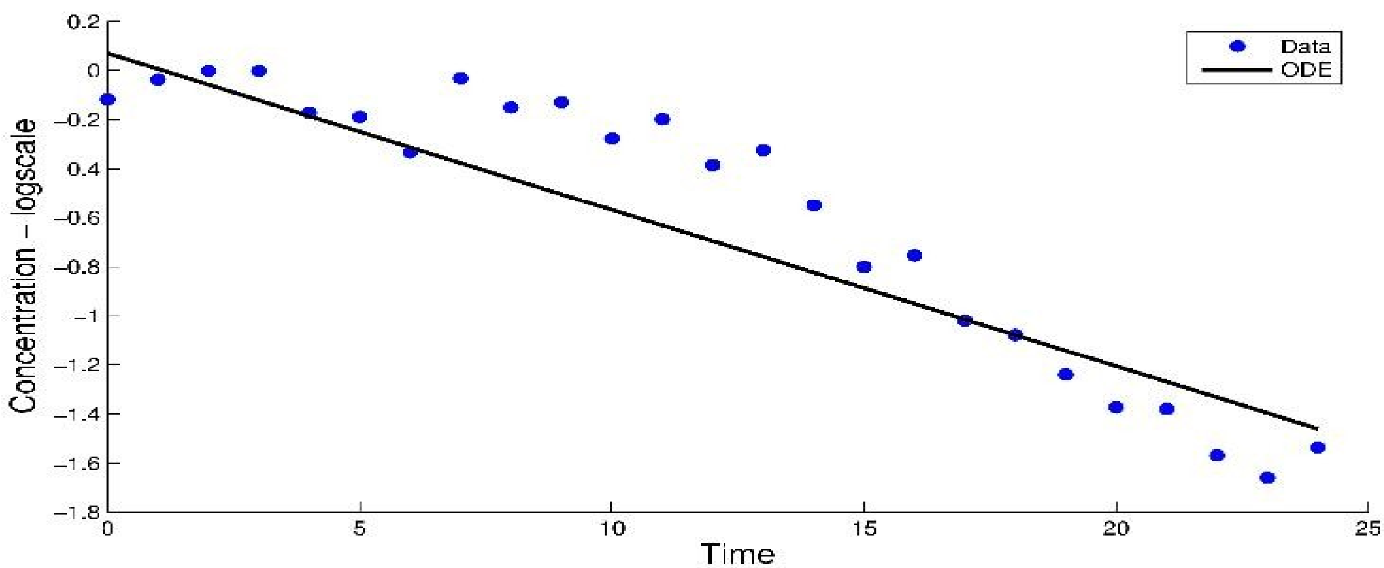
Traditional Dynamical Model

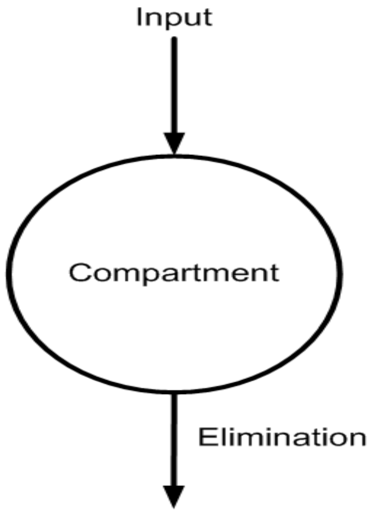


- Ordinary Differential Equation:

$$
\begin{aligned}
dA &= -KAdt \\
Y &= A + \epsilon
\end{aligned}
$$

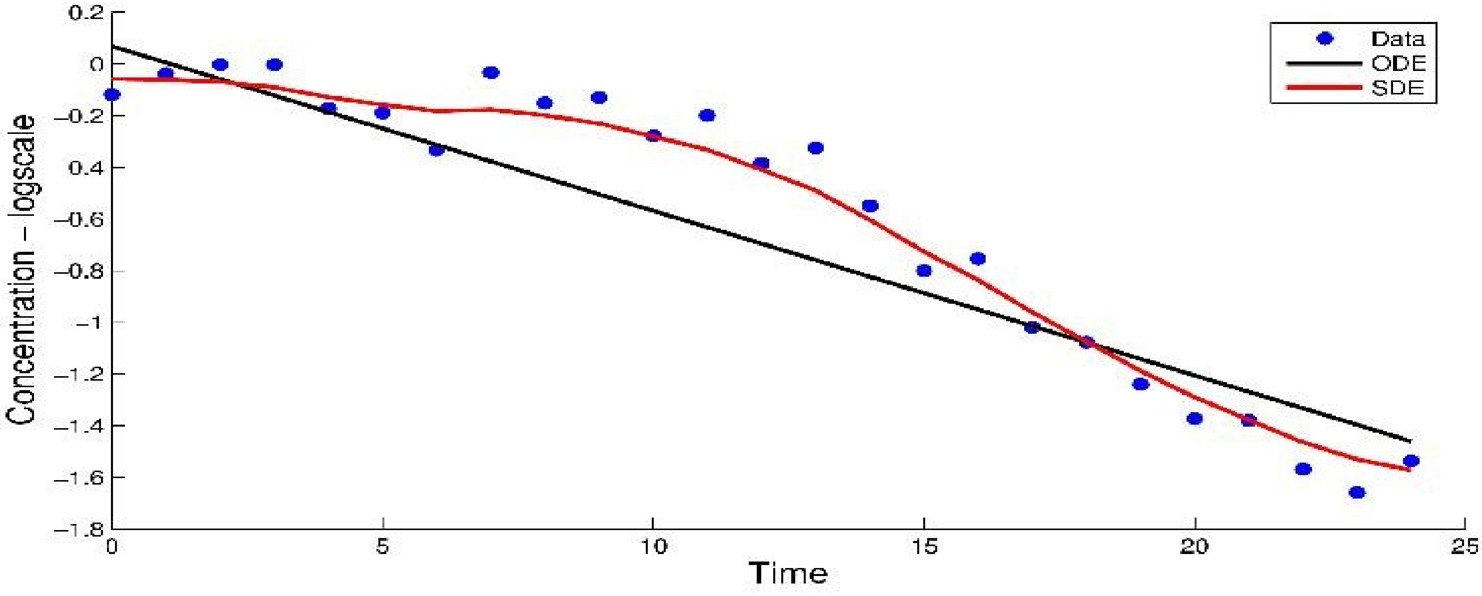


Stochastic Dynamical Model



- Stochastic Differential Equation:

$$
\begin{aligned}
dA &= -KAdt + \sigma dw \\
Y &= A + e
\end{aligned}
$$



The grey box model

Drift term

Diffusion term

$$dX_t = f(X_t, u_t, t, \theta)dt + \sigma(X_t, u_t, t, \theta)d\omega_t$$ System equation

$$Y_k = h(X_k, u_k, t_k, \theta) + e_k,$$ Observation equation

Observation noise

Notation:

$\boldsymbol{X}_t$: State variables

$\boldsymbol{u}_t$: Input variables

$\boldsymbol{\theta}$: Parameters

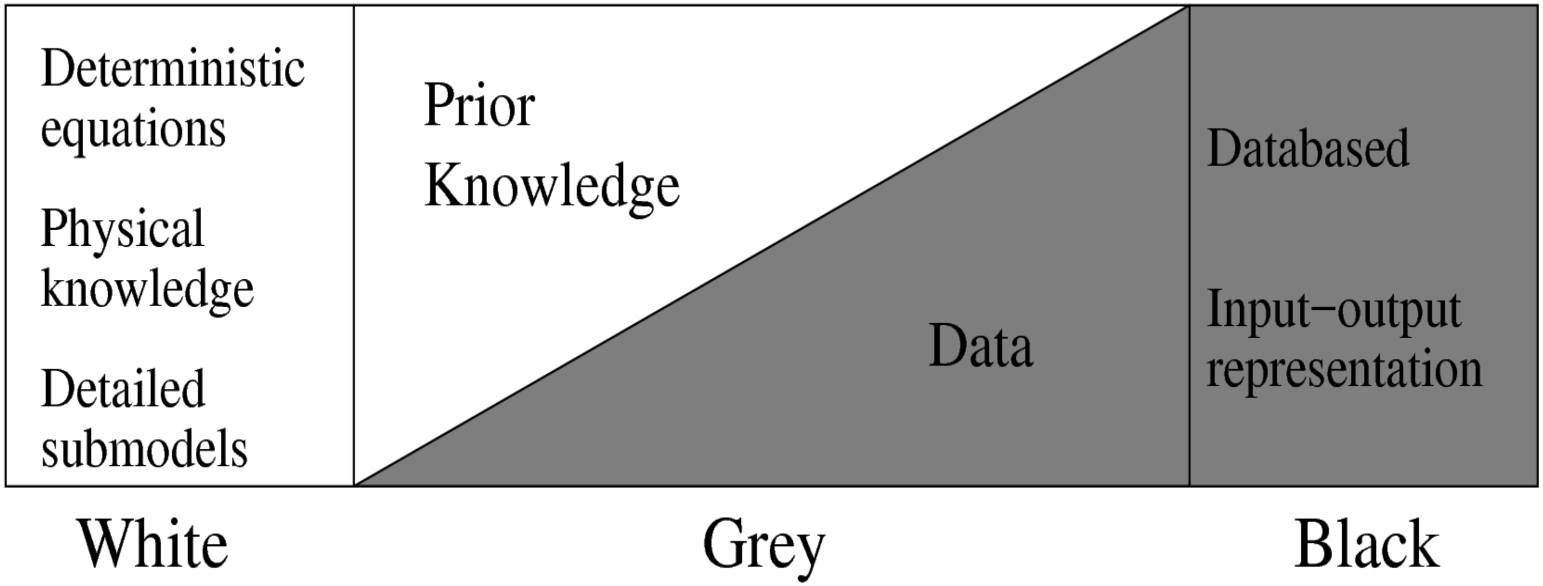
$\boldsymbol{Y}_k$: Output variables

t: Time

$\boldsymbol{\omega}_t$: Standard Wiener process

$\boldsymbol{e}_k$: White noise process with $N(\boldsymbol{0}, \boldsymbol{S})$

Grey-box modelling concept



- Combines prior physical knowledge with information in data
- Equations and parameters are physically interpretable

Grey-Box Modelling

- Bridges the gap between physical and statistical modelling
- Provides methods for model identification
- Provides methods for model validation
- Provides methods for pinpointing model deficiencies
- Enables methods for a reliable description of the uncertainties, which implies that the same model can be used for **k-step forecasting**, **simulation** and **control**

Case study

Model for the thermal characteristics of a small office building

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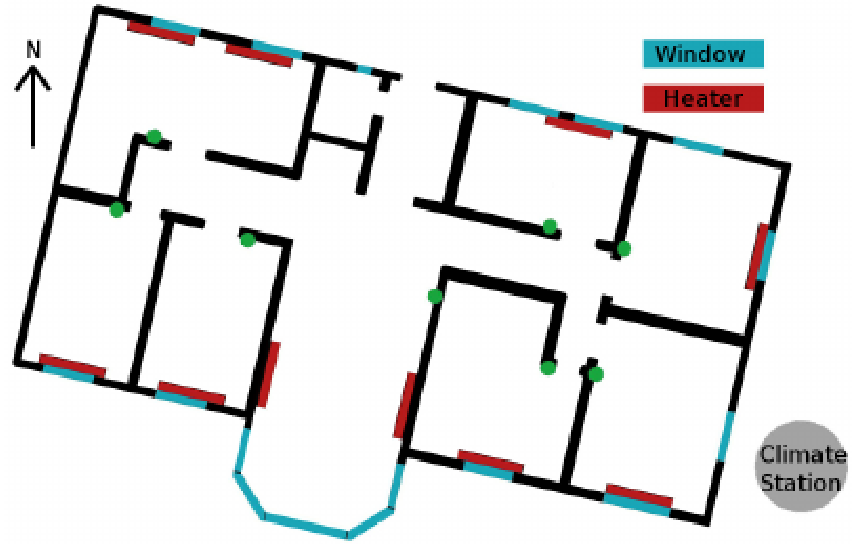
Test case: One floored 120 m^2 building

Objective

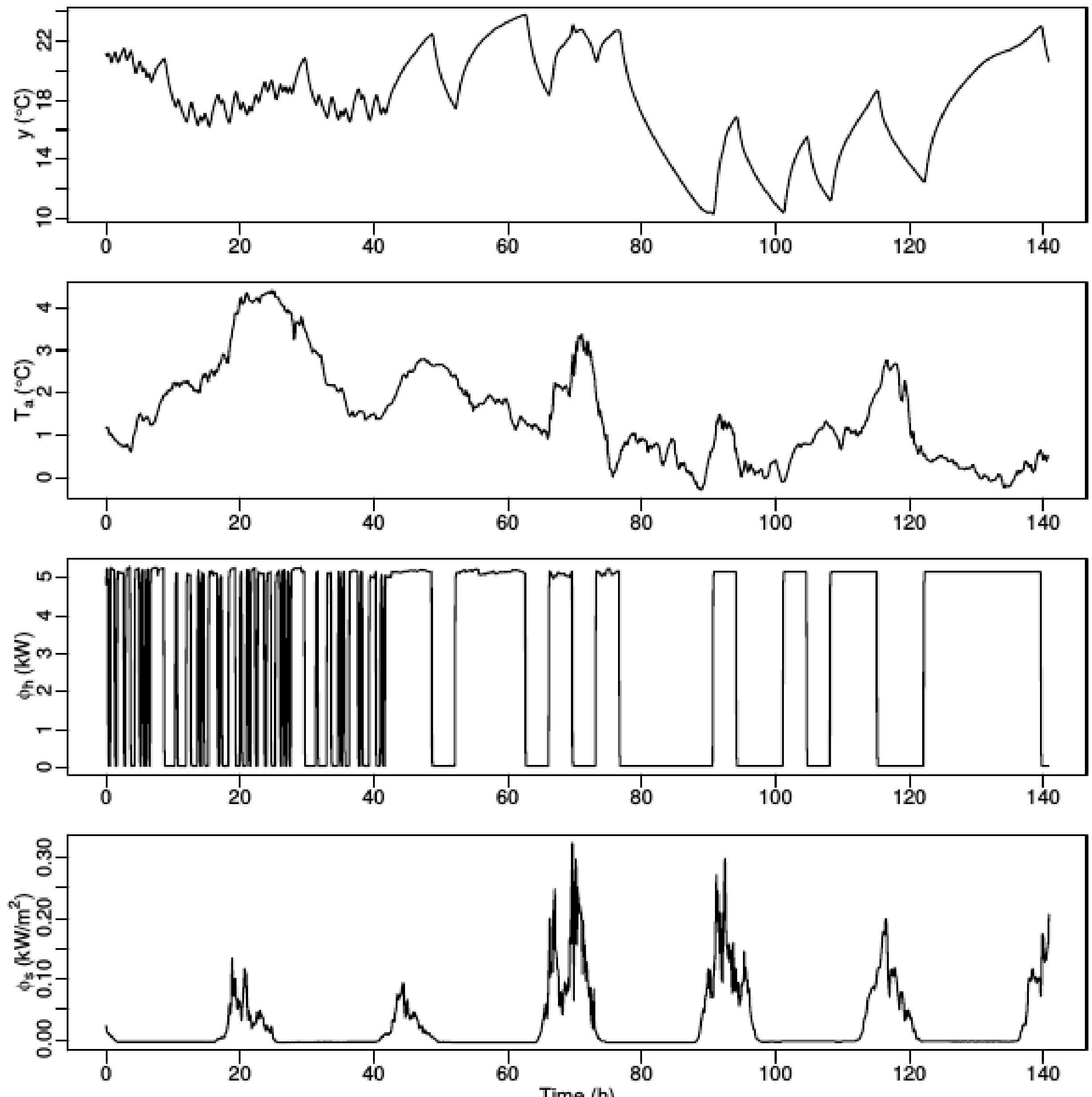
Find the best model describing the heat dynamics of this building ([1], [4])



Data

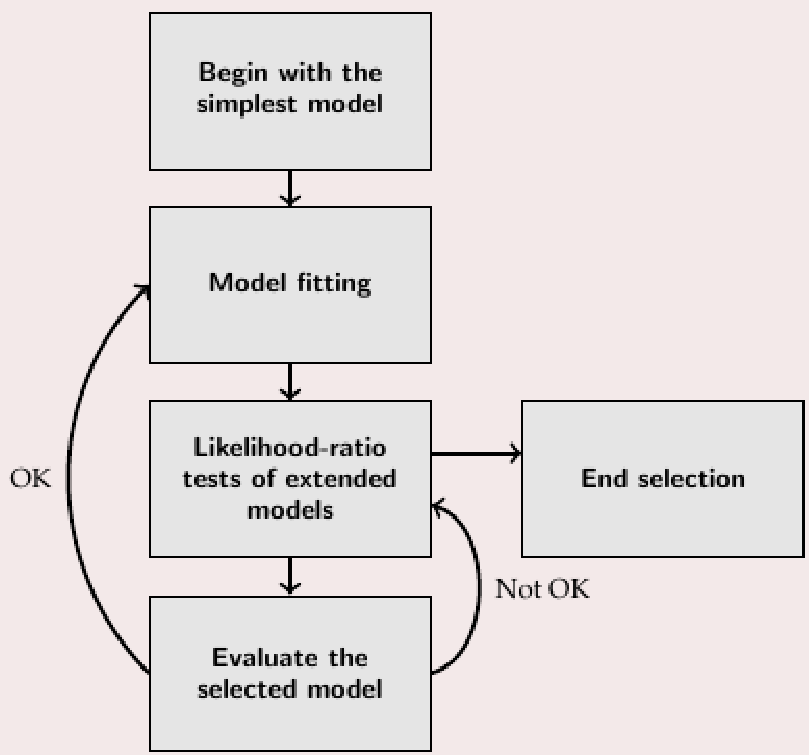
Measurements of:

- y_t Indoor air temperature
- T_a Ambient temperature
- Φ_h Heat input
- Φ_s Global irradiance

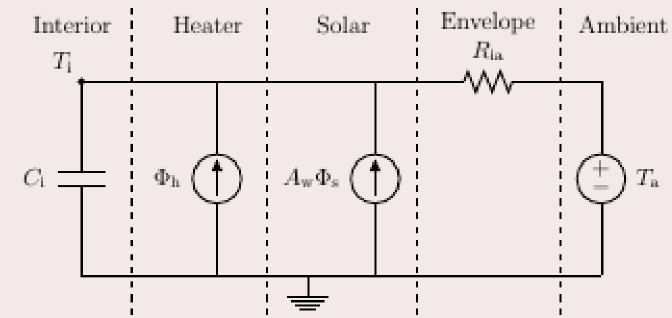


SELECTION PROCEDURE

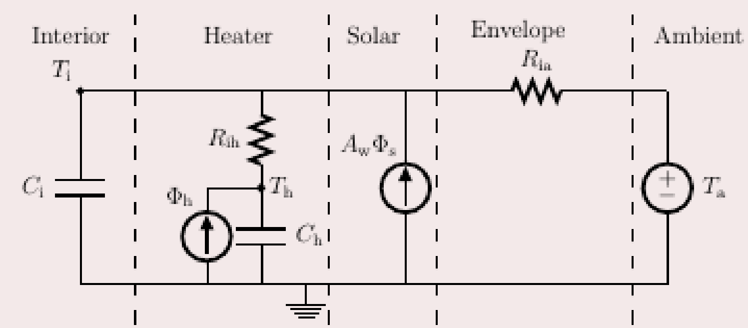
Iterative procedure using statistical tests



Simplest model

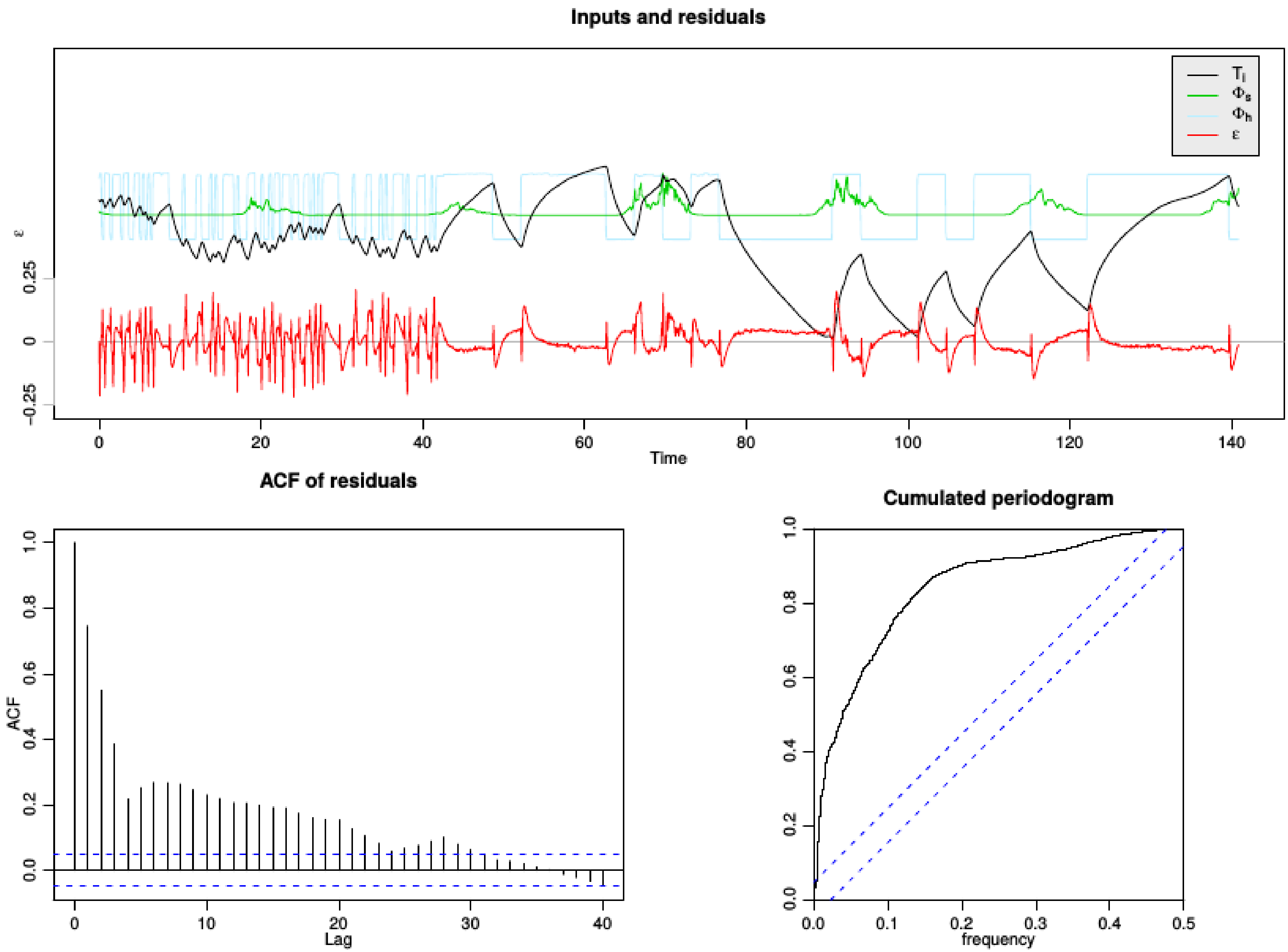


First extension: heater part

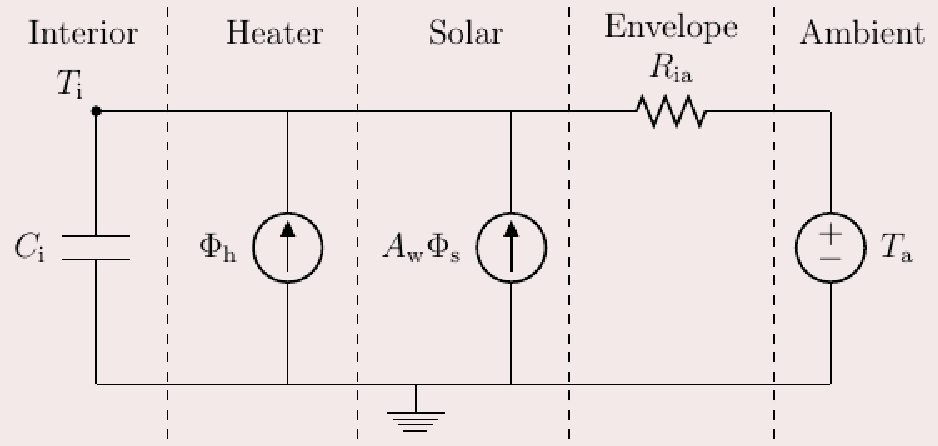


Start	$Model_{Ti}$			
$l(\theta; \mathcal{Y}_N)$	2482.6			
m	6			
1	$Model_{TiTe}$	$Model_{TiTm}$	$Model_{TiTs}$	$Model_{TiTh}$
$l(\theta; \mathcal{Y}_N)$	3628.0	3639.4	3884.4	3911.1
m	10	10	10	10
2 ...				

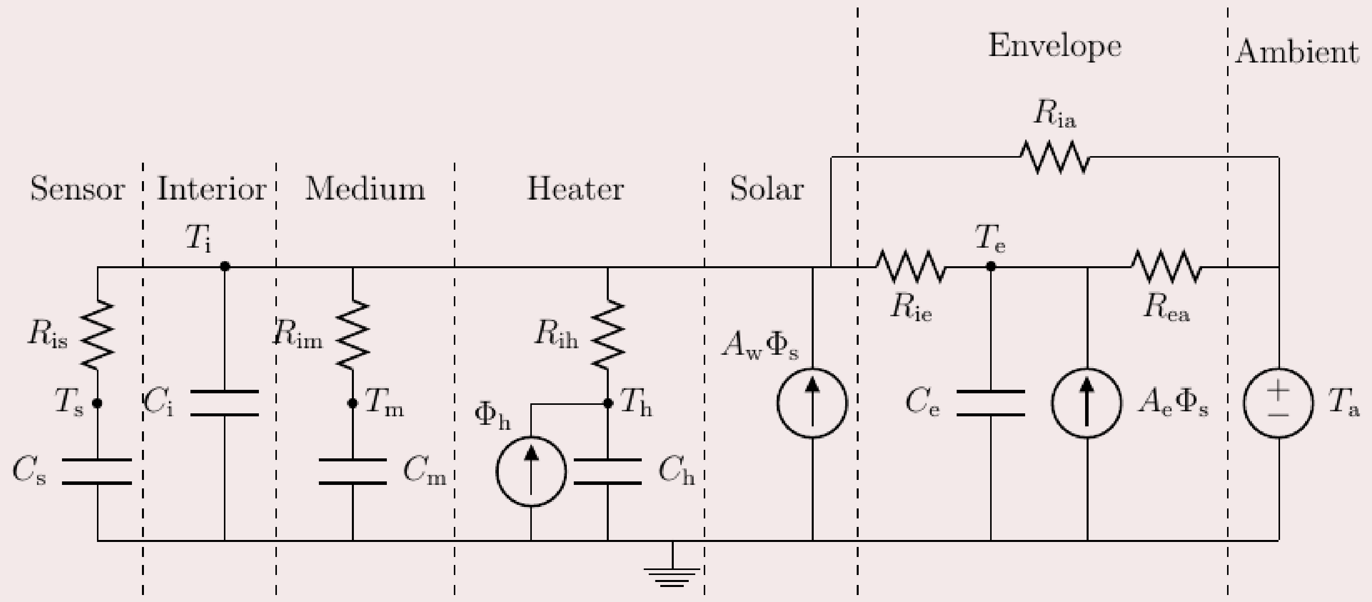
EVALUATE THE SIMPLEST MODEL



Simplest model



Most complex model applied



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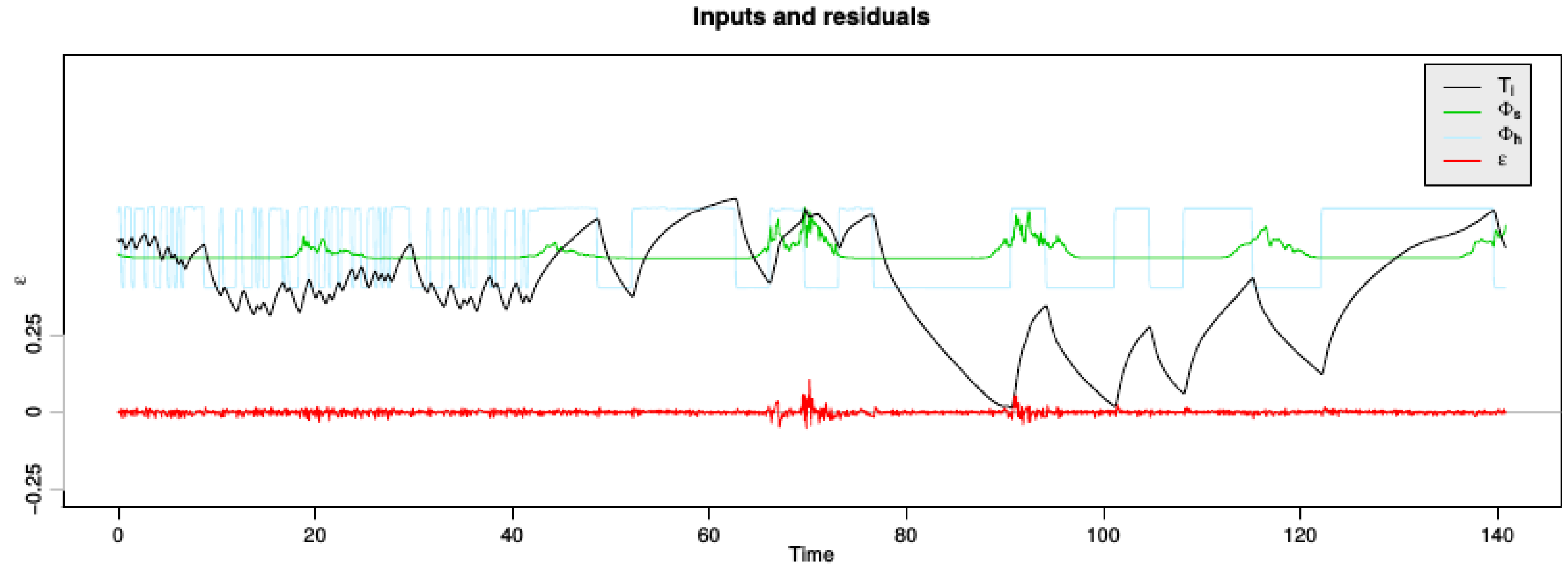
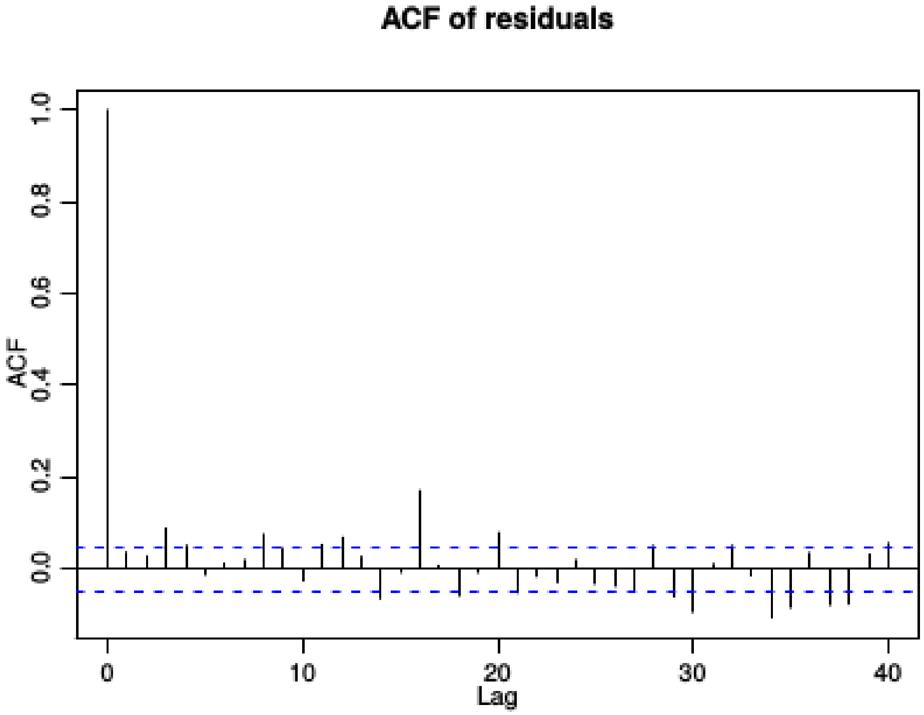
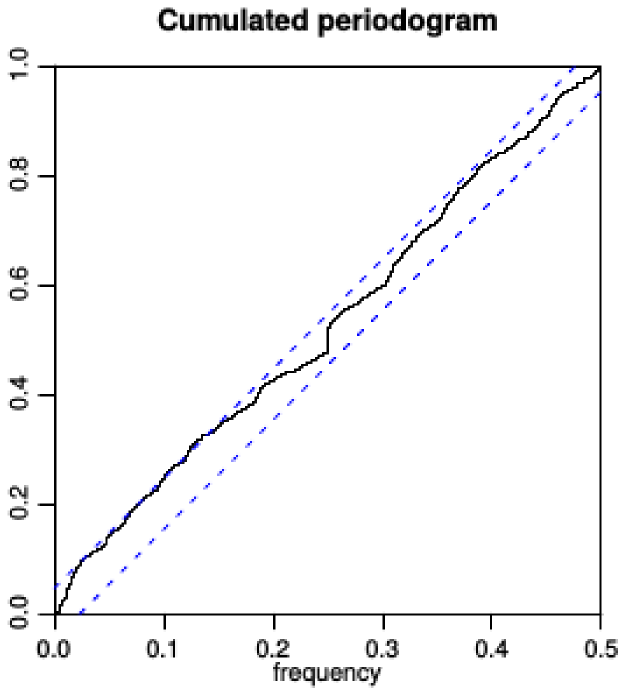

Inputs and residuals
T_i
Φ_s
Φ_h
ε
ε
Time
0
20
40
60
80
100
120
140
0.25
0
−0.25


ACF of residuals
ACF
Lag
0
10
20
30
40
0.0
0.2
0.4
0.6
0.8
1.0


Cumulated periodogram
frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.2
0.4
0.6
0.8
1.0

Grey-box modelling

Continuous time models *(grey-box: stochastic state-space model)*

$$\text{States} = \text{Fun}_1(\text{States}, \text{Inputs}) + \text{Fun}_2(\text{Inputs}) \cdot \text{SystemError}$$
$$\text{Measurements} = \text{Fun}_3(\text{States}, \text{Inputs}) + \text{Fun}_4(\text{Inputs}) \cdot \text{MeasurementError}$$

- Used for buildings (single- and multi-zone), walls, systems (hot water tank, integrated PV, heat pumpts, heat exchanger, solar collectors, ...)
- Formulate the model based on physical knowledge
- Maximum likelihood estimation
  (we have the entire statistical framework available)
- Description of the system noise is part of the model provides some very useful possibilities
  (e.g. control the weight of data in the estimation depending on input signals)
- Software, for example our R package `CTSM-R` [1]

[1] `http://ctsm.info`

Thanks ...

- For more information

  www.ctsm.info

  www.henrikmadsen.org

  www.smart-cities-centre.org

- ...or contact
  - Henrik Madsen (DTU Compute)

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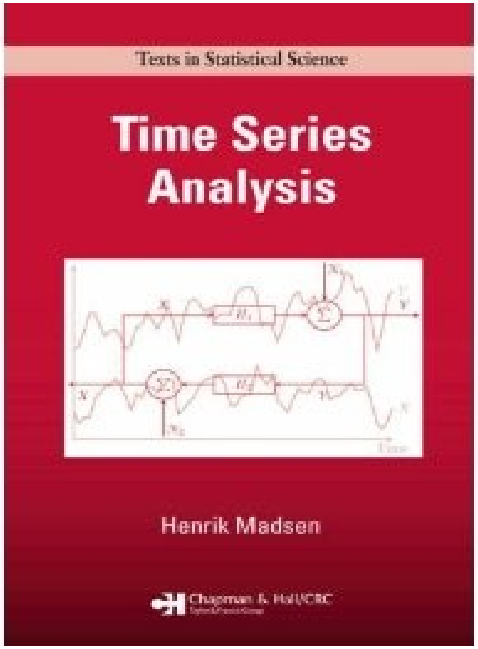
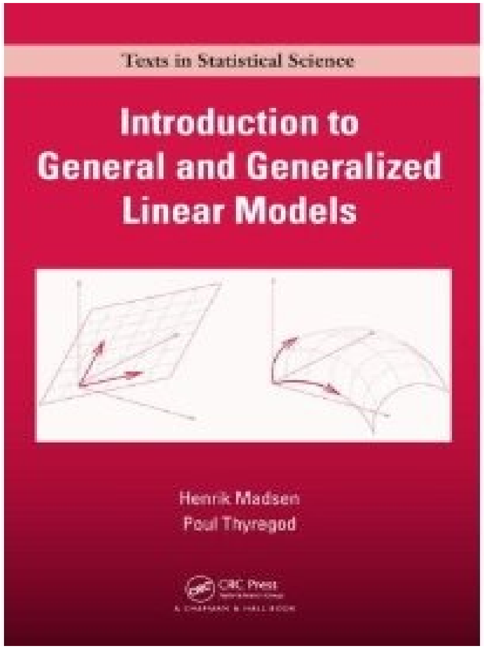
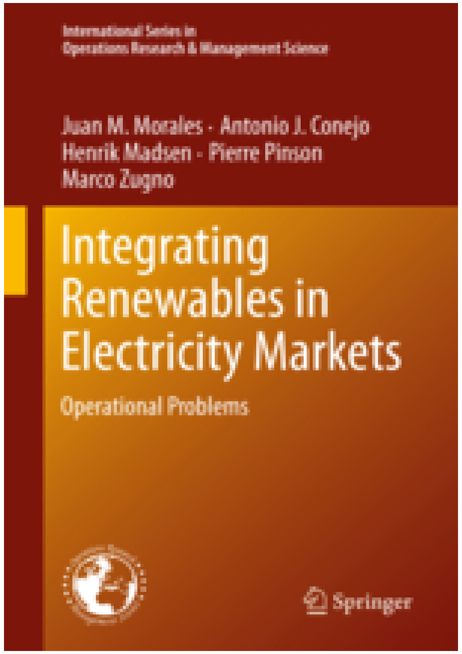
- Acknowledgement CITIES (DSF 1305-00027B)

Some 'randomly picked' books on modeling ....







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