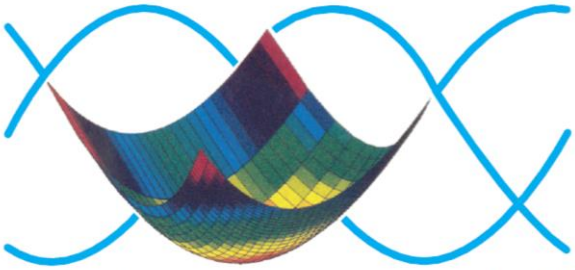
DYNASTEE



Experimental set-up and measurement of the Round Robin Test Box at Plataforma Solar de Almeria
Overview of available data and analysis topics

María José JIMÉNEZ

1

CONTENTS

- **Introduction**
  - The role of simplified case studies to develop skills and methodologies
- **Round Robin Test Box**
  - Building
  - Experiment set up
  - Data
- **Data analysis topics**
  - Qualitative data analysis and pre-processing
  - Constructing models from measured data and building physics

2

Case study: Round robin test box

- A **simplified building** has been considered as a case study.
  - Round robin test box Annex 58
- Its **detailed and accurate knowledge** reinforces and complements the validation criteria.
- The robustness of the method has been analysed by comparing the results from a **long testing period** including different test and weather conditions.
  - **Benchmark data and set-up**

INTRODUCTION (CONTEXT)

- **Dynamic models allows getting characteristic (steady state and others) parameters from dynamic tests**
  - Key feature for energy performance assessment of “as built” buildings, under dynamic outdoors weather and in occupancy conditions.
- **Key distinctive aspects of these “real life” tests conditions:**
  - Time varying measurements, calls for the application of system identification techniques and time series analysis tools.
  - Many other physical phenomena in these tests which are not present in other tests such as well controlled tests in laboratories and steady state.
- **Role of simplifications to get accurate results and design cost effective tests**

INTRODUCTION (CONTEXT)

- **Dynamic test conditions versus time dependent parameters**
  - Parameters can be constant (intrinsic) or time varying
- **Dynamic analysis must be robust:**
  - Giving stable estimates for constant parameters
  - Allowing identifying dependencies for non constant indicators

Usefulness of well known simple systems

- Simplicity in the test component doesn't mean simple analysis
  - Dynamic features are still present
  - Complex physical phenomena occur
- Simplicity in the component allows us to put the focus on
  - The different analysis approaches highlighting the main steps
  - Dynamic features and other observable complex physical phenomena that occur
- Previous knowledge about thermal characteristics give additional validation criteria
  - External validity
- Well known characteristics facilitate to identify wrong results and check analysis skills

Usefulness of well known simple systems

- Facilitate detection of models that in principle could be considered good candidates but can give wrong results, even for a so simple case study
- Skills in validation strategies and techniques, play an important role in the process of detecting and rejecting wrong results
- Simplicity is very useful to develop awareness regarding the relevance of validation. It helps also to acquire skills in identifying and avoid mistakes that lead to wrong results

Usefulness of a wide variety of data series

- Useful support to validation
- Optimum and not optimum data series are useful to explore the accuracy of the applied approaches for different not optimum test conditions

CONTENTS

- Introduction
  - The role of simplified case studies to develop skills and methodologies
- **Round Robin Test Box**
  - Building
  - Experiment set up
  - Data
- Data analysis topics
  - Qualitative data analysis and pre-processing
  - Constructing models from measured data and building physics

Case study

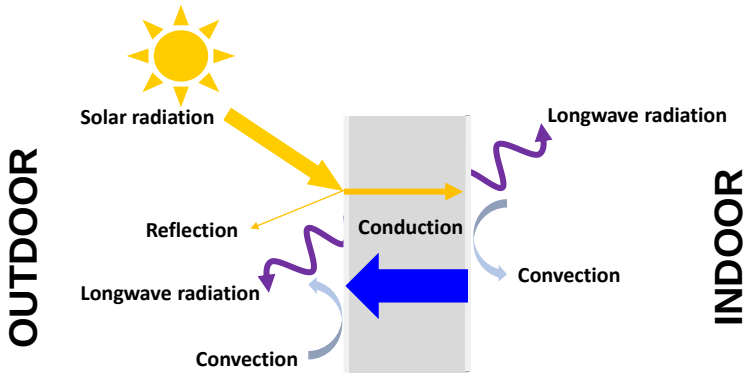
Round robin test experiment. IEA EBC annex 58

- Comparative experiment on testing and data analysis
- Scale model of a simplified building
- Tested by different partners: Different weather and measurement devices

Case study

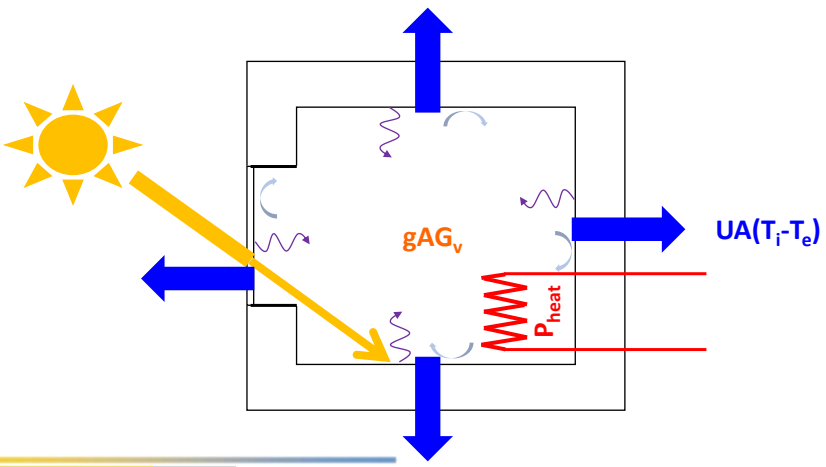
Practising possibilities using these data

1. Energy balance in a Surface



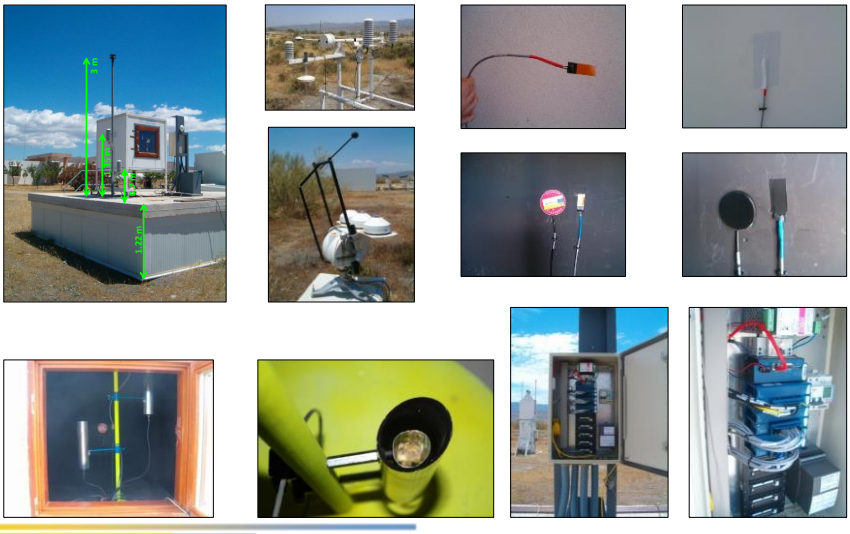
Practising possibilities using these data

2. Energy balance in a Volume



Location

Measurement devices



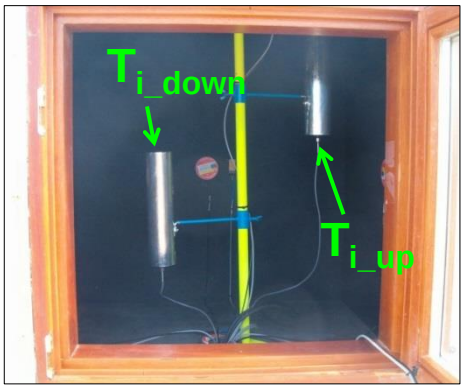
Measurement devices

15

15

Measurement devices

Air temperature: Sensor must measure the air temperature. How?



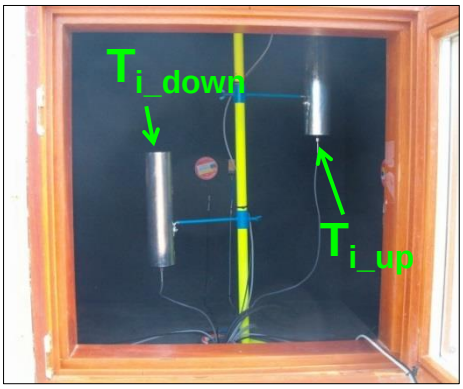
Indoor air temperature:
Sensor protected from solar radiation by aluminium cylinders that allow ventilation

16

16

Measurement devices

Air temperature: Sensor must measure the air temperature. How?



Indoor air temperature:
Sensor protected from solar radiation by aluminium cylinders that allow ventilation

Outdoor air temperature:
Shielded and ventilated devices
Natural ventilation driven by solar radiation
Solar radiation increases ventilation effect

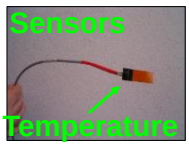
17

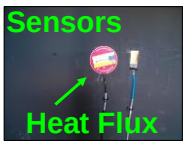
17

Measurement devices

Surface temperature: Sensor must measure the surface temperature
Heat flux through a surface: Sensor must measure the heat flux through the surface

How ?





Requisites:
The sensor must behave identically to the measured surface
- The sensors must be well integrated in the surfaces
- Contact between sensor and surface must be guaranteed
- Sensor surface must have the same optical properties as the measured surface

Implementation:
Glowing sensor to surfaces.
Painting the sensor with the same colour of the measured surfaces
Or protecting the sensor with adhesive tape with the same colour of the surface

18

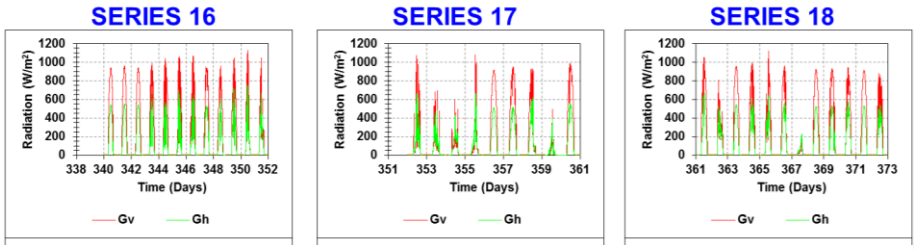
18

Requisites to tests campaigns for analysis

- The experiment design must guarantee that the phenomena to be characterised are happening and strong enough for their analysis. Phenomena are strong enough, when the amplitude of the corresponding driving variable is significantly higher than the uncertainty in its measurement. Otherwise signal to noise is poor.
- **Identification of heat transfer coefficient to the outdoors**, requires strong enough heat loss through the building envelope. Achieved maximising the indoor to outdoor air temperature difference, which is the driving variable in this case.
- **To identify the overall gA-value**, requires strong enough solar gains. Achieved when the experiment contains sunny days, when solar radiation is high, which is the driving variable in this case.
- **To identify the effective heat capacity** the system must be excited by dynamic input signals in a wide range of frequencies covering the characteristic time constants of the system.
- A good representation or indoor air temperature is necessary which requires homogeneity.

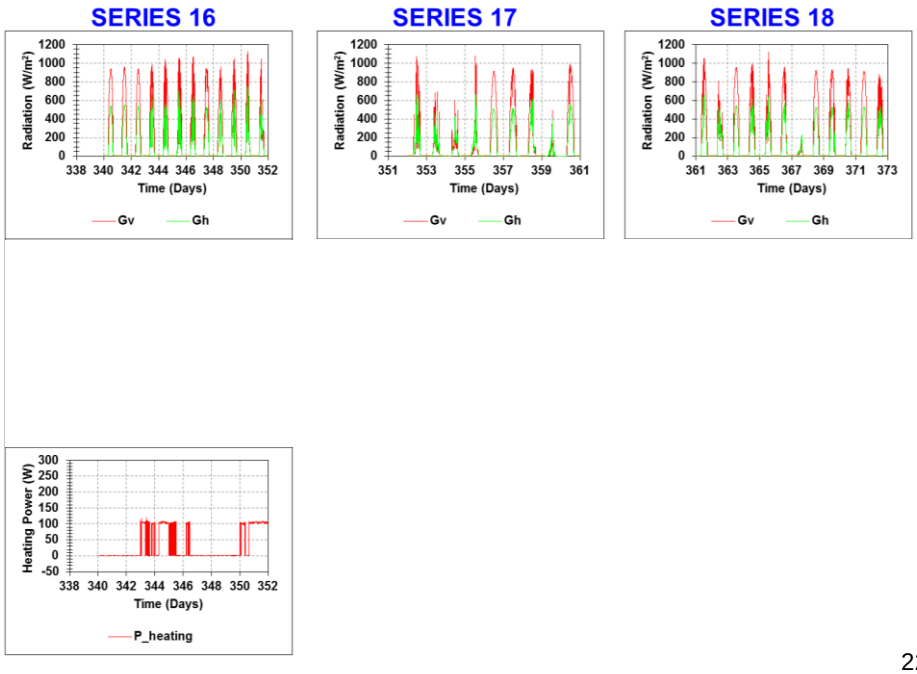
Data series

- **Series 16:** Since 06/12/2013, 12 days. With a ROLBS power sequence. Designed to optimise the test for the system identifications techniques.
- **Series 17:** Since 18/12/2013 9 days. Coheating test, but setting the indoor air temperature set point to 35°C. Designed to have a reference analysis, also to explore the application of steady-estate approaches and to analyse the capability to apply the system identification techniques to this type of tests. Also useful to analyse causality issues and different variables as input signal
- **Series 18:** Since 27/12/2013, 12 days: Aiming to reproduce as possible a Coheating test, but setting the indoor air temperature set point to 21°C. More realistic conditions (close to comfort) to explore the possibilities to apply the identification techniques to in-use buildings and on board monitoring systems. Also interesting to analyse causality issues and different variables as output signal. Increased difficulty: Low ΔT and correlation of T_i to solar radiation.
- **Other data available:** 9-month test campaign with other test and boundary conditions. Other seasons, infiltrations, different orientations or including PCM.


SERIES 16
Radiation (W/m²)
1200
1000
800
600
400
200
0
338 340 342 344 346 348 350 352
Time (Days)
Gv
Gh
SERIES 17
Radiation (W/m²)
1200
1000
800
600
400
200
0
351 353 355 357 359 361
Time (Days)
Gv
Gh
SERIES 18
Radiation (W/m²)
1200
1000
800
600
400
200
0
361 363 365 367 369 371 373
Time (Days)
Gv
Gh

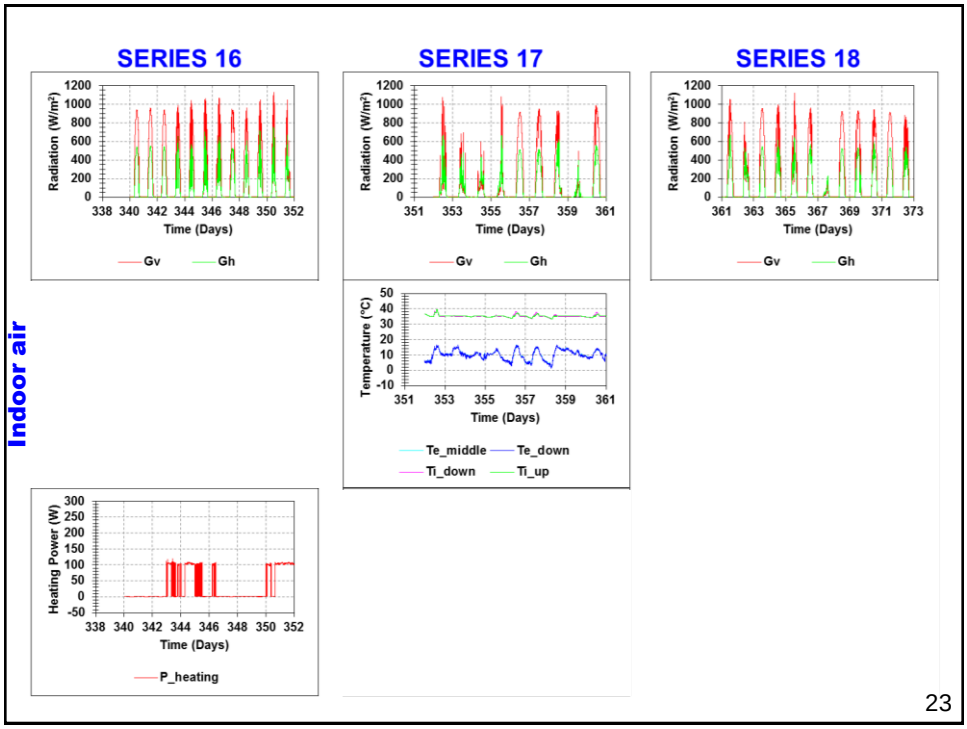
21

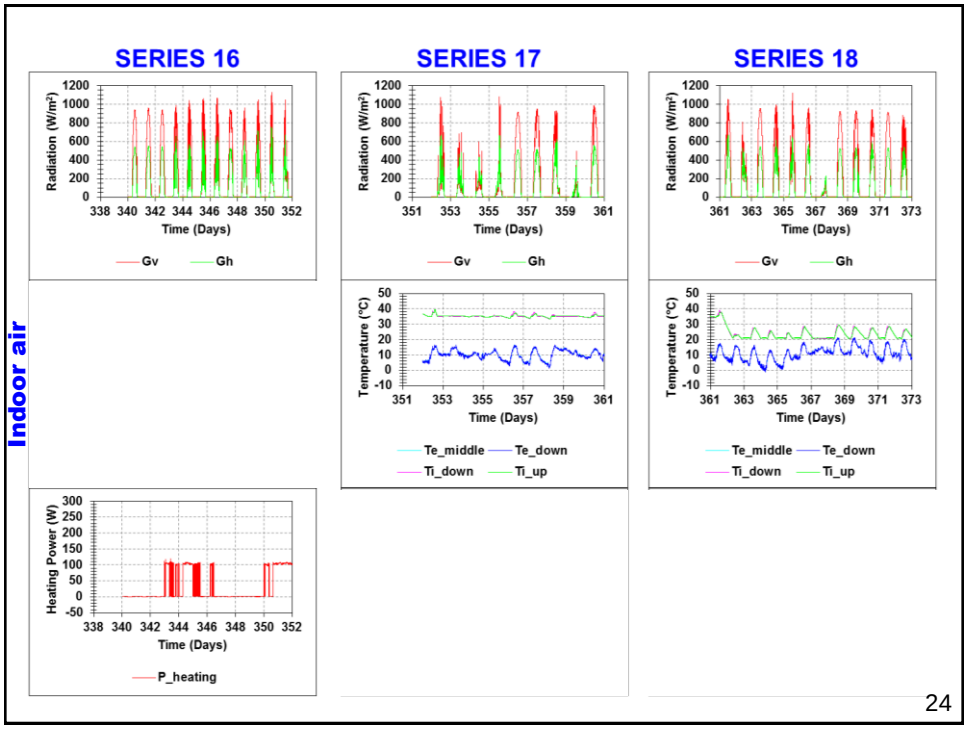
21

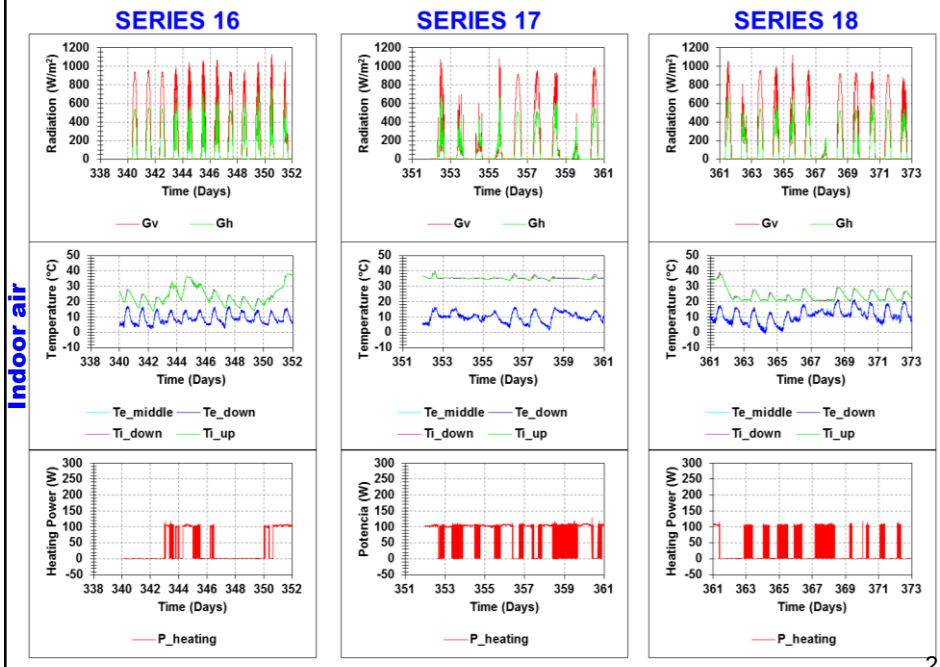

SERIES 16
Radiation (W/m²)
1200
1000
800
600
400
200
0
338 340 342 344 346 348 350 352
Time (Days)
Gv
Gh
SERIES 17
Radiation (W/m²)
1200
1000
800
600
400
200
0
351 353 355 357 359 361
Time (Days)
Gv
Gh
SERIES 18
Radiation (W/m²)
1200
1000
800
600
400
200
0
361 363 365 367 369 371 373
Time (Days)
Gv
Gh
Heating Power (W)
300
250
200
150
100
50
0
-50
338 340 342 344 346 348 350 352
Time (Days)
P_heating

22

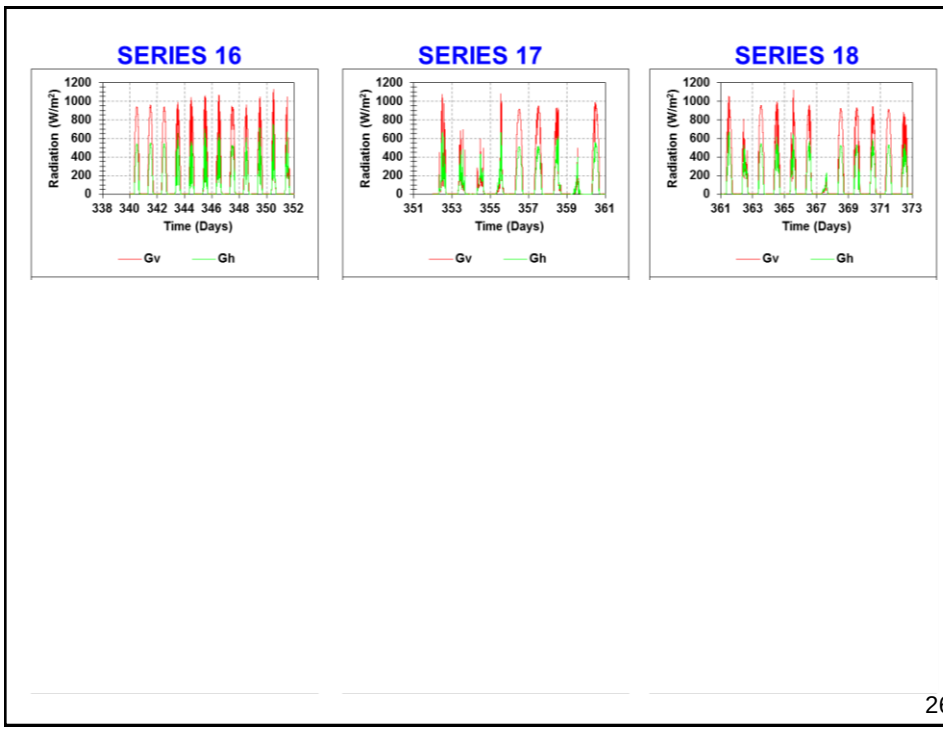
22


SERIES 16
SERIES 17
SERIES 18
Indoor air
Radiation (W/m²)
Time (Days)
Gv
Gh
Temperature (°C)
Te_middle
Te_down
Ti_down
Ti_up
Heating Power (W)
P_heating
23

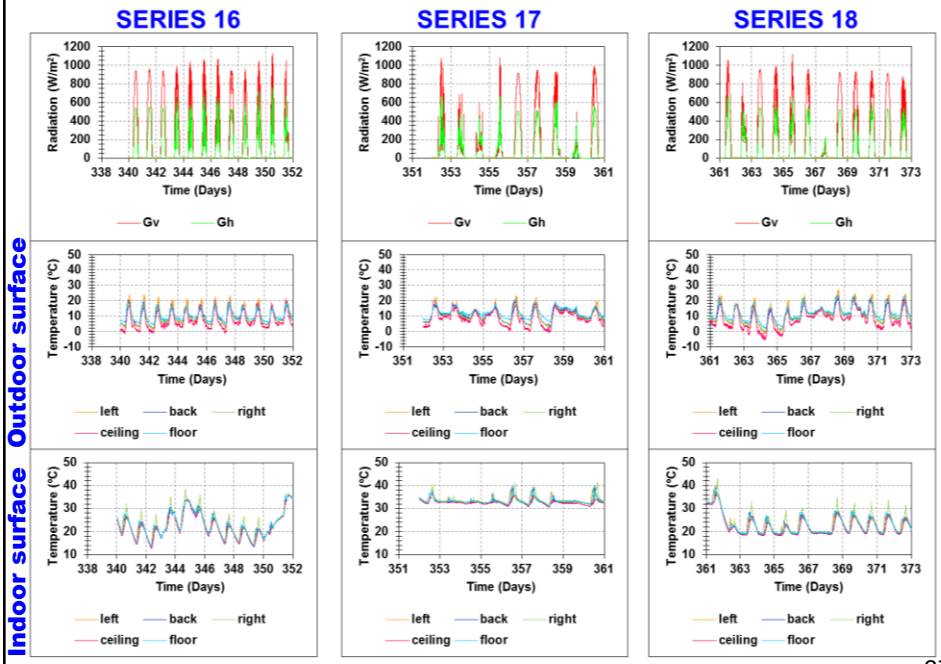

SERIES 16
SERIES 17
SERIES 18
Indoor air
Radiation (W/m²)
Time (Days)
Gv
Gh
Temperature (°C)
Te_middle
Te_down
Ti_down
Ti_up
Heating Power (W)
P_heating
24


SERIES 16
SERIES 17
SERIES 18
Indoor air
Radiation (W/m²)
Temperature (°C)
Heating Power (W)
Potencia (W)
Time (Days)
Gv
Gh
Te_middle
Te_down
Ti_down
Ti_up
P_heating

25


SERIES 16
SERIES 17
SERIES 18
Radiation (W/m²)
Time (Days)
Gv
Gh

26



27

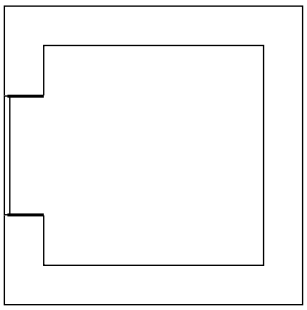
CONTENTS

- **Introduction**
  - The role of simplified case studies to develop skills and methodologies
- **Round Robin Test Box**
  - Building
  - Experiment set up
  - Data
- **Data analysis topics**
  - Qualitative data analysis and pre-processing
  - Constructing models from measured data and building physics

28

Candidate models including and not including solar gains through opaque walls.

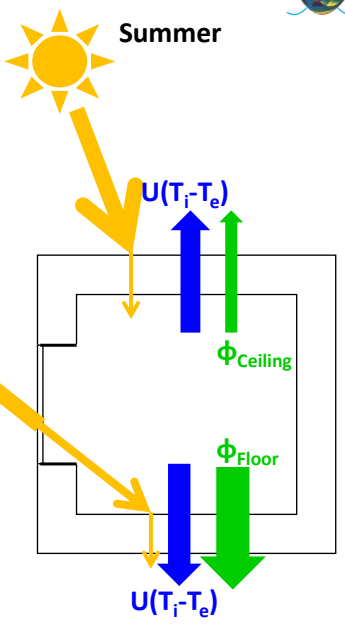
Do they make sense?



Yes taking into account next slides……

29

29

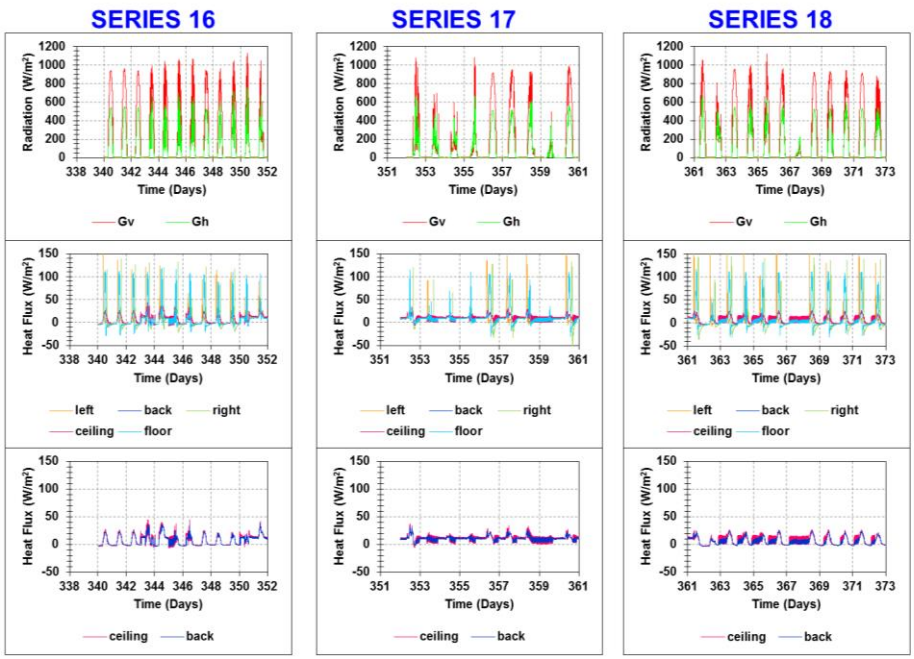


External surface Temperature:
Winter Belgium: Minor differences
Summer Spain: Mayor differences

Internal surface Heat Fluxes:
Winter Belgium: MAYOR differences
Summer Spain: MINOR differences

30

30



31

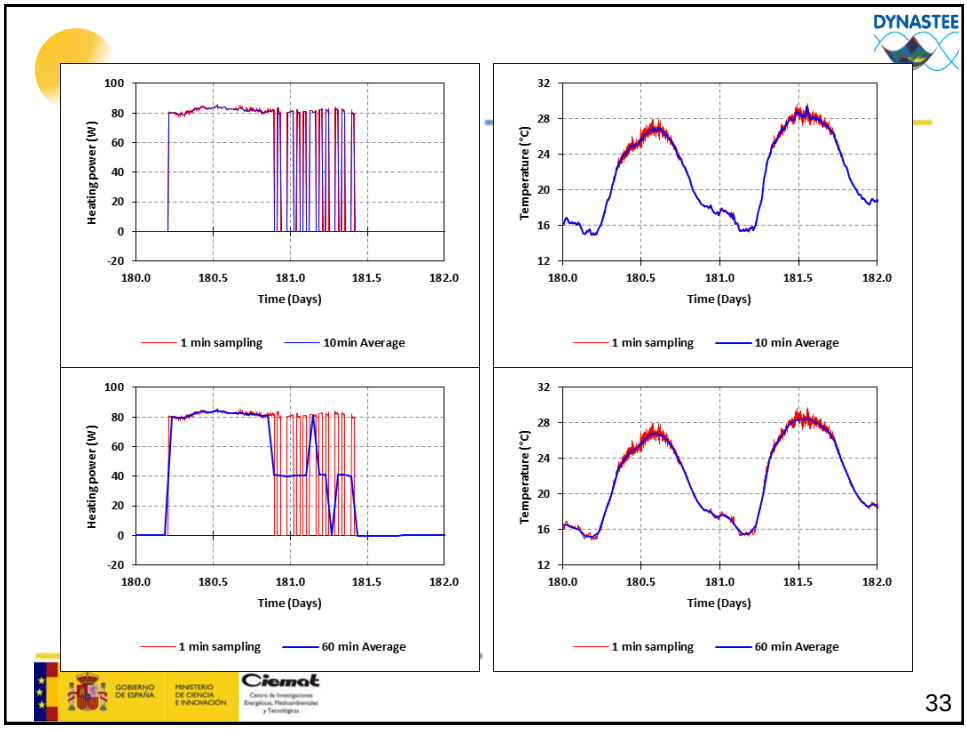
31

Pre-processing, Averaging, Filtering

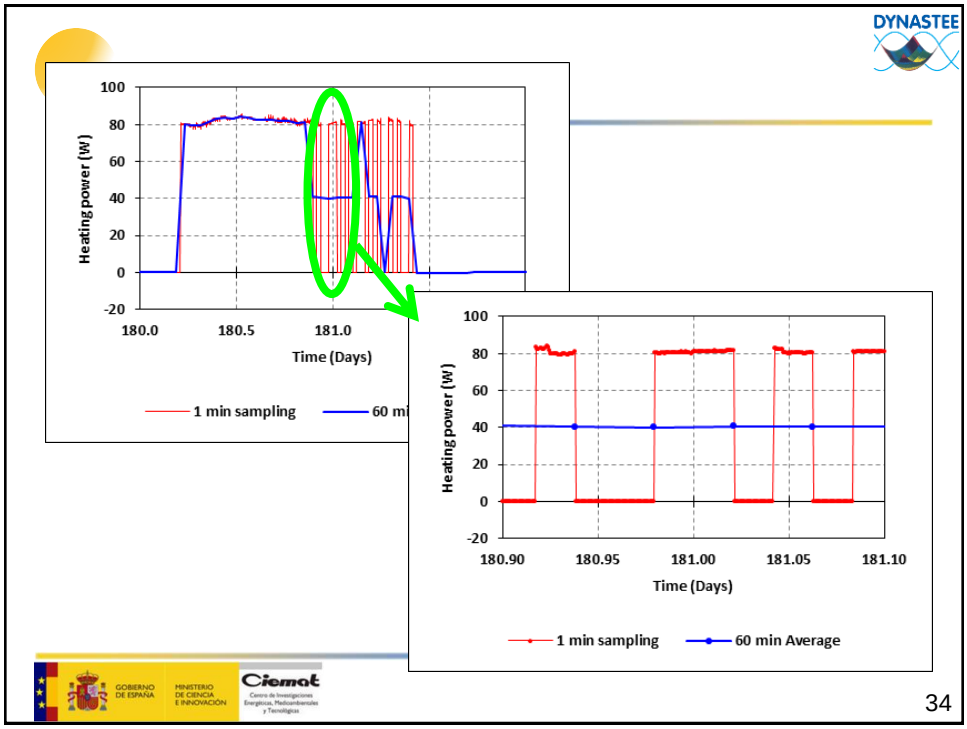
- Data analysis starts with qualitative analysis of data based on data overview, aiming to detect any abnormal behavior in the tendencies of variables, sensor failures, etc.
- Filtering techniques are useful when there is certainty that removed information doesn't correspond to the phenomena that we want to study
- Filtering and averaging could have harmful effects if it removes relevant information to the process under study (See aliasing in statistical guidelines)
- If averaging or filtering are applied they must be justified: what does it means? which are the expected benefits?, why improvements are expected?, etc.

32

32


DYNASTEE
Heating power (W)
Time (Days)
1 min sampling
10min Average
Temperature (°C)
10 min Average
60 min Average
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat
33

33


DYNASTEE
Heating power (W)
Time (Days)
1 min sampling
60 min Average
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat
34

34

METHODS FOR DATA ANALYSIS: SUMMARY

- **STEADY STATE**
  - Average method, linear regression…
- **DYNAMIC APPROACHES**
  - Linear models in transfer function form
    - ARX, ARMAX
  - State space models
    - RC, SDE

Construction of candidate models

Based on physical knowledge

- Starting point is an **energy balance equation including**:
  - the characteristic (usually intrinsic) **parameters that must be identified**
  - the **time recorded variables** driving the main heat fluxes of the system.
- The characteristics of the studied component and given test conditions are taken into account to build all the candidate models in all the applied approaches.
- It is important to be aware that all these considerations must be taken into account also to define the specifications of experiment set up.

Construction of candidate models

HYPOTHESES DERIVED FROM PHYSICAL KNOWLEDGE OF THE SYSTEM

Candidate models must be written trying to give answer to the following questions

- What is the **system** to which the energy balance equation will be referred to?. Is a volume?, is a flat surface?
- What are the **phenomena theoretically** in the energy balance equation?
- Which of these **phenomena are relevant** in practice to the considered case study and given test conditions?
- What is the most **efficient way of modelling** each relevant phenomena?. Efficiency is referred to model accuracy, cost of measurement devices, and model simplicity.
- Which are the **main driving variables** of each of the phenomena recognised as relevant for the considered case study?
- Which variables must be considered inputs and outputs according to **causality**.

If it is not possible to answer some of these questions a priory, **several candidate models** according to the different possibilities can be considered and evaluated.

37

Analysis approaches applied and key issues common to all the analysis approaches

- Analysis to obtain the HLC of the whole building based on the **ENERGY BALANCE EQUATION IN THE AIR VOLUME** confined by the house envelope
- Analysis to obtain the U of the opaque walls based on the **ENERGY BALANCE EQUATION IN THEIR INTERIOR SURFACE**
- First step: check the **availability and quality of the driving variables** of the terms required to write candidate models based on this energy balance.
- Data: Several data set used to check robustness and replicability of results
- Common principles to different **approaches**:
  - **RC Models** Identified using LORD, (ot CTSM-R)
  - **Linear regression**
  - **ARX Models** Identified with MATLAB IDENT
  - Etc.

38

Analysis approaches applied and key issues common to all the analysis approaches

- Analysis to obtain the HLC of the whole building based on the **ENERGY BALANCE EQUATION IN THE AIR VOLUME** confined by the house envelope
- Analysis to obtain the U of the opaque walls based on the **ENERGY BALANCE EQUATION IN THEIR INTERIOR SURFACE**
- First step: check the **availability and quality of the driving variables** of the terms required to write candidate models based on this energy balance.
  - Heat lost to outdoor
  - Solar gains
  - Heat supplied by heating system (to obtain HLC) or Heat Flux (to obtain U)
  - Other contributions that could be present in other real life cases: Internal gains due to appliances, Heat removed by the mechanical ventilation system, Heat exchanged with adjacent houses, Heat supplied due to metabolic activity

39

Key issues common to all the analysis approaches:
Modelling energy contributions to the energy balance

ENERGY BALANCE TERM	DRIVING VARIABLES
Heat lost to outdoor	T_{indoor}-$T_{outdoor}$
Solar gains	On site solar radiation
Internal gains due to appliances	Total electricity consumption
Heat removed by the mechanical ventilation	Air flow, and supply and return temp
Heat supplied by the heating system	Heating power
Heat flux through the interior surface	Heat flux through the interior surface
Heat exchanged with adjacent houses (j)	T_{indoor_1}-T_{indoor_j}
Heat supplied due to metabolic activity	? *(Applied Energy. 199, pp. 121–141)*

40

METHODS FOR DATA ANALYSIS: SUMMARY

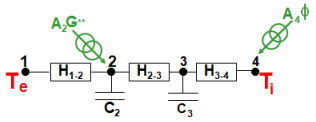
- **STEADY STATE**
  - Average method, linear regression…
- **DYNAMIC APPROACHES**
  - Linear models in transfer function form
    - ARX, ARMAX
  - State space models
    - RC, SDE

RC MODELS

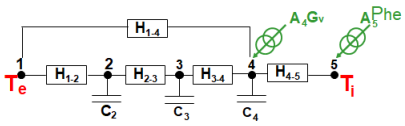
- Electrical analogy, with energy balance referred to a node of the system.
- Justified translation from thermal system to electrical scheme is required
- **Typical aspects** that require considering different candidate models
  - Different **number of resistances** in series (different number of nodes) are recommended for systems with **un-known heat capacity**
  - Evaluation of **solar radiation transmitted through opaque walls**: Is or isn't relevant (absorbed during the day in the walls and released to outdoors at night and don't reach indoors)?
  - **Parallel branches** representing building envelope with low mass glassing elements and heavier opaque walls
  - Symmetry can be assumed to avoid over-parameterisation
- **Any other relevant contribution to the energy balance must be represented**

RC Models Identified with LORD. Possibilities

1. **Mono-dimensional analysis of opaque walls**
   - To obtain the U value of the opaque walls
   - Several candidate models. Relevant options:
     - 3 to 7 nodes
     - Outputs: Ti, ϕ
     - Including and non-including solar radiation
     - Systematic analysis of the ceiling considering all the options
     - Analysis of floor and left, right, back walls using best model found for the ceiling

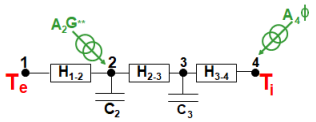


2. **Tri-dimensional analysis of the whole building**
   - To obtain the UA and gA values of the whole building envelope
   - Several candidate models. Relevant options:
     - 3 to 7 nodes representing opaque walls
     - Parallel branch representing the windov
     - Outputs: T_i, $P_{heating}$
     - All candidate models including G_v
     - Evaluation of best model found for the considering non-measured variables

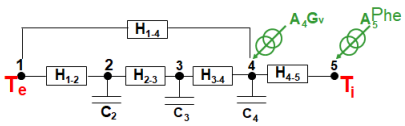


RC Models Identified with LORD. Possibilities

1. **Mono-dimensional analysis of opaque walls**
   - To obtain the U value of the opaque walls
   - Several candidate models. Relevant options:
     - 3 to 7 nodes
     - Outputs: Ti, ϕ
     - Including and non-including solar radiation
     - Systematic analysis of the ceiling considering all the options
     - Analysis of floor and left, right, back walls using best model found for the ceiling



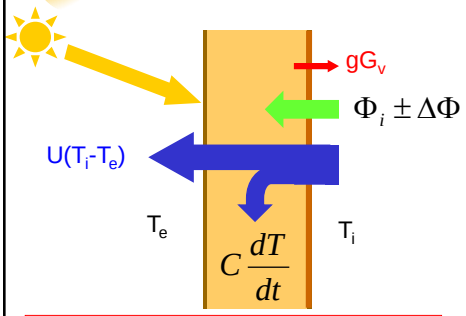
2. **Tri-dimensional analysis of the whole building**
   - To obtain the UA and gA values of the whole building envelope
   - Several candidate models. Relevant options:
     - 3 to 7 nodes representing opaque walls
     - Parallel branch representing the windov
     - Outputs: T_i, $P_{heating}$
     - All candidate models including G_v



STEADY STATE ANALYSIS

- **Steady state test:** all physical quantities are time independent (ISO 9251: 1987).
- **Steady state equations**
  - Steady state equations **based on instantaneous measurements are not valid** for dynamic tests
- **Integrated dynamic** equations are analogous to **steady state** equations.
  - Using time averaging to represent integrals
  - Steady state equations **based on averages can lead to accurate results** for dynamic tests under certain conditions
  - **Many drawbacks: Usually require extremely long test periods, etc.**

METHODS BASED ON AVERAGES. SEEN AS DYNAMIC INTEGRATED APPROACHES



$$\Phi_i = C\frac{dT}{dt} + U(T_i - T_e)$$

Considering:

- Integrals for long periods, Δt
- Integration period **long enough** to :

$$\int^{\Delta t} C\frac{dT}{dt}dt << \int^{\Delta t} \Phi_i dt - \int^{\Delta t} U(T_i - T_e)dt$$

- Averages to estimate integrals:

$$0 \cong \overline{\Phi_i} - U\left(\overline{T_i} - \overline{T_e}\right)$$

- Wind speed, solar radiation, long wave radiation?
- If their influence on Ø, is higher than ΔØ. Depend on the component and weather.
- Other effects, other systems

NO

YES

- **Generalisation**

$$\overline{y} = a_1\overline{x_1} + a_2\overline{x_2} + ... + a_n\overline{x_n} + b$$

Published papers relevant to this method

K. Chávez, D.P. Ruiz, M.J. Jiménez. 2019. Dynamic integrated method applied to assessing the in-situ thermal performance of walls and whole buildings. Robustness analysis supported by a benchmark set-up. *Applied Thermal Engineering*. **152C**, pp. 287-307. DOI: 10.1016/j.applthermaleng.2019.02.065

J.A. Díaz, M.J. Jiménez. 2017. Experimental assessment of room occupancy patterns in an office building. Comparison of different approaches based on CO_2 concentrations and computer power consumption. *Applied Energy*. **199**, pp. 121–141. DOI: 10.1016/j.apenergy.2017.04.082

L. Castillo, R. Enríquez, M.J. Jiménez, M.R. Heras. 2014. "Dynamic integrated method based on regression and averages, applied to estimate the thermal parameters of a room in an occupied office building in Madrid". *Energy and Buildings*. **81**, pp. 337-362. DOI: 10.1016/j.enbuild.2014.06.039

I. Naveros, M.J. Jiménez, M.R. Heras. 2012. "Analysis of capabilities and limitations of the regression method based in averages, applied to the estimation of the U value of building component tested in Mediterranean weather". *Energy and Buildings*. **55**, pp. 854-872. DOI: 10.1016/j.enbuild.2012.09.028

TRANSFER FUNCTION FORM (ARX, etc)

- Output is linear function of a number of past readings of the inputs and outputs
- Physical parameters found comparing equations that must coincide:
  - The steady-state energy balance equation
  - The ARX model, when all its inputs and outputs are constant.
- ARX model **MUST** contain the same variables as steady state energy balance eq.
  - Key step in this approach is to deduce and write the appropriate steady state energy balance equation that must be based on physical knowledge.
- Different candidate models based on different assumptions and approximations
- Assignment of inputs and outputs based on causality

Published papers relevant to this method

Jiménez M.J., Madsen H., Andersen K.K. 2008. Identification of the Main Thermal Characteristics of Building Components using MATLAB. *Building and Environment*. 43(2), pp. 170-180. DOI: 10.1016/j.buildenv.2006.10.030

Jiménez M.J., Madsen H., Andersen K.K., "How to get physical parameters using MATLAB". Presented at "International Conference on Dynamic Analysis and Modelling Techniques". Organised by PASLINK EEIG and JRC. Ispra. (Italy). 13-14 November 2003. ISBN 92-894-7794-6. Paper in the DYNASTEE USB: \Ispra2003PapersPDF\p129_Jimenez.pdf

Jiménez M.J.; Heras M.R. 2005. "Application of multi-output ARX models to estimate the U and g values of building components from outdoors testing". Solar Energy. 79(3), pp. 302-310. DOI: 10.1016/j.solener.2004.10.008

M.J. Jiménez, B. Porcar, M.R. Heras. 2008. "Estimation of UA and gA values of building components from outdoor tests in warm and moderate weather conditions". Solar Energy. 82(7), pp. 573-587. DOI: 10.1016/j.solener.2008.02.013

STOCHASTIC STATE SPACE MODELS

- Very useful and flexible to represent physical systems governed by differential eq.
  - Offers a very high potential to model a wide variety of physical systems
- Diffusion terms and modelling errors facilitate very accurate parameter estimates
- System equations can include measured as well as non-measured states
  - Which is a very useful in modelling physical systems
- RC models can be considered. This family of models:
  - Are a reduced subset of the state space models than can be used
  - Don't make use of these capabilities in their full extent

Published papers relevant to this method

M.J. Jiménez, H. Madsen, H. Bloem, B. Dammann. 2008. “Estimation of Non-linear Continuous Time Models for the Heat Exchange Dynamics of Building Integrated Photovoltaic modules”. Energy and Buildings. 40(2), pp. 157-167. DOI: 10.1016/j.enbuild.2007.02.026

N. Friling, M.J. Jiménez, J.J. Bloem, H. Madsen. 2009. “Modelling the heat dynamics of building integrated and ventilated photovoltaic modules”. Energy and Buildings. 41(10), pp. 1051-1057. DOI: 10.1016/j.enbuild.2009.05.018

Jiménez M.J., Madsen H. 2008. “Models for Describing the Thermal Characteristics of Building Components”. Número especial sobre ensayos de cerramientos en condiciones reales. Building and Environment. 43(2), pp. 152-162. DOI: 10.1016/j.buildenv.2006.10.029

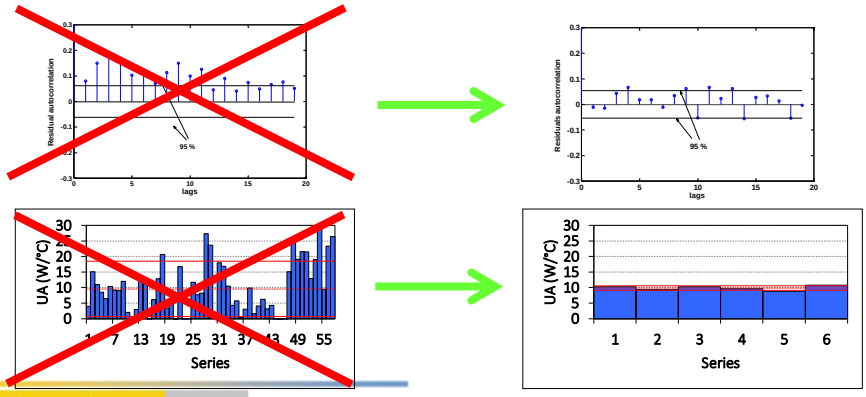
Model validation

- Fit to the data. The model residuals should be 'small' and 'white noise'.
- Internal validity. The model should agree with data other than data used for parameter estimation (cross validation)
- External validity. The result from the model should not (without greater motivation) conflict with previous experiences or other known conditions.
- Dynamic stability. From a steady state, the model should give an output upon a temporary change in an input variable that is gradually faded out (if the model is intended to describe dynamic characteristics).
- Identifiability. It should be possible to determine the parameters of the model uniquely from the data
- Simplicity. The model should be as small as possible

U. Norlén. 1994. In:
Workshop on Application of System Identification in Energy Savings in Buildings

Model validation

- **Mandatory**
- **Statistical** criteria are very useful in the process of model selection
- Results must not contradict **physical knowledge** and common sense
- If validation criteria are not fit, results must be rejected and models reformulated



Interpretation of residuals

- **Residuals with a frequency of 24 hours** very frequent in insufficient models
- Non negligible correlation between model residuals and solar radiation, could inspire more **detailed description of the solar radiation** to improve model.
- **Sometimes better modelling solar radiation is not a solution:** Many variables can have relevant correlation with solar radiation, so **any other effect** depending on them and not properly modelled **can show residuals in the same frequency**.

Interpretation of residuals

- Many variables can have relevant correlation with solar radiation, so **any other effect** depending on them and not properly modelled **can show residuals in the same frequency**. Examples:
  - **Air leakage** that can depend on wind speed and/or outdoor air temperature, both depending on solar radiation
  - **Longwave effects** stressed by high surface temperatures due to solar radiation
  - U depending on **thermal conductivities** depending on temperature of materials that depends on solar radiation
  - **Wrong resampling** disregarding the sampling theorem

Frequent mistakes in model building

- Use equation from literature that include approximation under strong hypotheses that doesn't fit the particular studied problem
- Use excessively detailed equations when some their terms are in practice negligible, bringing too many variables some of them supplying exclusively noise instead of information
- Ignore causality issues
- Ignore some aspects of reality of sensors
- Interpretation of problems in the residuals analysis in the frequency of 24 hours
- Eliminate from energy balance equations constant inputs

Recommended reference

Chapter 11 of: IEA, EBC Annex 58, Report of Subtask 3, part 1. Thermal performance characterization based on full scale testing - description of the common exercises and **physical guidelines**

Link to the full document

Link to physical guidelines

Link to PSA_RRbox_DataSeries20.zip

Thank you for the attention

María José Jiménez
Energy Efficiency in Buildings R&D Unit, CIEMAT;
Carretera de senés s/n; 04200; Tabernas, Almería, SPAIN
e-mail: mjose.jimenez@psa.es