DYNASTEE DYNamic Analysis, Simulation and Testing applied to the Energy and Environmental performance of buildings

Free On-Line Training Webinars; 22 and 29 September, 6 and 13 October 2021

Dynamic Calculation Methods for Building Energy Performance Assessment

Technical University of Denmark DTU · GCU Glasgow Caledonian University · Universidad del País Vasco / Euskal Herriko Unibertsitatea · Gobierno de España · Ministerio de Ciencia e Innovación · Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas · University of Salford Manchester

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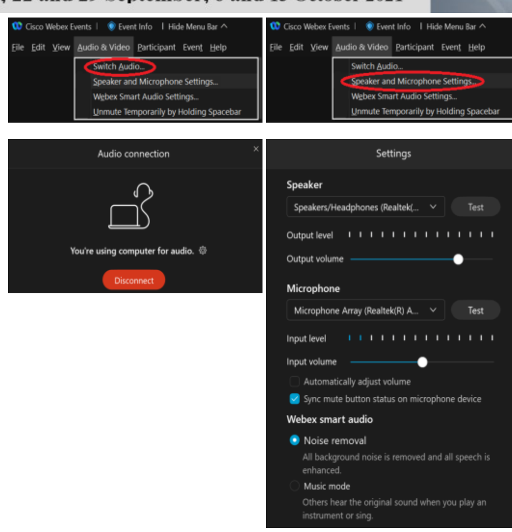

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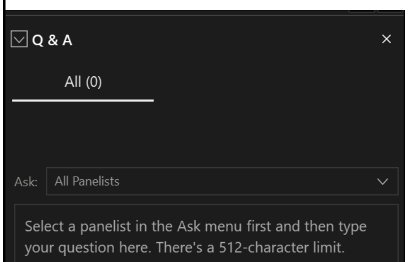

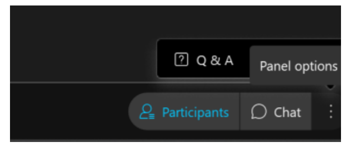

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NOTES:

1. The questions addressed to the speakers during this webinar- via the Q&A box- will be gathered and answered **during the last webinar of the series on October 13th**
2. After the end of the webinar you can also send further questions you might have, via email to Hans Bloem at: hans.bloem@inive.org
3. The webinar will be recorded and published at https://dynastee.info/ within a couple of weeks, along with the presentation slides.

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DYNamic Analysis, Simulation and Testing applied to the Energy and Environmental performance of buildings
Free On-Line Training Webinars; 22 and 29 September, 6 and 13 October 2021
2nd Webinar 29th September 2021
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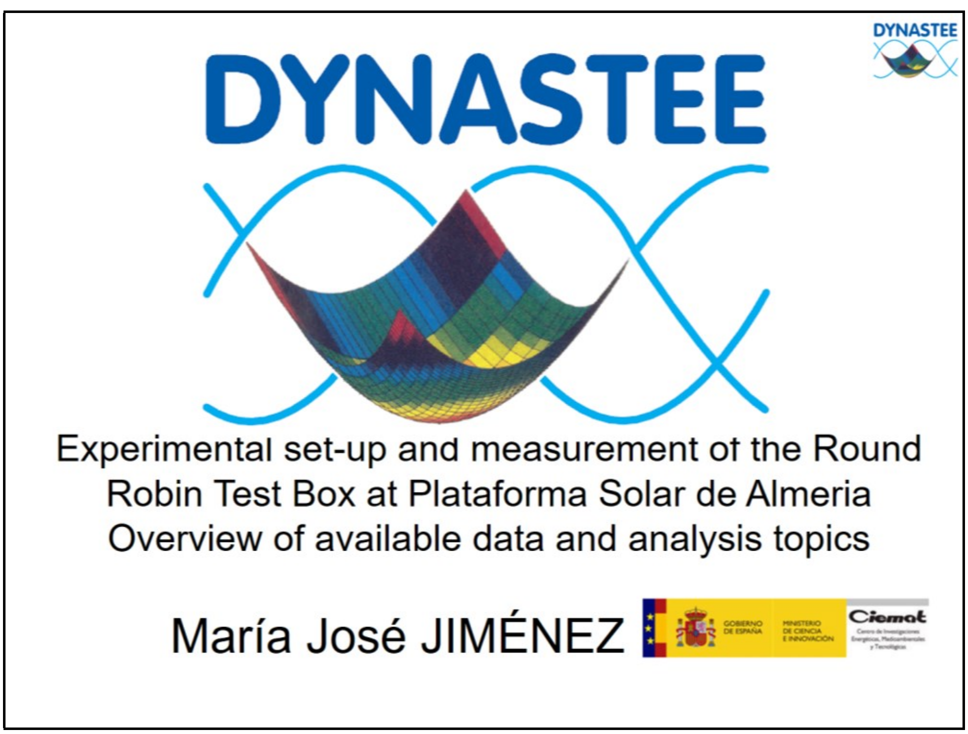
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Experimental set-up and measurement of the Round Robin Test Box at Plataforma Solar de Almeria
Overview of available data and analysis topics
María José JIMÉNEZ
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat

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- **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

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Case study: Round robin test box

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- 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 can be analysed by comparing the results from a **long testing period** including different test and weather conditions.
  - **Benchmark data and set-up**

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INTRODUCTION (CONTEXT)

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- **Dynamic models allows getting characteristic (steady state and others) parameters from dynamic tests campaigns**
  - Key feature for energy performance assessment of "as built" buildings, under dynamic outdoors weather and in-use 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**

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INTRODUCTION (CONTEXT)

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

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Usefulness of well known simple systems

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- 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
- Additional validation criteria: previous knowledge about thermal characteristics
  - External validity
- Well known characteristics facilitate to identify wrong results and check analysis skills

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Usefulness of well known simple systems

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- 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

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Usefulness of a wide variety of data series

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- 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

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Case study

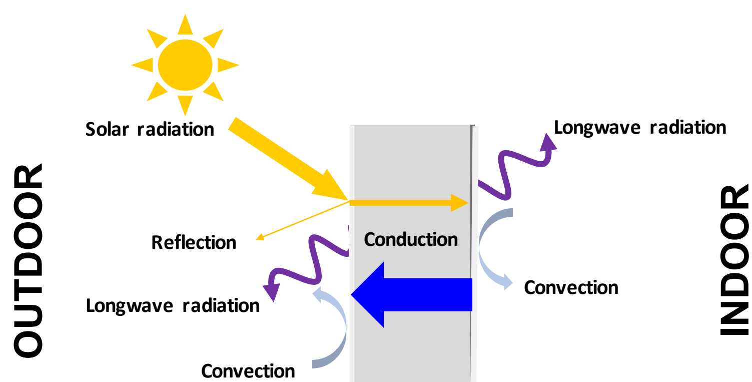
Round robin test experiment. IEA EBC annex 58

- 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

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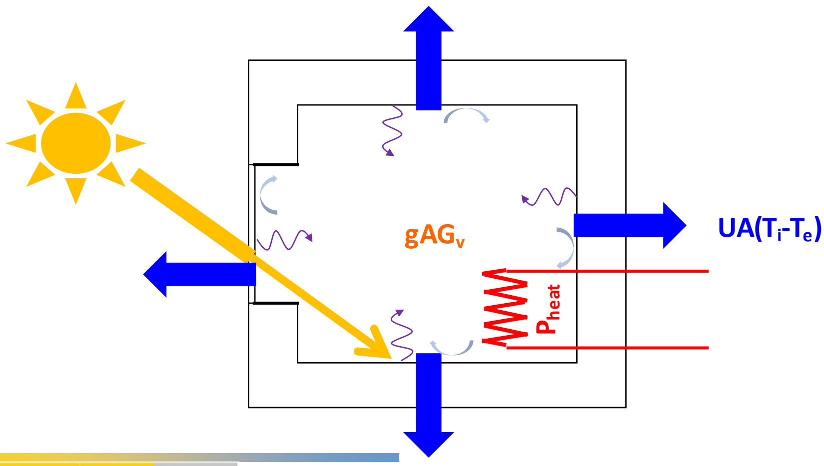
2. Energy balance in a Volume



Location: Plataforma Solar de Almería

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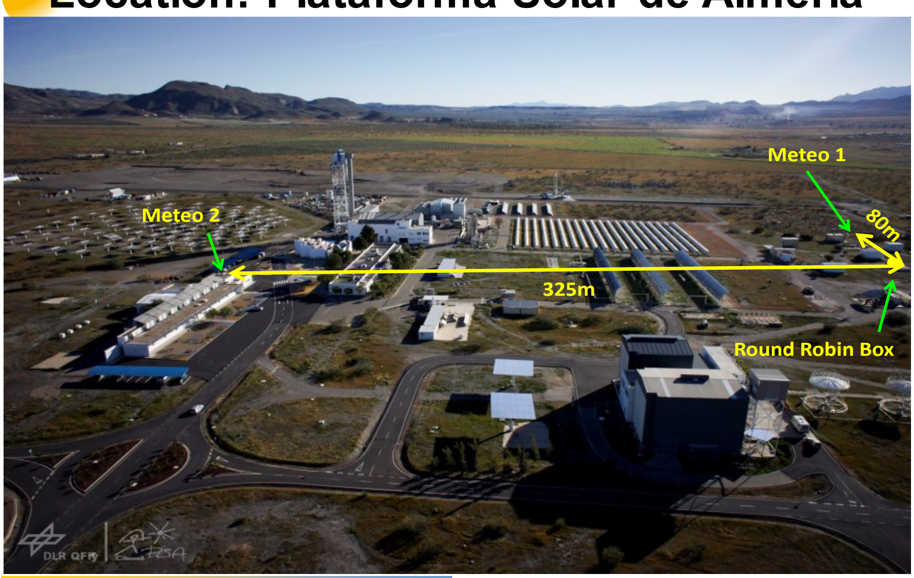

Measurement devices

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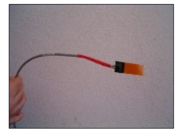






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Measurement devices

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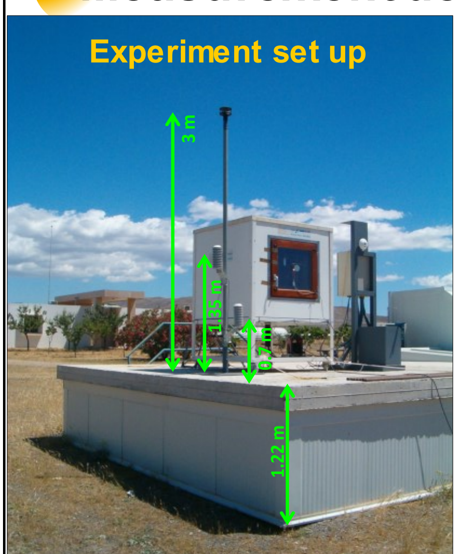

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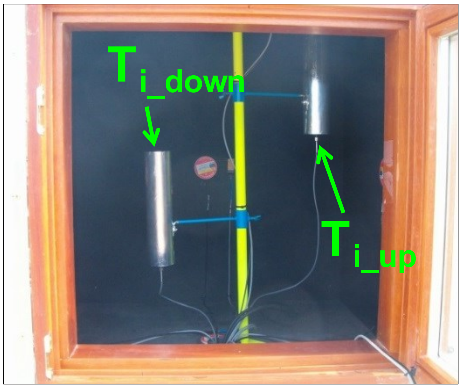
Measurement devices

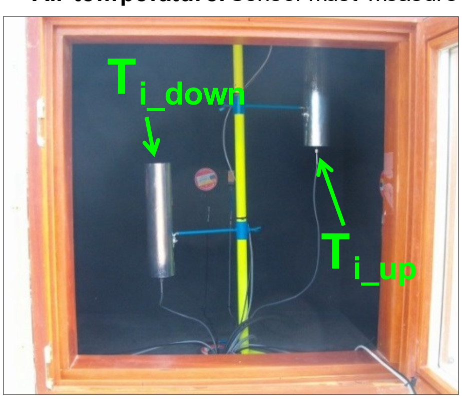
Air temperature: Sensor must measure the air temperature. How ?

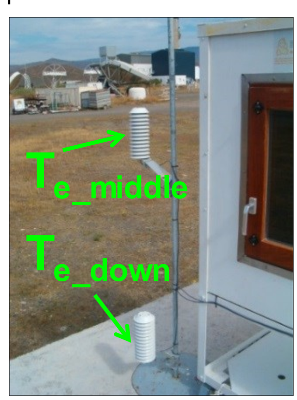


Indoor air temperature:
Sensor protected from solar radiation by aluminium cylinders that allow ventilation

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

Measurement devices

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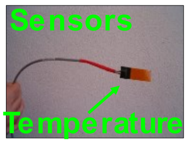
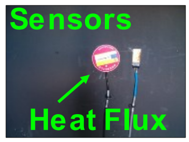
Surface temperature: Sensor must measure the surface temperature
Heat flux through a surface: Sensor must measure the heat flux through the surface

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

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Requisites to tests campaigns for analysis

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- The experiment design must guarantee that the phenomena to be characterised are happening and strong enough for their analysis. A phenomenon is 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.

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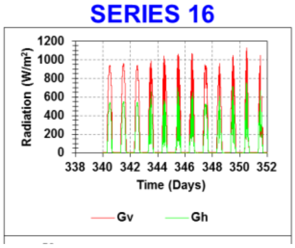
Data series

- **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-state 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



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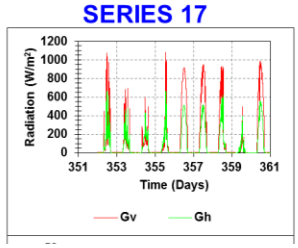

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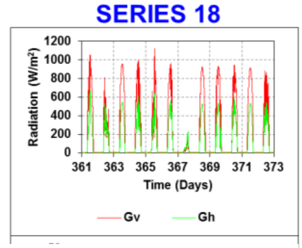

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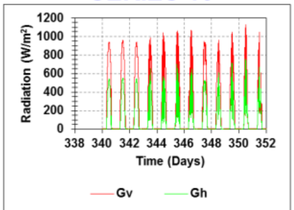

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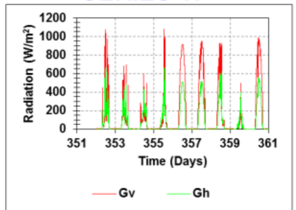

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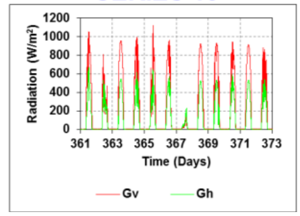

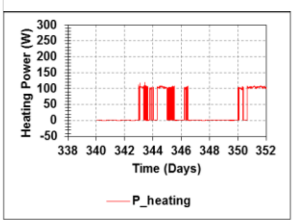

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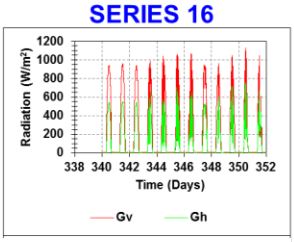

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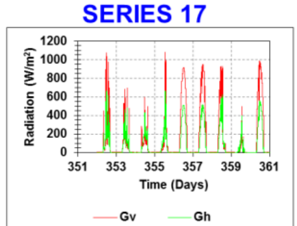

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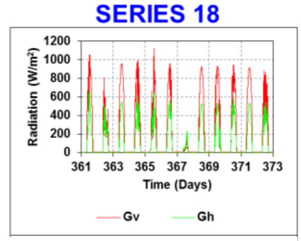
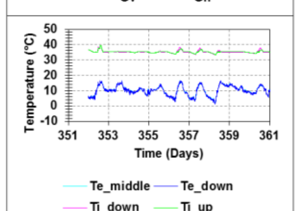
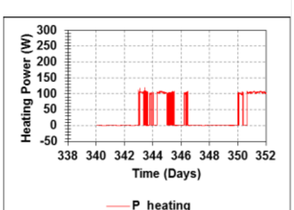


Indoor air





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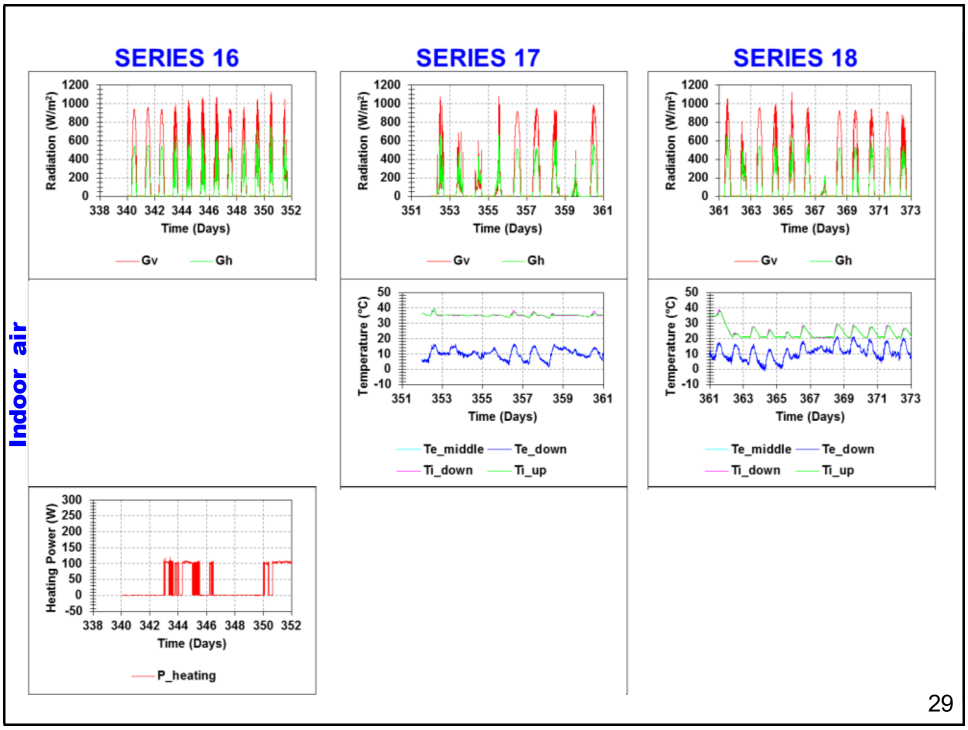
SERIES 16
SERIES 17
SERIES 18
Indoor air
Radiation (W/m²)
Time (Days)
Gv
Gh
Temperature (°C)
Te_middle
Te_down
Ti_down
Ti_up
Heating Power (W)
P_heating
29

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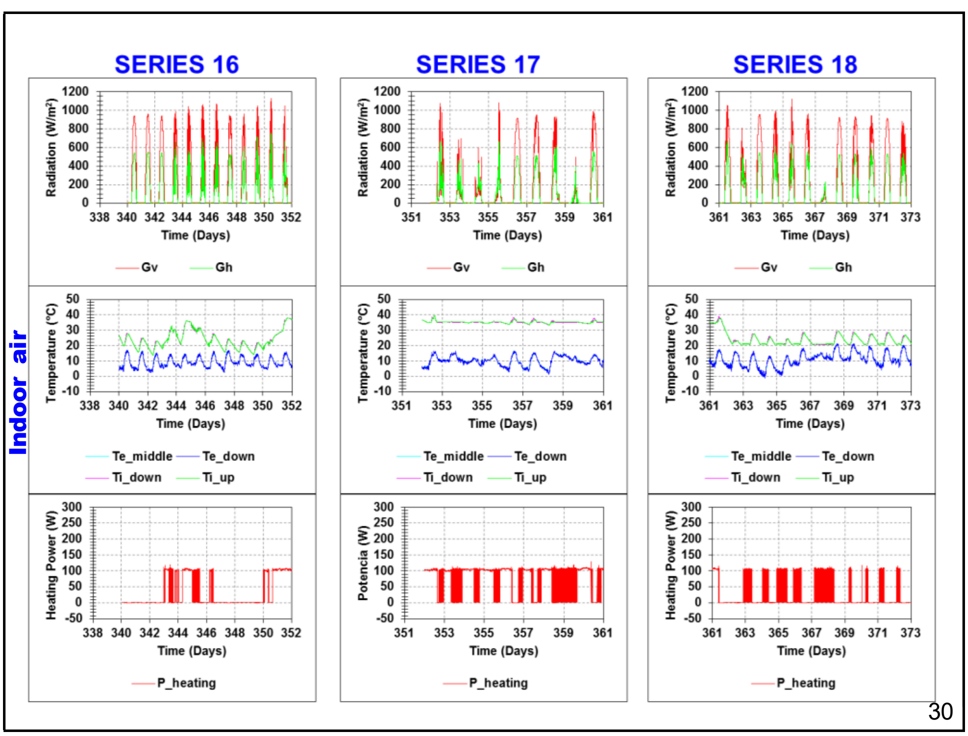
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Time (Days)
Gv
Gh
Temperature (°C)
Te_middle
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Ti_down
Ti_up
Heating Power (W)
Potencia (W)
P_heating
30

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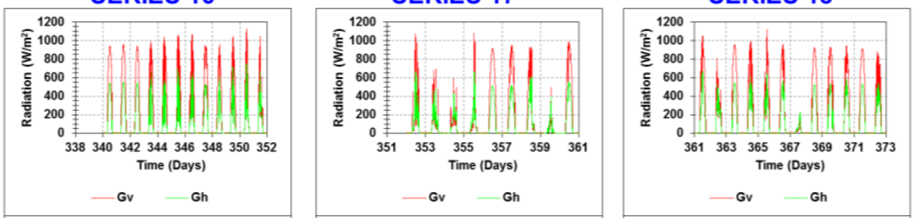
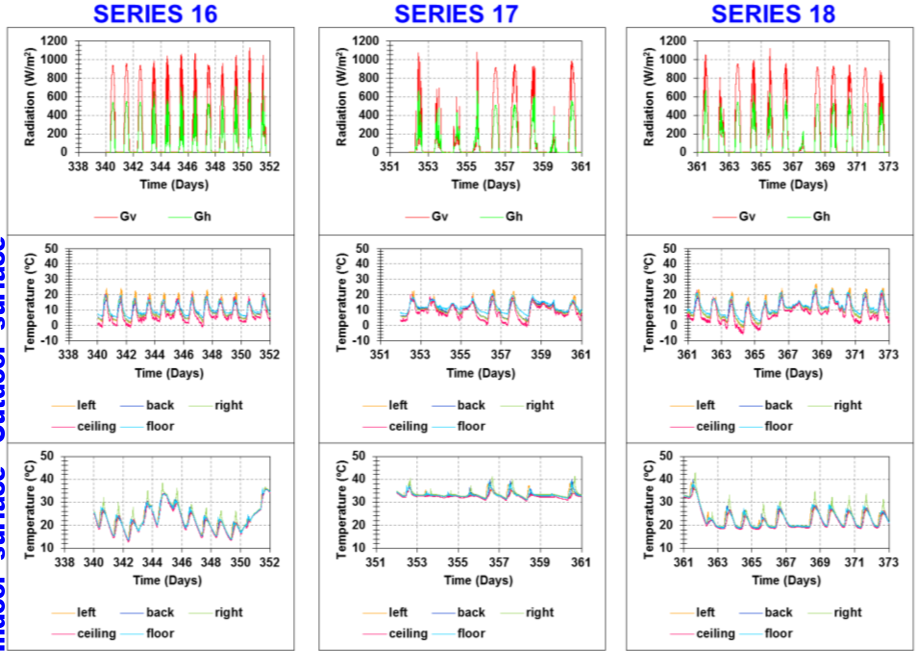
SERIES 16 SERIES 17 SERIES 18



SERIES 16 SERIES 17 SERIES 18

Outdoor surface

Indoor surface



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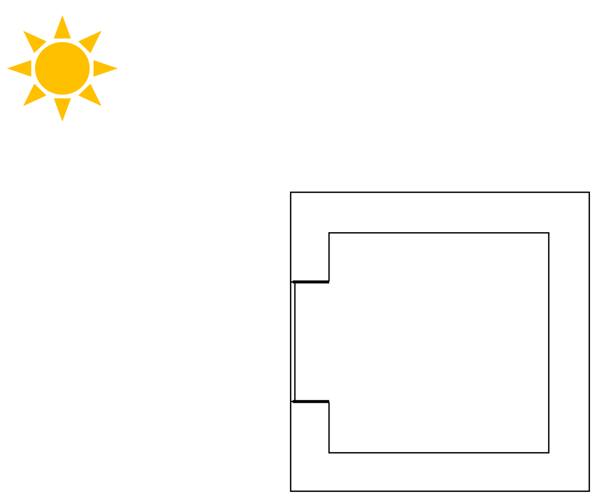
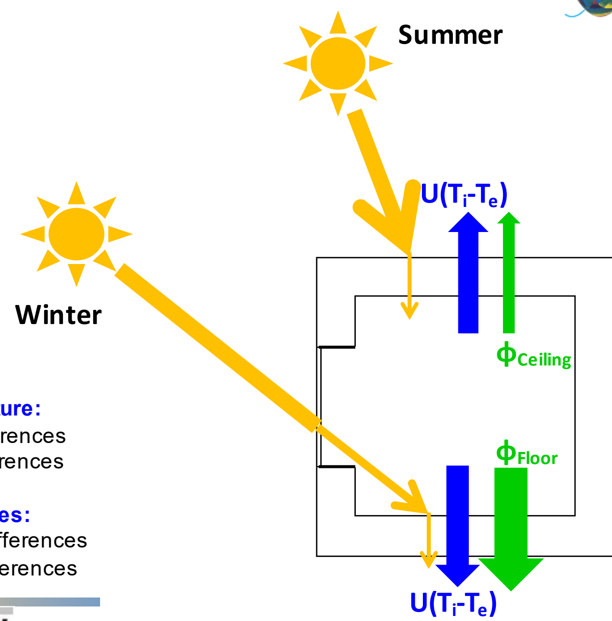
Candidate models including and not including solar gains through opaque walls.

Do they make sense?



Yes taking into account next slides……



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

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

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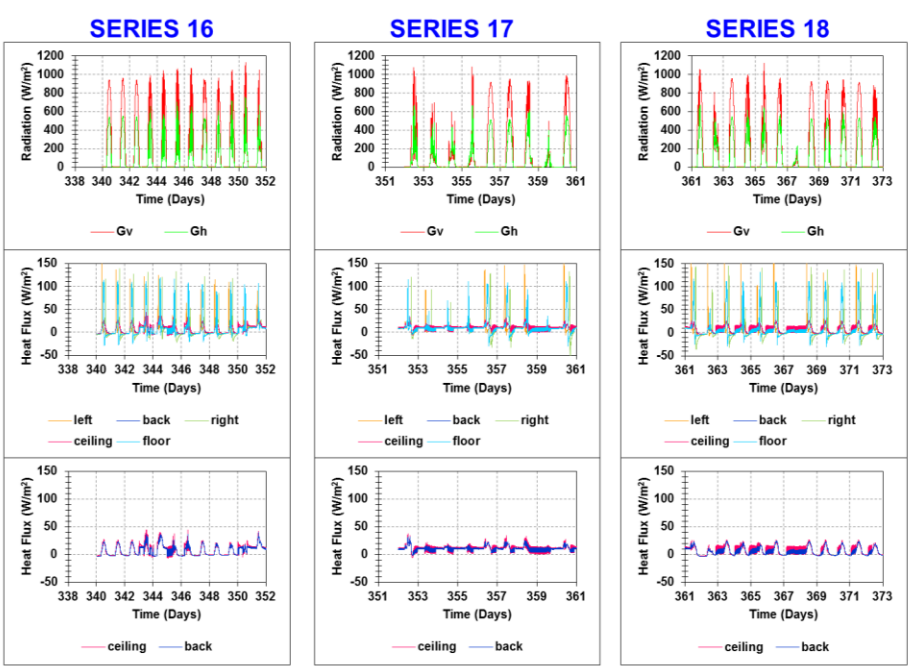

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Pre-processing, Averaging, Filtering

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- 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.

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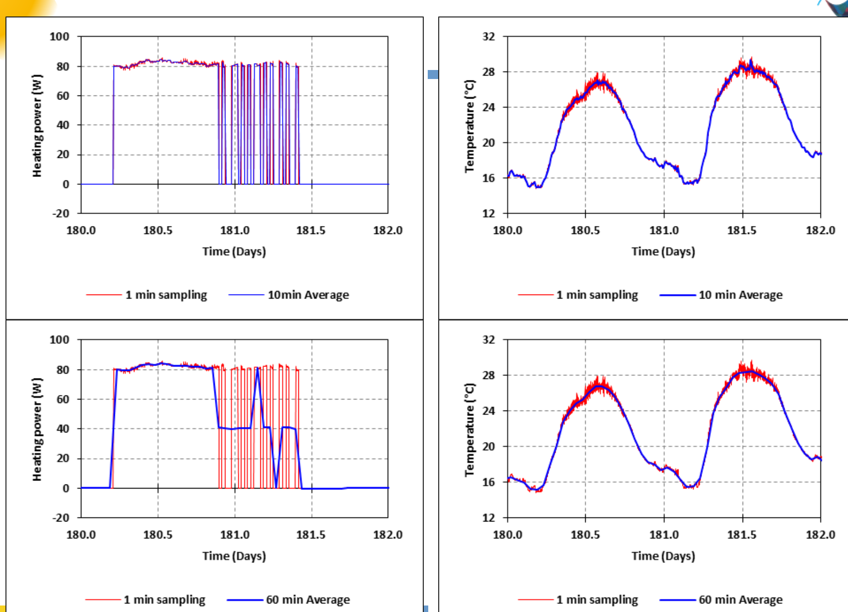

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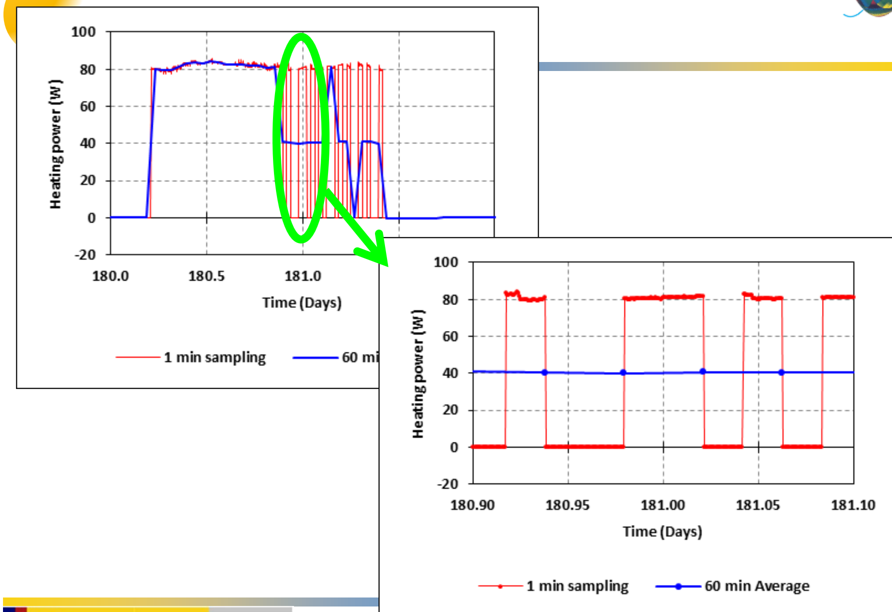

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METHODS FOR DATA ANALYSIS: SUMMARY

- **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.

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.

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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

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

ENERGY BALANCE TERM → **DRIVING VARIABLES**

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)*

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METHODS FOR DATA ANALYSIS: SUMMARY

DYNASTEE

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

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RC MODELS

DYNASTEE

- 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**

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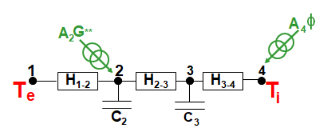
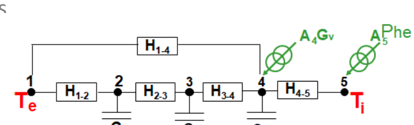
RC Models Identified with LORD. Possibilities

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 windo
     - 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

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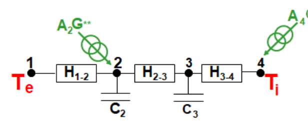

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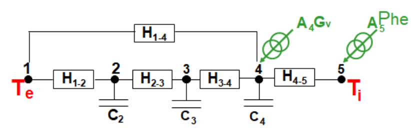

STEADY STATE ANALYSIS

DYNASTEE

- **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.**

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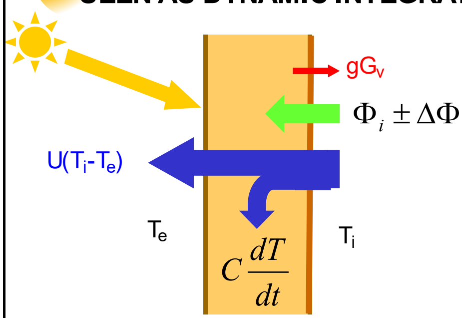
METHODS BASED ON AVERAGES.
SEEN AS DYNAMIC INTEGRATED APPROACHES

DYNASTEE



- 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

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

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:

NO → $$0 \cong \overline{\Phi}_i - U(\overline{T}_i - \overline{T}_e)$$

YES →

- **Generalisation**

$$\overline{y} = a_1\overline{x}_1 + a_2\overline{x}_2 + ... + a_n\overline{x}_n + b$$

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Published papers relevant to this method

DYNASTEE

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

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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

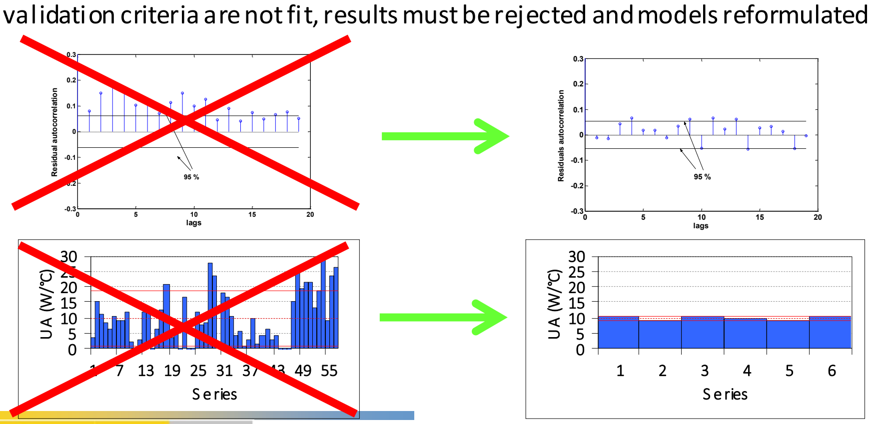
Model validation

- 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**.

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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

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Frequent mistakes in model building

DYNASTEE

- 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

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Recommended reference

DYNASTEE

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

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Thank you for the attention

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e-mail: mjose.jimenez@psa.es

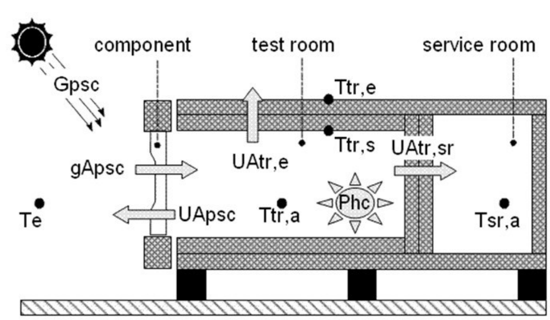
Introduction to LORD

Dr Paul Baker

Building Physics Consultant

Origins

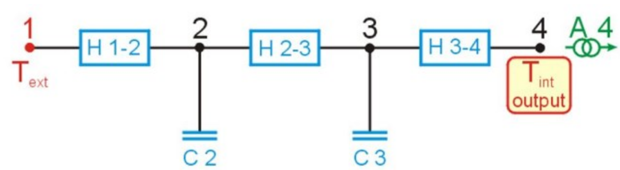
- LORD was developed for the PASLINK EEIG by Olaf Gutschker, BTU Cottbus, to analyse ***dynamic test cell data*** and deliver high quality performance characteristics for building components tested in real climates.



Purpose

- LORD can be used for components (walls, windows etc), whole rooms or more complicated systems;
- to obtain ***thermal transmittance values***, ***solar gain factors***, and possibly dynamic information (e.g. capacitances, time constants).
- A transient mathematical model is assumed. The parameters of the model (e.g. resistances, capacitances and heat flow admittances) essentially define the dynamic and steady-state thermal and solar properties of the system.

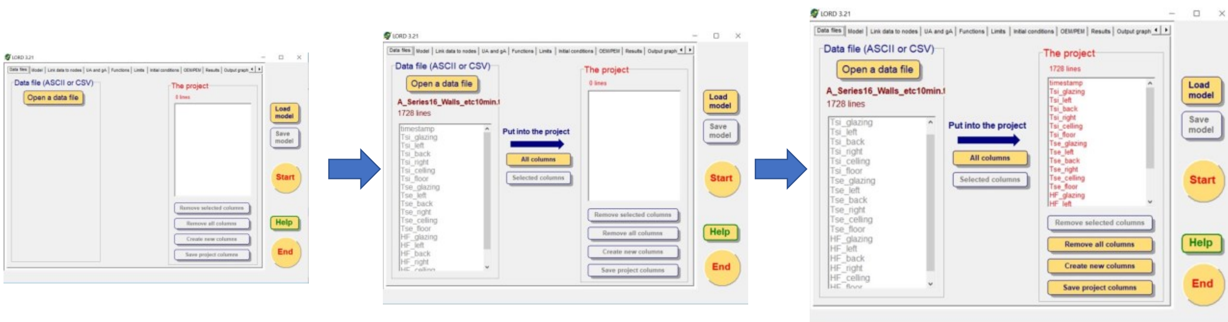
The user defines a RC-network



- Initial guesses of the parameter values are made.
- The ***output*** of the actual test (for instance, the test room temperature T_{int} as a function of time) is compared with the ***output*** which the model produces for the same ***input*** conditions.
- By statistical analysis of the deviations between the model and the measured outputs, the parameter values are progressively adjusted in order to improve the agreement.
- Read LORD Manual and other documents which will be provided.

(Mostly) User friendly interface

Step 1 - Input data: go to Data File tab.

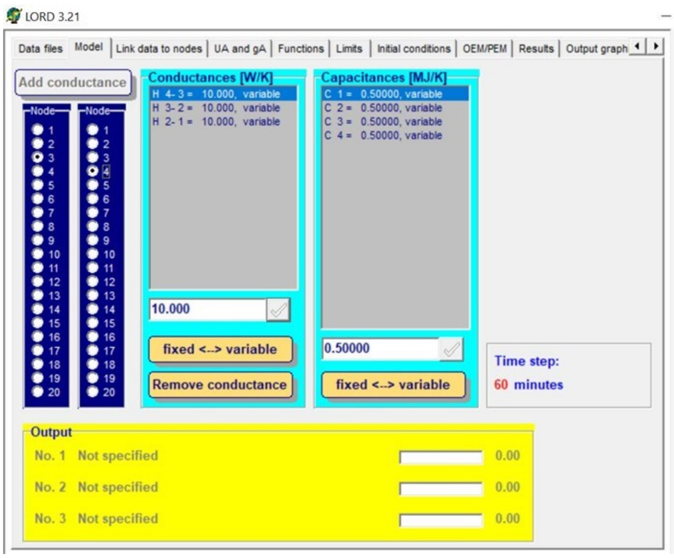


File formats – tab deliminated or CSV

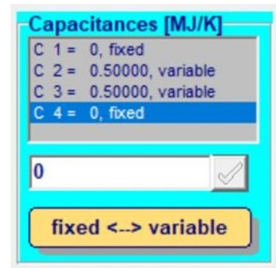
Headers must be enclosed in single quotation marks

	A	B	C	D	E	F	G
1	'timestamp'	'Tsi_glazing'	'Tsi_left'	'Tsi_back'	'Tsi_right'	'Tsi_celling'	'Tsi_floor'
2	41614	22.7454834	26.606781	26.6628572	27.2989349	26.4609832	28.63676
3	41614.00694	22.5884704	26.4465637	26.4946289	27.1242904	26.2911529	28.49256
4	41614.01389	22.4506836	26.2751311	26.3376159	26.9624634	26.134137	28.34516
5	41614.02083	22.3161011	26.1245224	26.1822051	26.7862244	25.9658966	28.19936
6	41614.02778	22.1959381	25.9626922	26.0299851	26.6083832	25.7912597	28.04554
7	41614.03472	22.0549438	25.7896576	25.8681641	26.4337463	25.6230316	27.91416
8	41614.04167	21.9043121	25.6278382	25.7063447	26.263916	25.4532013	27.77157

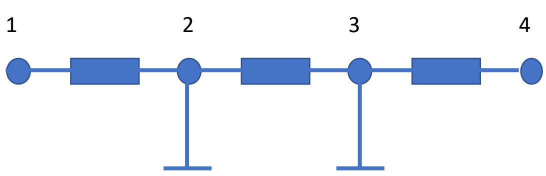
Step 2 – Create a model



Usually set capacitances at internal and external nodes to zero.

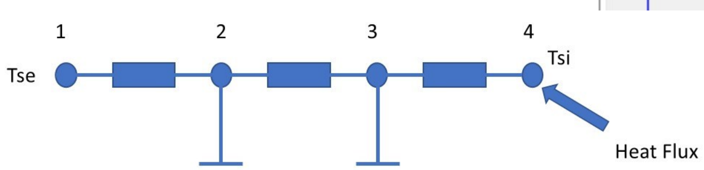


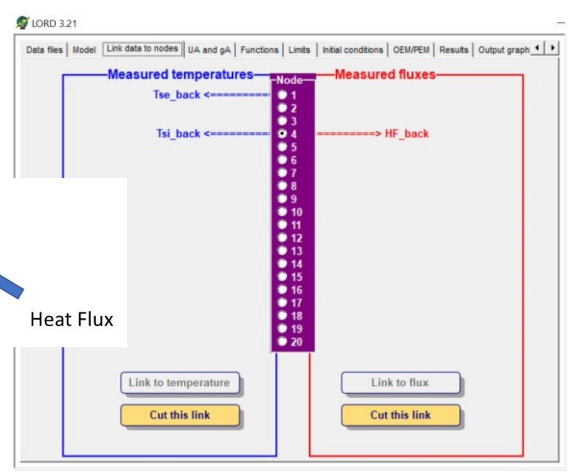
Check that time step is correct (note default is 60 minutes)



Step 3 – Link data to nodes

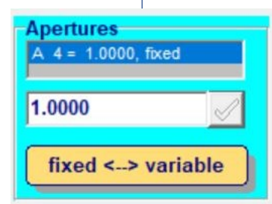
We now have a basic four node model which could be applied to heat flow measurements through a wall.





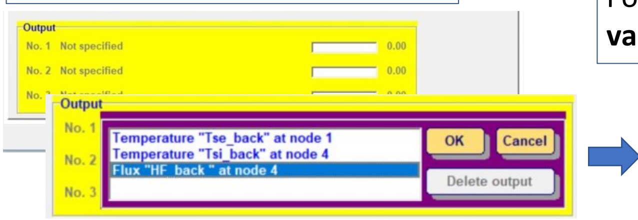
Step 4 – Go back to Model!

Fix Aperture = 1
for measured *Heat Flux or Heating Power*



For *Solar Radiation* **Aperture is variable.**

Select Output

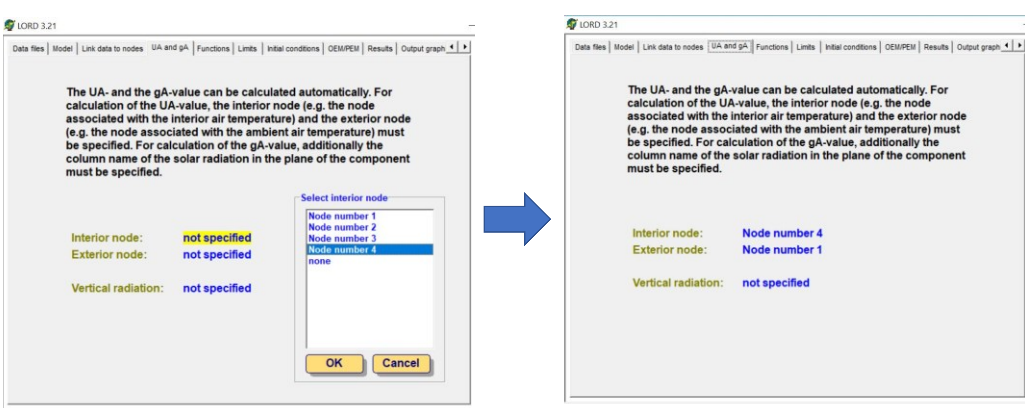


SS21

Step 5 - UA & gA

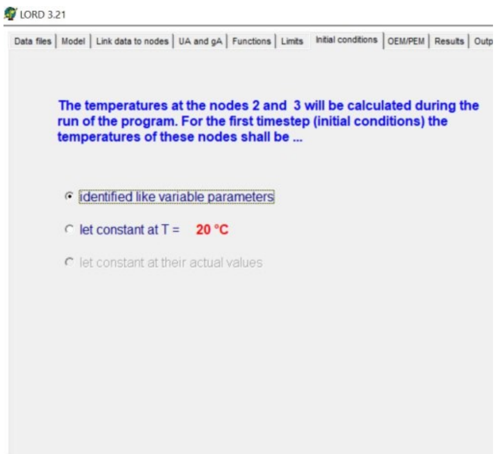
Note for 1-D heat flux measurements = U- & g-values

For our 4-node model we need to specify interior & exterior nodes:

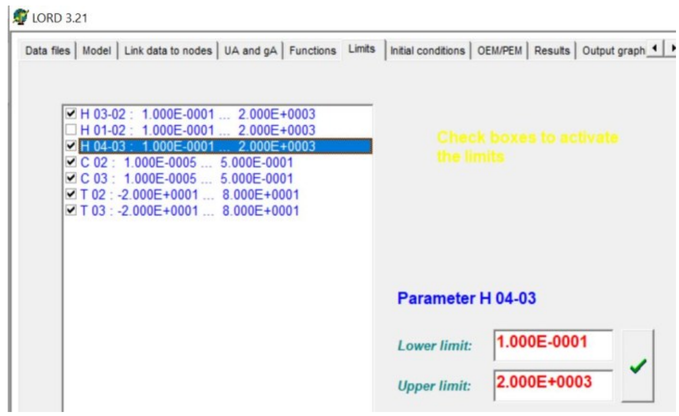


SS21

Step 6 – Initial Conditions



Step 7 – Limits

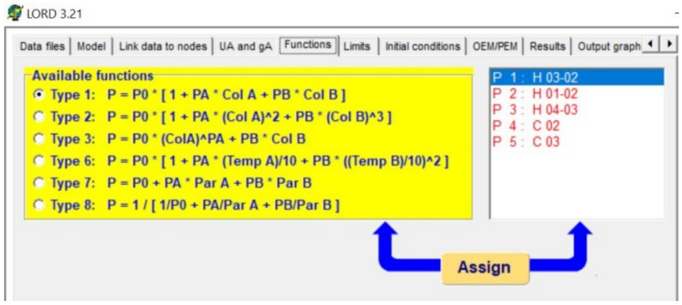


Step 8 – OEM/PEM

Recommend

- LORD originally developed using OEM. PEM added later.
- In general, the residuals using PEM are smaller than using OEM.
- The identification process takes much longer using PEM.
- PEM can only be used if the outputs are measured temperatures.
- Ask a statistician to explain!

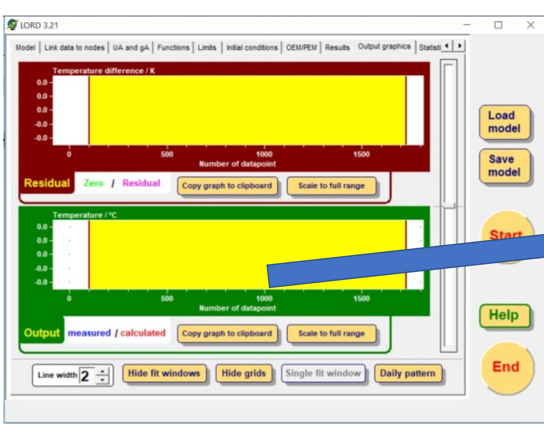
Other Options - Functions

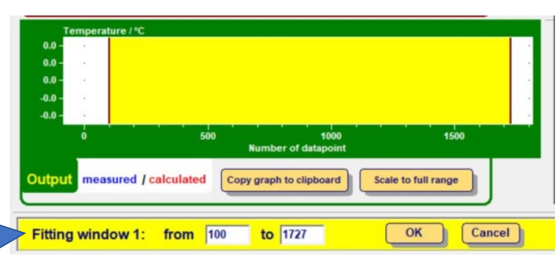


For example, it is possible to create a variable resistance dependent on a measured parameter such as wind speed.

Other Options – Output Graphics & 'Fitting Windows'

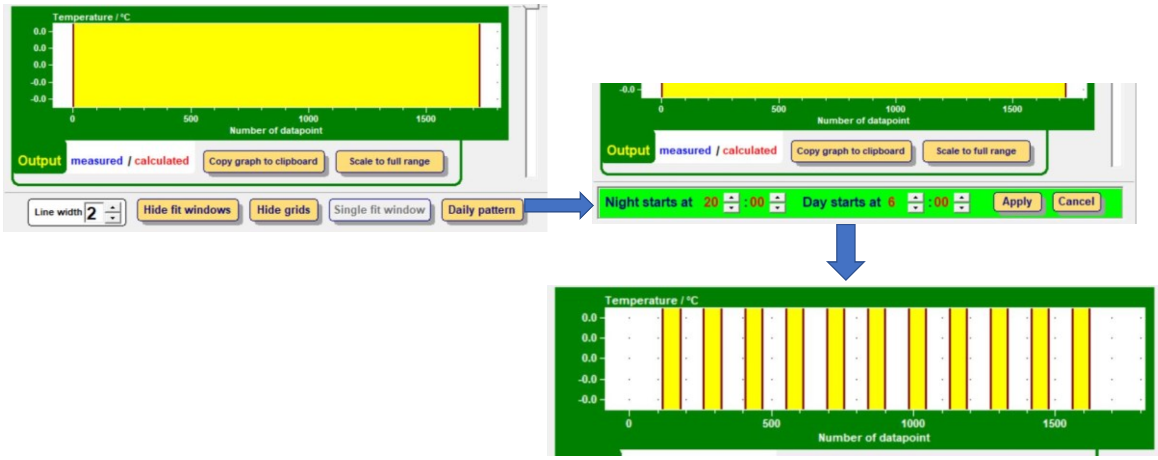
- Fitting windows can be used to select only part of the data for analysis.
- See LORD help for instructions.



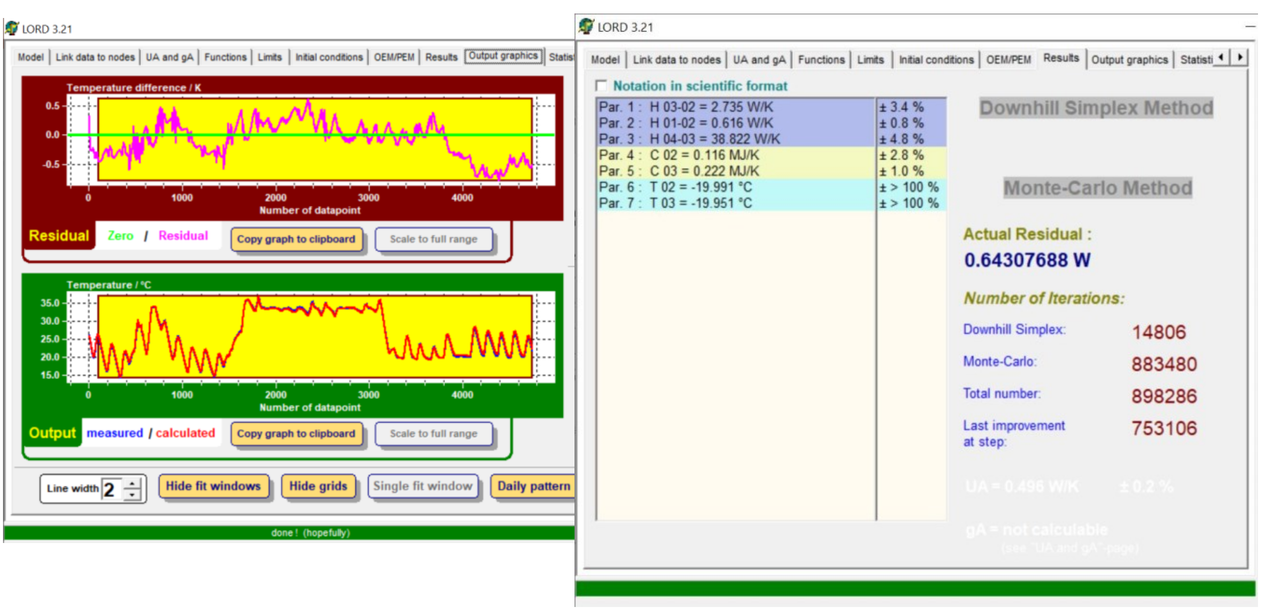


Right Click on Yellow Window to change Fitting Window

Daily Pattern – useful, for example, for excluding daytime data for heat flow measurements through windows.



Run!



Results - Output File *. log gives all input and output information

Back_10min-5 - Notepad

File Edit Format View Help

```
Log-File, created by LORD
================================

Date: 17/08/2020
Time: 14:39:33

Time step: 10.00 minutes

Fitting window:
number 1 -  from 100 to 4751

======================
Model and start values
======================

------------------
Conductances [W/K]
------------------
H  4- 3 =   38.822,  variable, limited between 0.10 and 2000.00
H  3- 2 =    2.7352,  variable, limited between 0.10 and 2000.00
H  2- 1 =    0.61610,  variable

-------------------
Capacitances [MJ/K]
-------------------
C  1 =   0, fixed
C  2 =   0.11647, variable, limited between 0.000 and 0.500
C  3 =   0.22201, variable, limited between 0.000 and 0.500
C  4 =   0, fixed

---------
Apertures
---------
A  4 =  1.0000, fixed

-------------------
Parameter functions
-------------------
not specified

-------------------------------------------
Columns in the data file and links to nodes
-------------------------------------------
Node number 1 ----> temperature "Tse_back"
Node number 4 ----> temperature "Tsi_back"

Node number 4 ----> flux "HF_back "

-------
Outputs
-------
No.1: Flux "HF_back " at node 4, weight = 1.00
No.2: Not specified
No.3: Not specified

------------------
Initial conditions
------------------
Initial temperatures were identified.
```

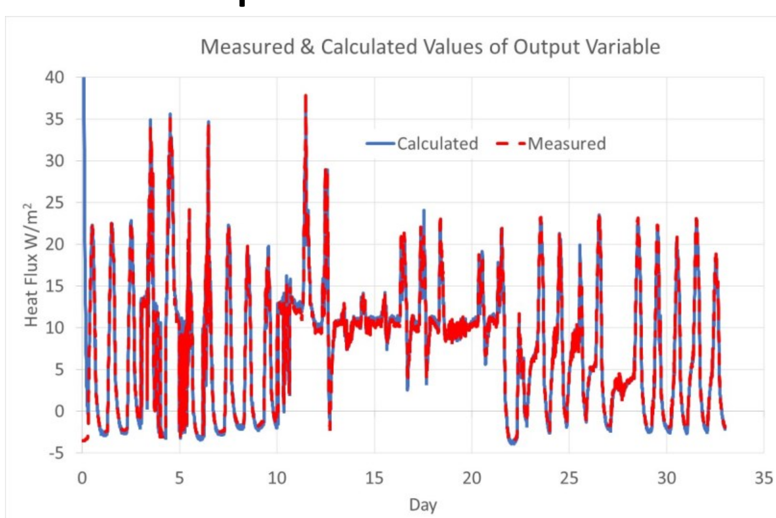
```
=======
Results
=======

----------
Iterations
----------
Downhill Simplex Method: 31800
Monte Carlo Method: 972710
Total number of iterations: 1004510
Last improvement at step: 943995

--------------------------------------------
Residual at end of calculation : 0.64307645 W
--------------------------------------------

----------
Parameters
----------
Par. 1 :  H 03-02 = 2.722 W/K ± 3.4 %
Par. 2 :  H 01-02 = 0.617 W/K ± 0.8 %
Par. 3 :  H 04-03 = 38.762 W/K ± 4.8 %
Par. 4 :  C 02 = 0.0194 MJ/K ± 2.8 %
Par. 5 :  C 03 = 0.0370 MJ/K ± 1.0 %
Par. 6 :  T 02 = -19.996 °C ± > 100 %
Par. 7 :  T 03 = -19.952 °C ± > 100 %

---------
UA and gA
---------
Interior node: Node number 4
Exterior node: Node number 1
Column with vertical radiation: not specified

---------
UA and gA
---------
Interior node: Node number 4
Exterior node: Node number 1
Column with vertical radiation: not specified

UA = 0.496 W/K ± 0.1 %
gA = not calculable

------------------
Cross - Correlation
------------------

            | H 03-02    H 01-02    H 04-03    C 02       C 03
------------+-------------------------------------------------------
H 03-02     | 1.0000     -0.6792    0.0133     0.0285     -0.3329
H 01-02     | -0.6792    1.0000     -0.0808    -0.0098    0.3028
H 04-03     | 0.0133     -0.0808    1.0000     0.2362     -0.2504
C 02        | 0.0285     -0.0098    0.2362     1.0000     -0.4843
C 03        | -0.3329    0.3028     -0.2504    -0.4843    1.0000
```


Results - Output File *.res gives measured & calculated values of output variable

Back_10min-5 - Notepad

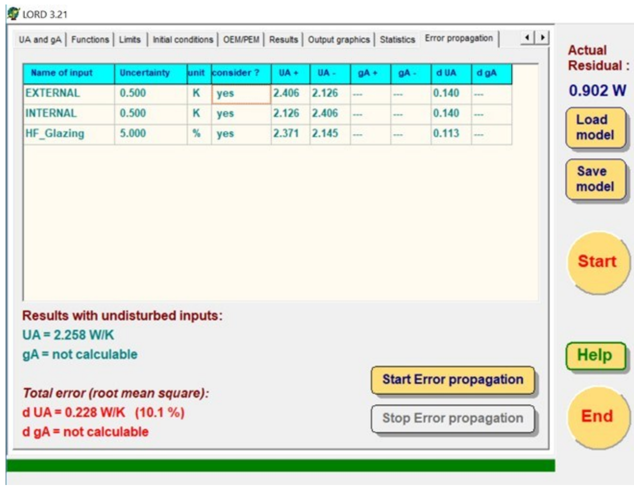
File Edit Format View Help

Day	Calc. 1	Meas. 1
0.0069444	1122.4832	-3.5312
0.0138889	710.7753	-3.5433
0.0208333	461.6966	-3.5464
0.0277778	309.8872	-3.5555
0.0347222	216.0325	-3.5646
0.0416667	157.2057	-3.5706
0.0486111	119.2652	-3.5676
0.0555556	94.4965	-3.5433
0.0625000	77.8772	-3.5585
0.0694444	65.5455	-3.5706
0.0763889	56.3539	-3.5494
0.0833333	49.1957	-3.5585
0.0902778	43.4346	-3.5555
0.0972222	38.9503	-3.5525
0.1041667	34.7030	-3.5494
0.1111111	31.0022	-3.5433
0.1180556	27.7674	-3.5191
0.1250000	24.9462	-3.5100
0.1319444	22.8053	-3.5009
0.1388889	20.2331	-3.4888
0.1458333	17.9165	-3.4888
0.1527778	16.0493	-3.4676
0.1597222	14.3594	-3.4646
0.1666667	12.9064	-3.4465



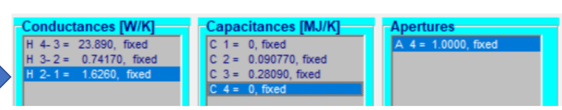
Save Model

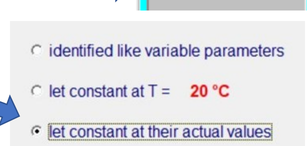
A final option is to run Error Propagation:



Using LORD for Simulation/Validation

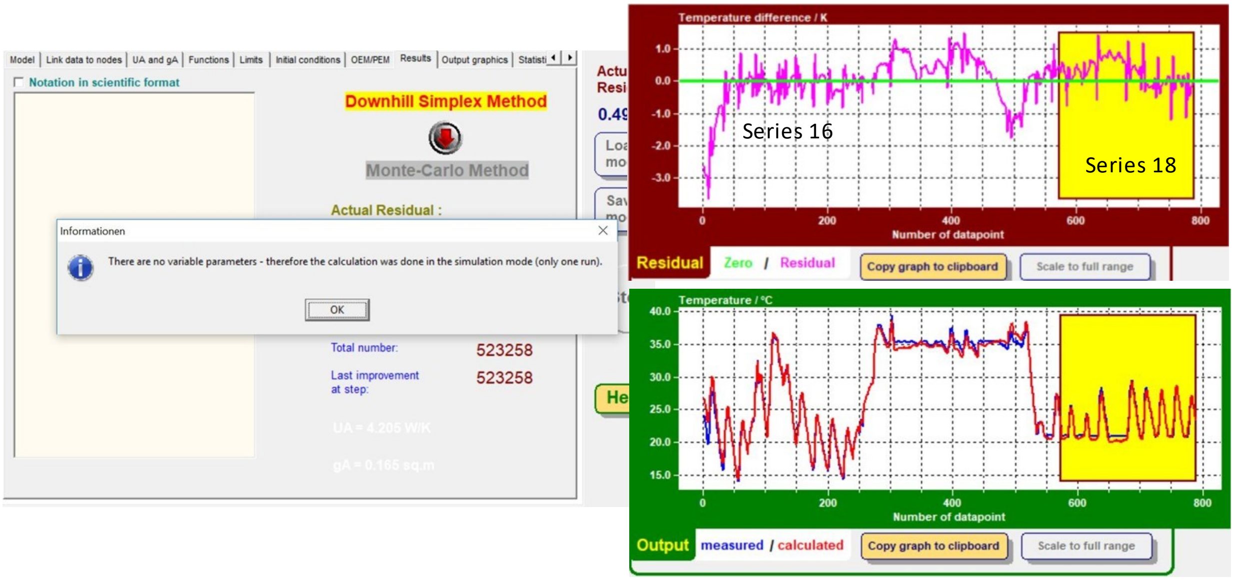
- Example: validate results from one part of a data series on another part – identify model on Series 16 and apply to Series 18.
- Run LORD for Series 16 only.
- Obtain results & save model.
- Fix all parameters.
- Set initial conditions.





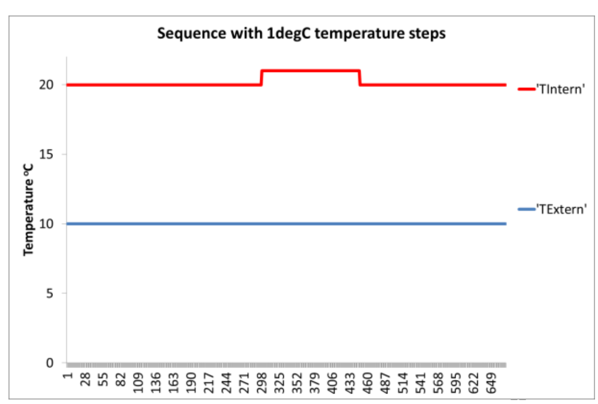
- Move window over Series 18.
- Run LORD.

Using LORD for Simulation/Validation



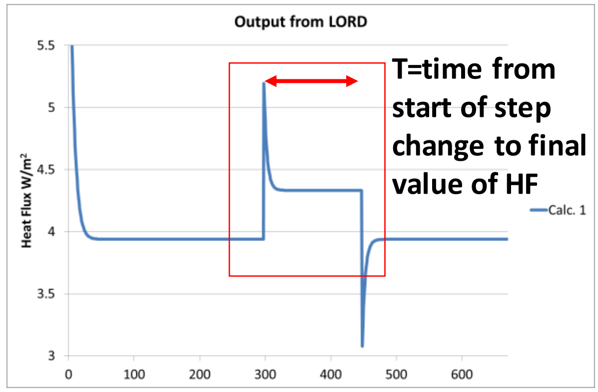
Simulation mode – time constants

- Run LORD with data set
- Save model when satisfied with results
- Create simulated data file:
  - ➢heat flux as original file (which is not used in next step using LORD in simulation mode)
  - ➢**with fixed external temperature**
  - ➢**fixed internal temperature with a 1degC step change....**



Simulation mode – time constants

- Open the simulated data file.
- Load the model used previously.
- Fix the parameters in the model.
- Fix the initial conditions.
- Set the output to Heat Flux.
- Run LORD
  - it will run in simulation mode.
- Open ***.res file in Excel
- Find period corresponding to step change..



Time Constants and Capacitance

T = 47 hours

Time constant = τ or 3τ

τ = 63.212% x T = 29.7 hours 3τ = 95% x T = 44.6 hours

The Resistance of the model =2.54 m^2K/W

Capacitance = Time Constant/R

For τ: Capacitance = **11.7** Wh/Km^2

For 3τ: Capacitance = **17.6** Wh/Km^2

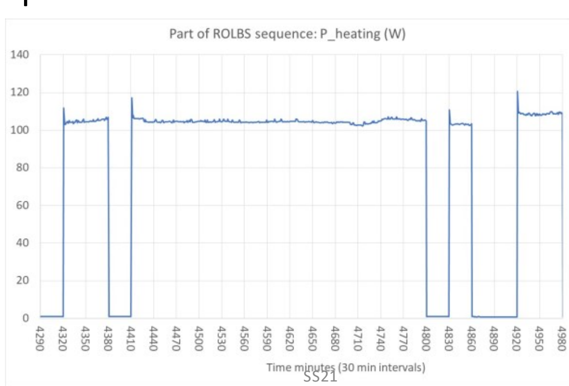
There are other methods of obtaining the capacitance

Application of LORD to Real Data

- Firstly the data must be processed for input in LORD
  - ❑Check integrity of data – plots!
    - ➢Missing data?
    - ➢Anomalies?
  - ❑What data interval to use? *Example of PSA Series 16-18 data follows.*
  - ❑Etc.

What is the optimum data interval in order *not* to loose dynamic information?

- Data are provided at 1 minute intervals (too much information – too long computation time?)
- The ROLBS sequence in Series 16 is based on 30 minute periods:



- Maximum interval to include all dynamic information is 30 minutes,
- Maybe better to use 10 minute averages.
- Check data to identify start of ROLBS:

A	B	AA	AY	AZ
		P_heating		P_heating
09/12/2013 01:21	4402	1.075042		
09/12/2013 01:22	4403	1.060033		
09/12/2013 01:23	4404	1.075042		
09/12/2013 01:24	4405	1.044998		
09/12/2013 01:25	4406	1.014981		
09/12/2013 01:26	4407	1.075042		
09/12/2013 01:27	4408	1.044998		
09/12/2013 01:28	4409	1.044998		
09/12/2013 01:29	4410	1.044998		
09/12/2013 01:30	**4411**	**117.2594**	09/12/2013 01:30	105.7771495
09/12/2013 01:31	4412	106.6699		
09/12/2013 01:32	4413	107.7513		
09/12/2013 01:33	4414	106.2493		
09/12/2013 01:34	4415	106.2343		
09/12/2013 01:35	4416	106.2343		
09/12/2013 01:36	4417	106.2493		
09/12/2013 01:37	4418	106.024		
09/12/2013 01:38	4419	106.039		

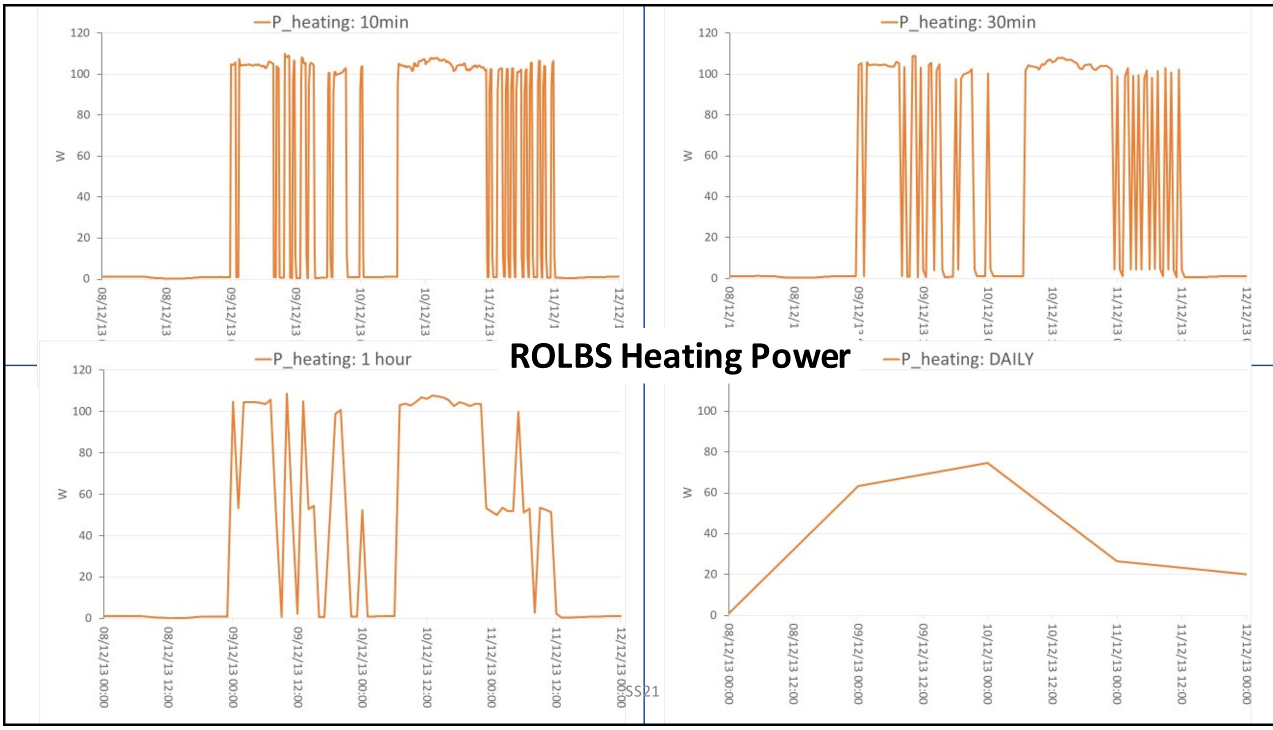
Inspect data: Sequence changes on the hour or half hour.

Therefore start averaging at the beginning of Series 16 at 6/12/13 00:00

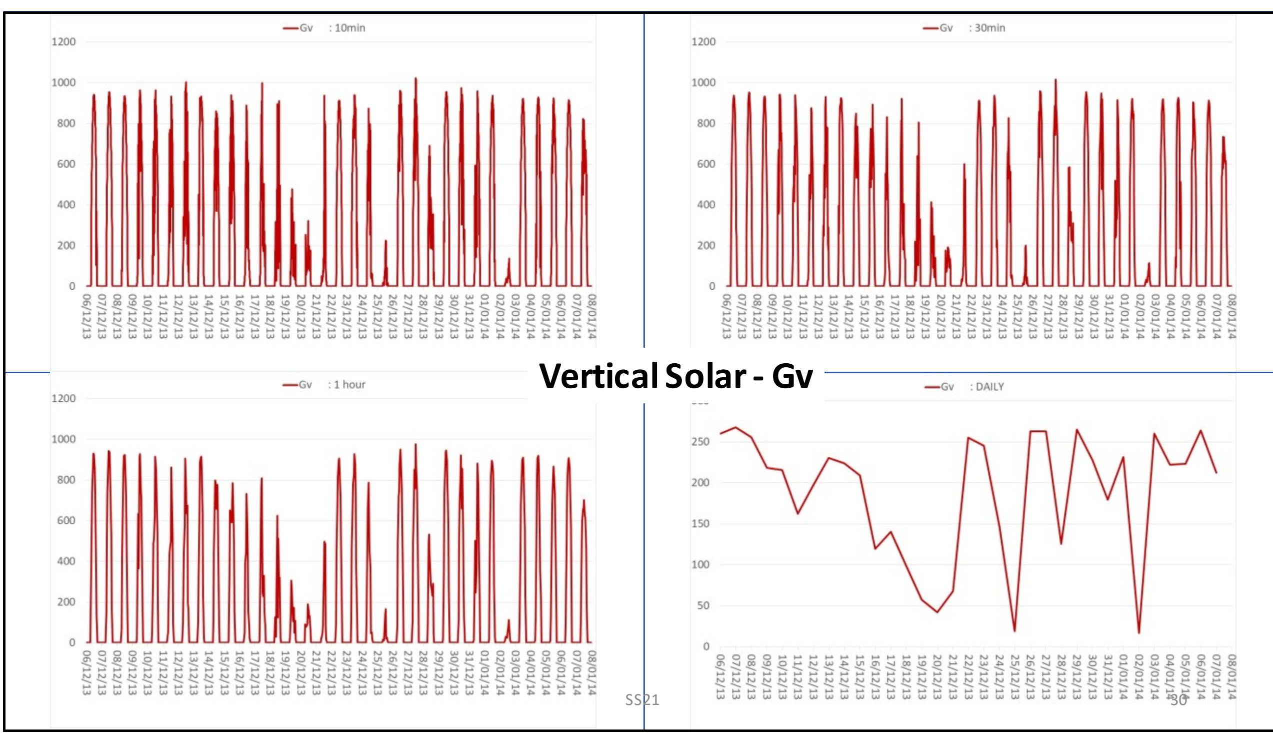
This captures all the dynamic information.

The following figures show the effect of different averaging periods….

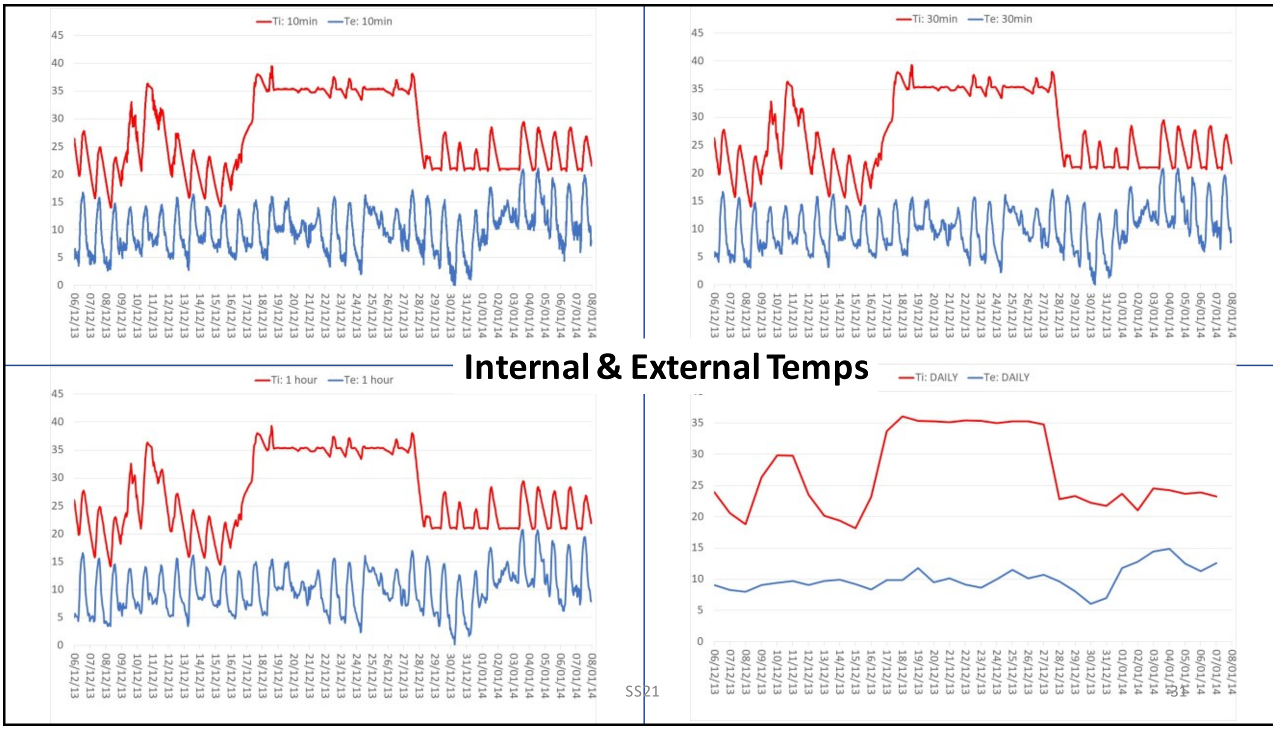
10 min	30 min
1 hour	24 hour


ROLBS Heating Power
P_heating: 10min
P_heating: 30min
P_heating: 1 hour
P_heating: DAILY
W
SS21

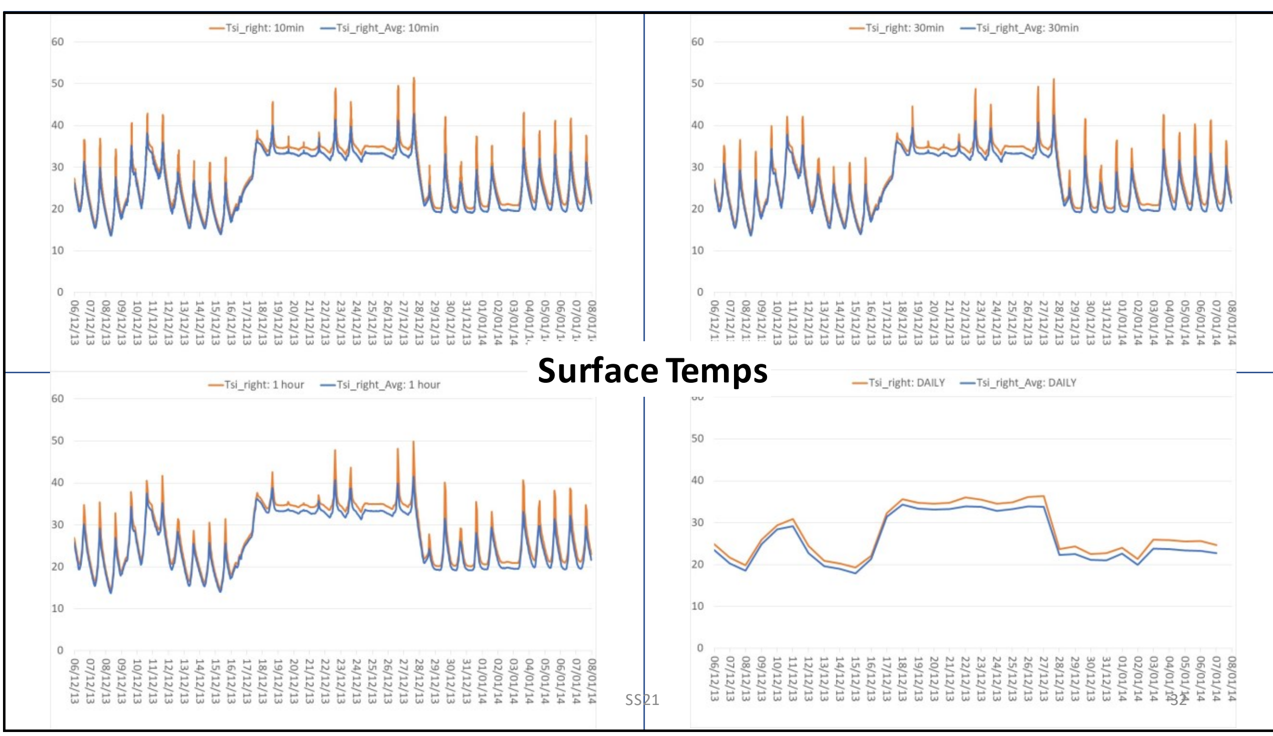
29


Vertical Solar - Gv
Gv : 10min
Gv : 30min
Gv : 1 hour
Gv : DAILY
SS21

30

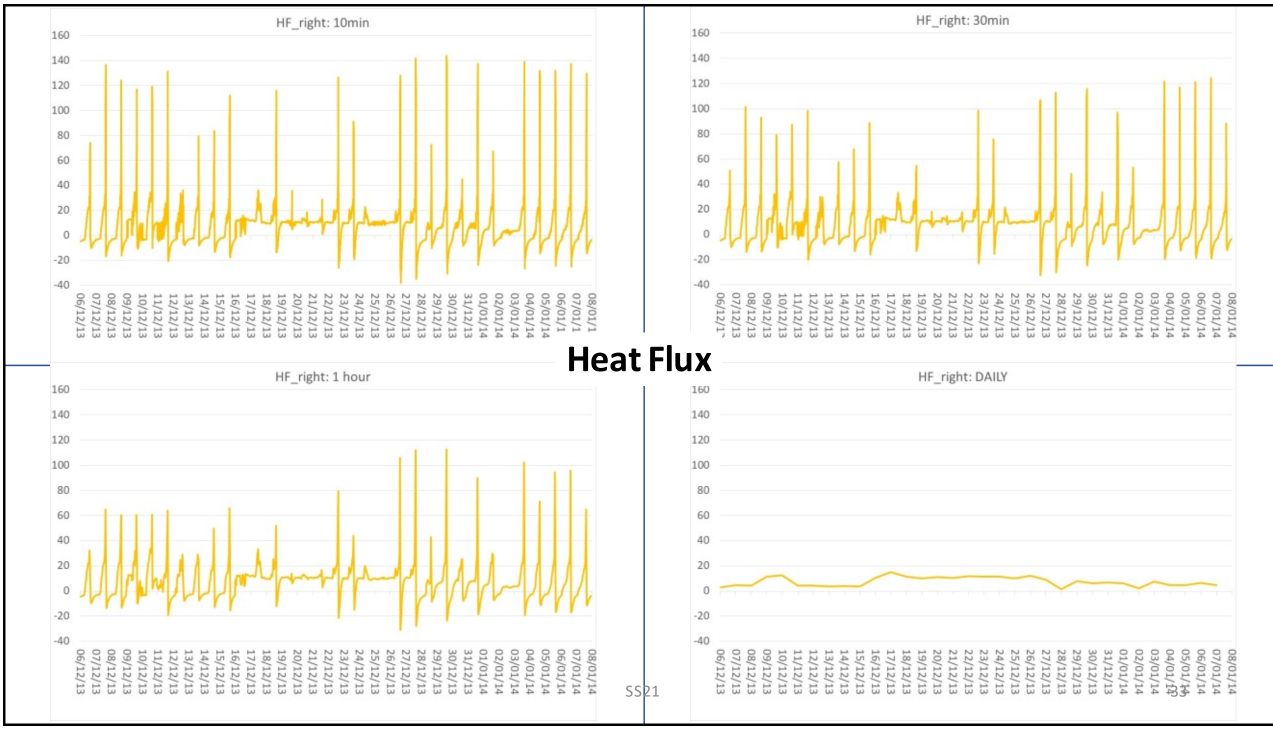

Internal & External Temps
Ti: 10min
Te: 10min
Ti: 30min
Te: 30min
Ti: 1 hour
Te: 1 hour
Ti: DAILY
Te: DAILY
SS21

31


Surface Temps
Tsi_right: 10min
Tsi_right_Avg: 10min
Tsi_right: 30min
Tsi_right_Avg: 30min
Tsi_right: 1 hour
Tsi_right_Avg: 1 hour
Tsi_right: DAILY
Tsi_right_Avg: DAILY
SS21

32

Heat Flux



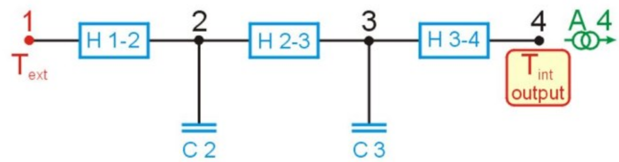
Applying LORD to Heat Flux Measurements from PSA data

- Firstly it is helpful to estimate results by *simple averaging* before running LORD on data.
- I've tried three approaches using the different temperatures available.......
- These give a good idea of the U-value result(s) you should be aiming for by identification.

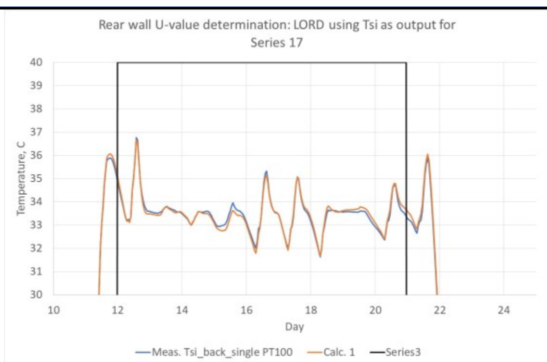
	U-value based on Tsi, Tse & HF				
	Left	*Back*	*Right*	*Ceiling*	*Floor*
ALL Data	0.44	0.46	0.41	0.45	0.53
Series 16	0.47	0.48	0.42	0.48	0.57
Series 17	0.45	0.45	0.42	0.45	0.48
Series 18	0.41	0.43	0.37	0.42	0.55
	U-value based on Ti, Te & HF				
	Left	*Back*	*Right*	*Ceiling*	*Floor*
ALL Data	0.46	0.45	0.44	0.52	0.55
Series 16	0.49	0.49	0.46	0.56	0.61
Series 17	0.45	0.44	0.44	0.49	0.47
Series 18	0.44	0.44	0.43	0.50	0.59
	U-value based on Tsi_Avg, Tse & HF				
	Left	*Back*	*Right*	*Ceiling*	*Floor*
ALL Data	0.47	0.46	0.44	0.48	0.60
Series 16	0.51	0.49	0.46	0.52	0.67
Series 17	0.46	0.45	0.45	0.49	0.52
Series 18	0.45	0.44	0.42	0.45	0.65

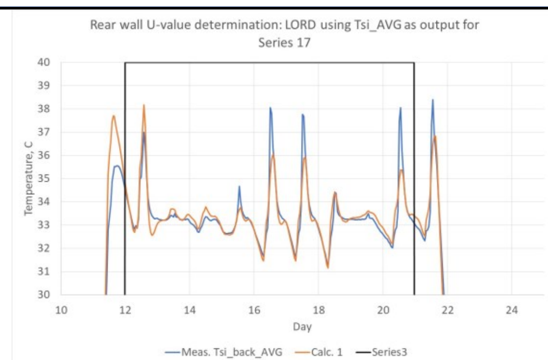
Using LORD

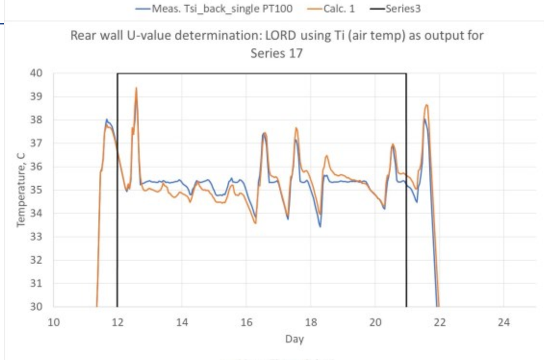
- The rear wall is used as an example.
- Use the basic 4 node model.



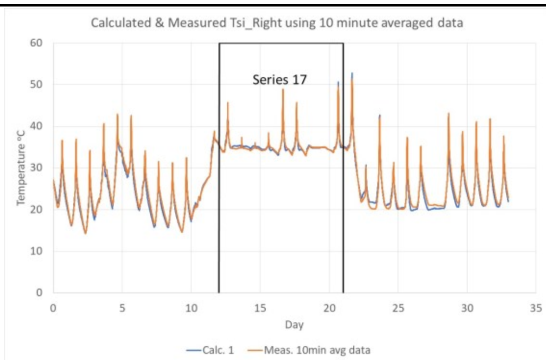
- I've used the external surface temperature Tse and the PT100 internal temperature Tsi because it is more local to heat flux sensor.
- I tried Tsi_Avg and Ti, however Tsi produced better results – lower residuals.

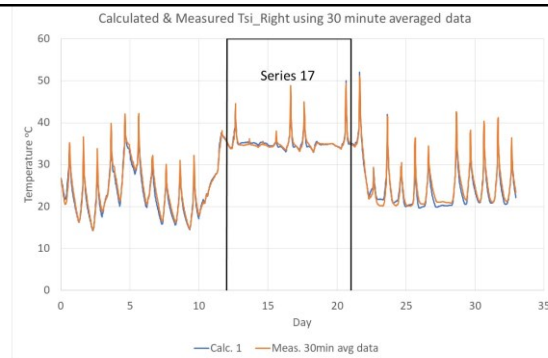


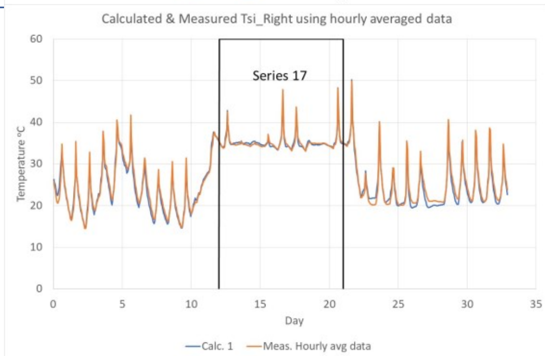




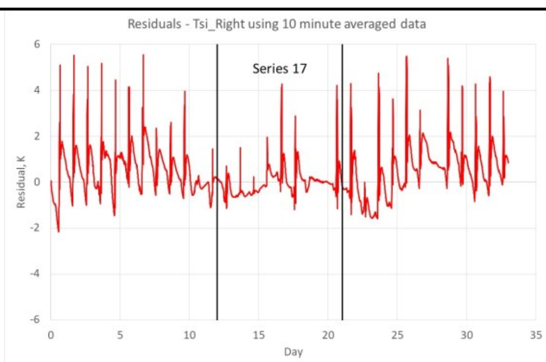
Tsi appears to give best fit

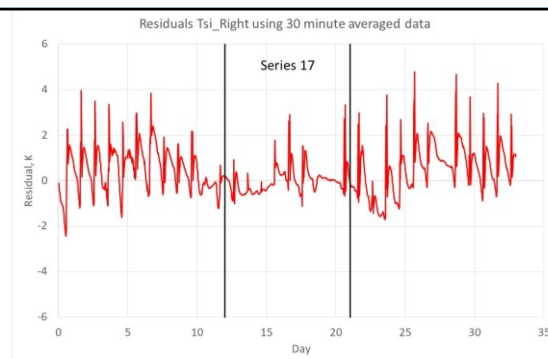


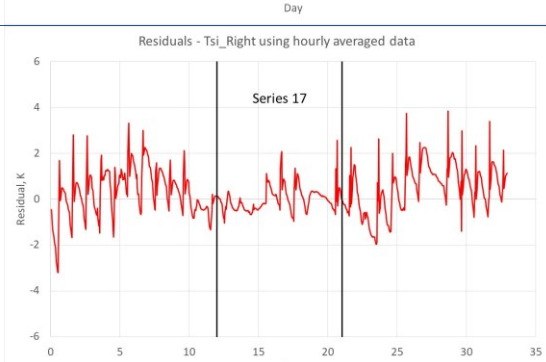




	Averaging Period	U-value, W/m^{2}K
LORD	10 min	0.42
LORD	30 min	0.42
LORD	Hourly	0.42
Averaging Method		0.42







- Using hourly average data improves residuals as smoothed out more extreme spikes – but maybe also need to improve model.
- For example: try using Heat Flux as output.

UA- & gA-values for whole test cell from Series 16-18 or 'Co-heating' test of a building

- For the heat flux measurements we can easily get an idea of the U-value by the *averaging method*, however this is not possible for UA- & gA-values.
- For steady state conditions, the electrical heat input to maintain a constant internal temperature within the test cell or building, will increase when the outside temperature falls and decrease when the solar radiation rises (in actuality these are always fluctuating, but dampened by the thermal inertia).
- However, neither the heat loss coefficient, nor the solar heat gain factor of the building envelope can be measured directly.

UA & gA

- But estimates can be made using the daily average data with ***Siviour Analysis*** for Series 16-18……

What is Siviour Analysis?

Daily averages (or longer) are produced.

$$P\_heating = UA \times \Delta T - gA \times Gv$$

Dividing by ΔT gives

$$\frac{P\_heating}{\Delta T} = \mathrm{UA} - \mathrm{gA} \times \frac{Gv}{\Delta T}$$

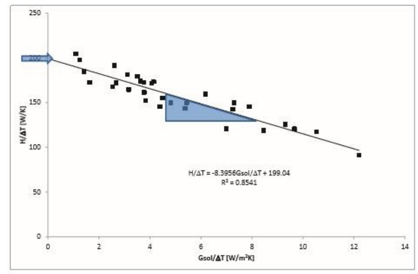
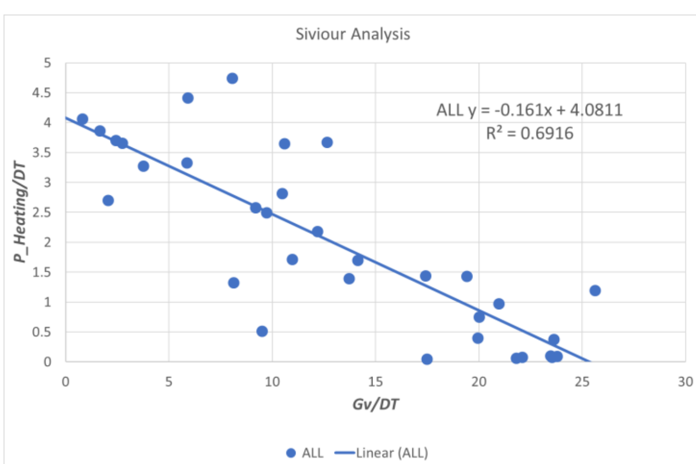


Figure A2: Example of X-Y plot of co-heating test data (Siviour analysis). The intercept of the linear regression line is the whole house heat loss coefficient and the slope is the solar gain factor

All data Series 16-18



Divide into 3 series

Series 17 gives the best fit:
UA= 4.06 W/K
gA= 0.145 m^2

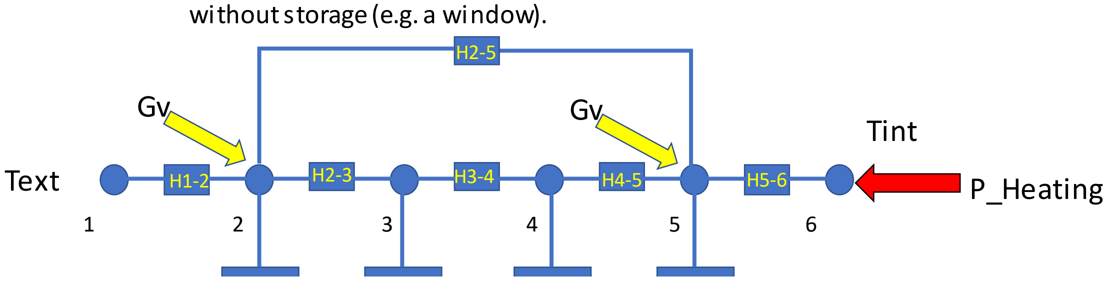
Best 'steady state' data series with high ΔT

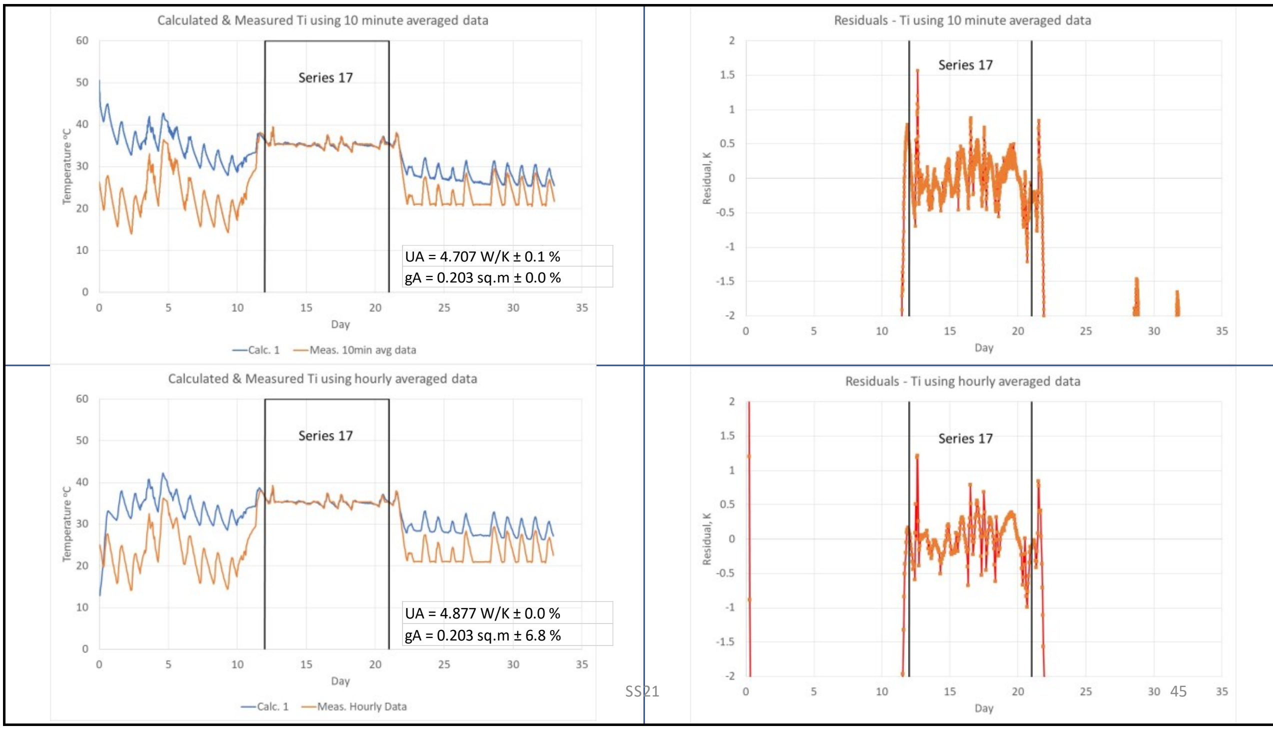
This suggest that the data series would *possibly* give good results for steady state parameters using LORD, etc.

'Whole Building' model

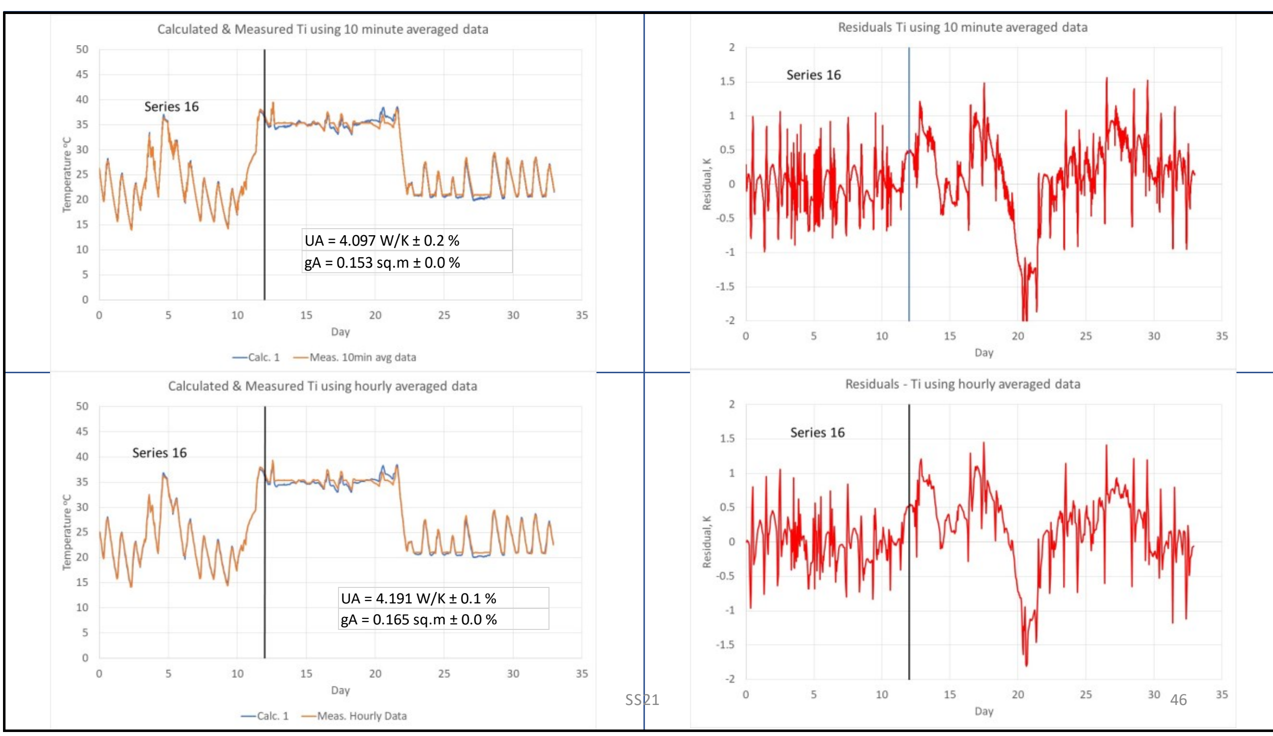
- Represent in LORD with six nodes (could be less!):

The additional parallel conductance H2-5 connected between node 2 and 5 allows for thermal conduction without storage (e.g. a window).




Calculated & Measured Ti using 10 minute averaged data
Series 17
Temperature °C
Day
UA = 4.707 W/K ± 0.1 %
gA = 0.203 sq.m ± 0.0 %
Calc. 1
Meas. 10min avg data
Residuals - Ti using 10 minute averaged data
Series 17
Residual, K
Day
Calculated & Measured Ti using hourly averaged data
Series 17
Temperature °C
Day
UA = 4.877 W/K ± 0.0 %
gA = 0.203 sq.m ± 6.8 %
Calc. 1
Meas. Hourly Data
SS21
Residuals - Ti using hourly averaged data
Series 17
Residual, K
Day
45

45


Calculated & Measured Ti using 10 minute averaged data
Series 16
Temperature °C
Day
UA = 4.097 W/K ± 0.2 %
gA = 0.153 sq.m ± 0.0 %
Calc. 1
Meas. 10min avg data
Residuals Ti using 10 minute averaged data
Series 16
Residual, K
Day
Calculated & Measured Ti using hourly averaged data
Series 16
Temperature °C
Day
UA = 4.191 W/K ± 0.1 %
gA = 0.165 sq.m ± 0.0 %
Calc. 1
Meas. Hourly Data
SS21
Residuals - Ti using hourly averaged data
Series 16
Residual, K
Day
46

46

Results

- Expected the more steady state Series 17 would give good results.
- However UA- & gA-values using Series 17 are high.
- Also the fit of the model to the rest of the data (Series 16 & 18) is poor.

- Series 16 gives better results and overall a better fit to *all* data.

- Do we use 10min or hourly data?
- Are there problems with high frequency data using LORD?
- Try different model?

Comments & Conclusions

- Important to understand the physical system, for example, the construction of the PSA test cell and sensor locations.
- Plot the data – check for integrity.
- Use simple averaging or Siviour analysis to estimate results prior to using identification techniques.
- Select suitable data averaging period, particularly for dynamic test sequences.
- Compare different parts of test sequences.
- Possible to estimate time constants using 'simulation' mode.

Useful Reference

- Baker P.H. and van Dijk H.A.L. PASLINK and dynamic outdoor testing of building components. Building and Environment Vol.43 pp143–151, 2008

Thank you Maria for your presentation

Thank you all for attending today's webinar

You can send further questions you might have, via email to

Hans Bloem at: hans.bloem@inive.org

The Webinar will now close.