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Building Integration of Solar Thermal Systems – TU1205 – BISTS

Modelling building integrated solar systems with MatLab: *methodology and examples*

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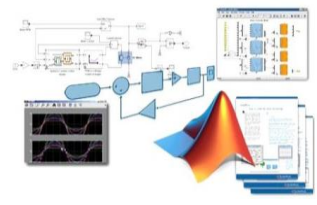
Content:

- **Development of simulation models for BISTS:**
  - **Motivation**
  - **Purposes**
- **Modelling approaches**
- **Examples**



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How to assess and predict the thermal behaviour of energy systems?

Experiment *Simulation*

A combination of experimental and the simulation results / findings are essential to determine the performance of complex energy systems.

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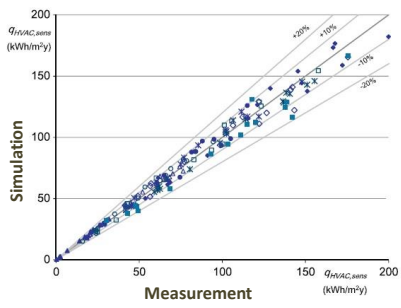
Simulations vs. Experiments



…to avoid unexpected and undesired performances or design failures…

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COST TU1205: *"Modelling and simulation of STS including optical and thermal modelling for different building integration scenarios and new models of the developed solutions."*

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"Moreover, a small number of studies has been reported in the field of thermal simulations of BI solar systems indicating that ***there is a need for energetic and thermal simulations particularly of active BIST systems that can provide space/water heating for the building****. In addition, few studies combine energetic with thermal simulation and majority of them refer to skin façades and thus, more studies about BIST and other BI solar systems are needed. Furthermore,* ***a small number of studies has been reported on the optical/thermal simulations*** *(for configurations such as solar collectors, louver shading devices, PV windows, heliostat field, etc.) signifying a gap in the literature in the area of optical models."*

Chr.Lamnatou, J.D.Mondol, D.Chemisana, C.Maurer, (2015) Modelling and Simulation of Building-integrated Solar Thermal Systems: Behaviour of The Coupled Building/System Configuration, Renewable and sustainable energy reviews, 48:178-191.

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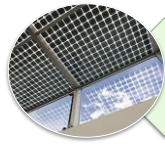
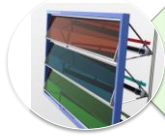
…developing a simulation tool:



…to study new building envelope technologies and innovative HVAC systems often supported by renewable energies and non-standard control strategies

…to evaluate design alternatives (e.g. new buildings design) and optimal retrofit measures of existing buildings



…to bridge the gap between the research products and their development and implementation into the built environment (e.g. BISTS)

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Models objectives

- Preliminary design of building design solutions
  - design, performance evaluation
- Energy performance of innovative building envelope solutions
  - simulation, prediction, etc.
- Tuning and development of control strategies
  - control system design
- Energy and comfort analyses
  - prognostics, diagnostics, etc.
- Better understanding of a particular phenomenon, or a combination of phenomena
- Improve knowledge of building physics and systems
- etc.

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Model definition

A set of mathematical equations (e.g., algebraic or differential) that describes the **input-output behavior** of a system.

…a mathematical model of a real world system is derived by using a combination of *physical laws* and/or *experimental* means…

***Physical laws** are used to determine the model structure (linear or nonlinear) and order.*

***Experimental data** are used to estimate and/or validate the parameters of the model.*

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PTC Mathca

python SOFTWARE FOUNDATION

OpenModelica

OCTAVE

…simulation model based on generic programming environments offer a viable solution for modelling novel building integrated technologies/phenomena and testing new alternative control methodologies…

Azzedine Yahiaoui. *A distributed dynamic simulation mechanism for building automation and control systems*. Eindhoven University Press, the Netherlands. 2013 ISBN: 978-90-386-3445-6.

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Model classification

- ***linear vs. non-linear***
- ***static vs. dynamic***
- ***deterministic vs. probabilistic***
- ***discrete vs. continuous***
- ***white box, black box and grey box***

… it depends!

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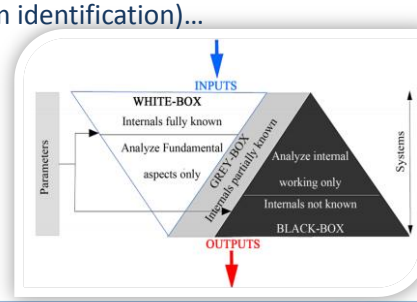
… ***white-box*** models describe all the phenomena and predict system performance efficiently and effectively. Building-plant knowledge (physical laws) is required…

…***black-box*** models can be adopted without any detailed information about the building-plant system knowledge, but measures or observations are required to relate inputs to outputs (e.g. artificial intelligence / statistical models / system identification)…

… ***grey-box*** models are appropriate in case of both observations and physical meanings…



Amara, F., Agbossou, K., Cardenas, A., Dubé, Y. and Kelouwani, S. (2015) Comparison and Simulation of Building Thermal Models for Effective Energy Management. *Smart Grid and Renewable Energy*, **6**, 95-112.

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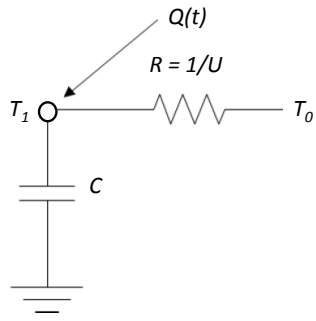
Thermal networks (Resistance Capacitance (*RC*)) are usually adopted for modelling thermal systems. It is based on the assumption of one dimensional modelling of the occurring thermal phenomena.



$$\frac{dT_1}{dt} = \frac{1}{C}\left(Q(t) + U\left(T_o - T_1\right)\right)$$

$$\frac{T_1^{i+1} - T_1^i}{\Delta t} = \frac{1}{C}\left(Q(t_i) + U\left(T_o - T_1^i\right)\right)$$

$$T_1^{i+1} = \frac{\Delta t}{C}\left(Q(t_i) + U\left(T_o - T_1^i\right)\right) + T_1^i$$

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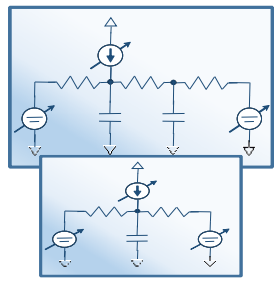
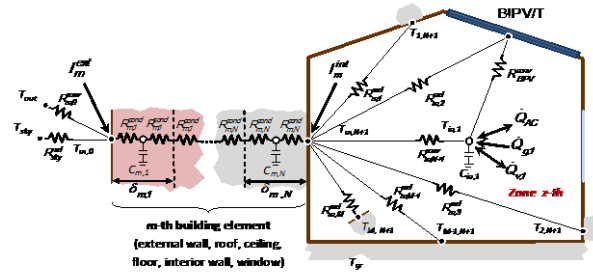
The higher the number of nodes, the higher the order of the system… and its complexity too!

Grey box



White-box



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…writing a model…

1. *Define the system, its components…*
2. *Define the level of detail, the inputs and outputs…*
3. *Formulate the mathematical model and assumptions…*
4. *Write the set of equations describing the model….*
5. *Solve the equations for the desired output variables….*

…examine the results and the assumptions….
if necessary: redesign the system!

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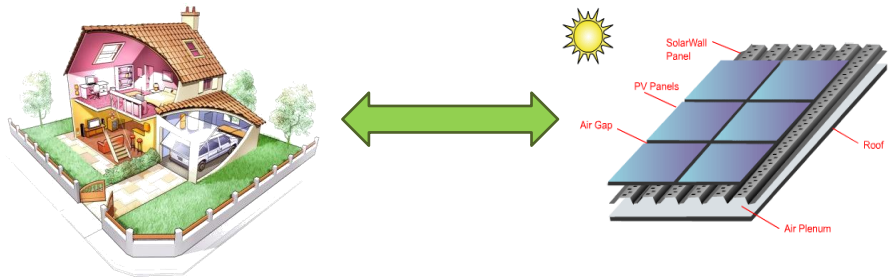
Modelling a **BISTS:** to assess the relationship between the building and the system, including both the passive and active effects due to the integration of the solar system on the building energy performance…



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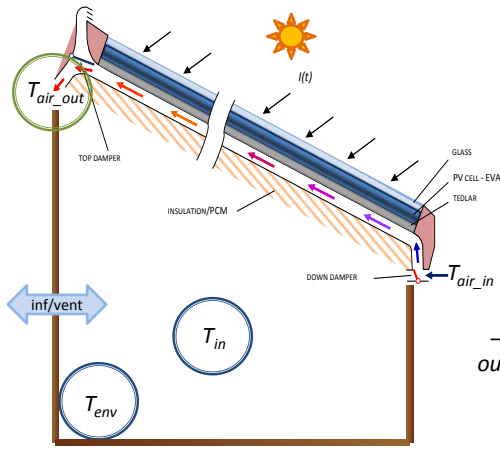
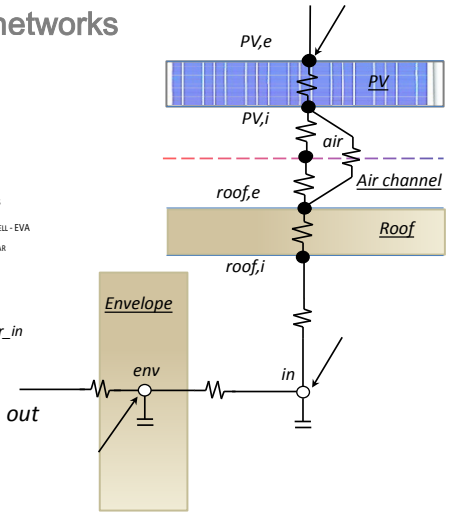
Reduced order thermal networks





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Model variables…

Indoor air temperature, lumped envelope temperature, PV - air channel - roof temperatures ⟶ $x = \left[T_{pv,e} \quad T_{pv,i} \quad T_{roof,e} \quad T_{roof,i} \quad T_{air}\right]$

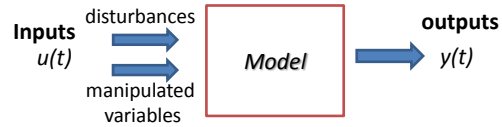
Inputs…

Uncontrolled: internal gains (people, lights) and weather conditions ⟶ $u = \left[T_{out} \quad P_{el} \quad G \quad T_{in}\right]$

Controlled: HVAC power

Outputs…

Model temperatures



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Assumptions…

- Heat transfer is one-dimensional
- Indoor air is fully mixed (temperature is uniform)
- Indoor air is lumped in a single node , T_{in} and C_{in}
- The building envelope is lumped in a single node, T_{env} and C_{env}
- Homogeneous, isotropic and time-invariant thermo-physical properties (density, specific heat and conductivity) are taken into account
- A linear system is modelled (linearized phenomena)

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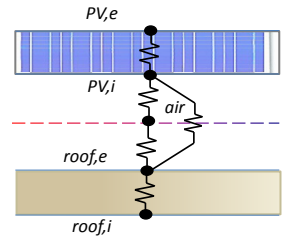
Non-capacitive nodes:

$T_{roof,e}$, $T_{roof,i}$, $T_{pv,e}$, $T_{pv,i}$ and T_{air}



…static

$$U_o\left(T_{pv,e}-T_o\right)+U_{pv}\left(T_{pv,e}-T_{pv,i}\right)+P_{el}=\alpha_{pv}\cdot G\cdot A_{pv} \quad \text{PV node ext}$$

$$U_{pv}\left(T_{pv,i}-T_{pv,e}\right)+U_{h1}\left(T_{pv,i}-T_{air}\right)=U_{rad}\left(T_{roof,e}-T_{pv,i}\right) \quad \text{PV node int}$$

$$U_{rad}\left(T_{roof,e}-T_{pv,i}\right)+U_{h2}\left(T_{roof,e}-T_{air}\right)=U_{roof}\left(T_{roof,i}-T_{roof,e}\right) \quad \text{Roof node ext}$$

$$U_{roof}\left(T_{roof,i}-T_{roof,e}\right)=U_{in}\left(T_{in}-T_{roof,i}\right) \quad \text{Roof node int}$$

$$T_{air\_out}=\exp\left[-\frac{(h_1+h_2)\cdot D\cdot L}{\dot{m}_{air}\cdot c_{p,air}}\right]T_{air\_in}+\left[1-\exp\left(-\frac{(h_1+h_2)\cdot D\cdot L}{\dot{m}_{air}\cdot c_{p,air}}\right)\right]\frac{h_1T_{pv,i}+h_2T_{roof,e}}{h_1+h_2} \quad \text{Tair node}$$

S. Pantic, L. Candanedo, A.K. Athienitis, (2010) **Modeling of energy performance of a house with three configurations of building-integrated photovoltaic/thermal systems**, Energy and Buildings 42, 1779–1789

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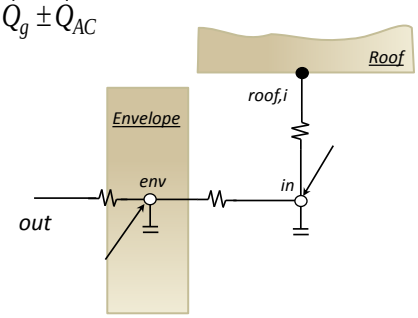
Capacitive nodes:

T_{in} and T_{env}

$$C_{in}\frac{dT_{in}}{dt}=\frac{T_{env}-T_{in}}{R_{int}^{eq}}+\frac{T_{out}-T_{in}}{R_v}+\frac{T_{roof,i}-T_{in}}{R_{roof}}+\dot{Q}_g\pm\dot{Q}_{AC}$$

$$C_{env}\frac{dT_{env}}{dt}=\frac{T_{out}-T_{env}}{R_{ext}^{eq}}+\frac{T_{in}-T_{env}}{R_{int}^{eq}}+\dot{Q}_{rad}$$



…dynamic

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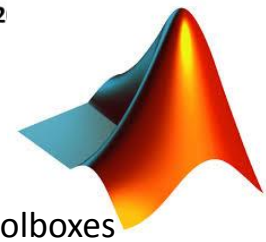
Matlab



- MatLab stands for *Matrix Laboratory*
- Matlab includes many functions and toolboxes to help in various applications (*Math, Statistics, and Optimization, Control Systems, Image Processing and Computer Vision, etc.)*
- It allows you to easily solve different technical computing problems, particularly those with matrix and vector formulas

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Desktop Tools and Development Environment

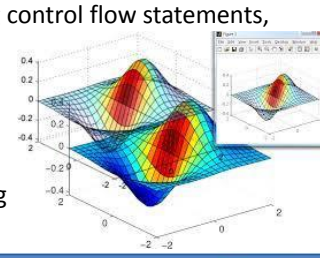
Includes the desktop and command window, an editor, a code analyzer, a workspace, files, and other tools, browsers for viewing help

Mathematical Function Library

Numerous algorithms (e.g. elementary functions and complex arithmetic, matrix inverse, matrix eigenvalues and fast Fourier transforms, etc.)

Language

It is a high-level matrix-array language, including control flow statements, functions, data structures, input/output, and object-oriented programming features



Graphics

MatLab has extensive facilities for displaying vectors and matrices as graphs, as well as editing and printing these graphs.

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Matrix form:

$$A \cdot x + B \cdot u = 0$$

$$\text{Matrix\_A} = \begin{bmatrix} 0 & \frac{-U_{pv}}{U_o + U_{pv}} & 0 & 0 & 0 \\ \frac{-U_{pv}}{U_{pv}+U_{h1}+U_{rad}} & 0 & \frac{-U_{rad}}{U_{pv}+U_{h1}+U_{rad}} & \frac{-U_{rad}}{U_{pv}+U_{h1}+U_{rad}} & \frac{-U_{h1}}{U_{pv}+U_{h1}+U_{rad}} \\ 0 & \frac{-U_{rad}}{U_{rad}+U_{h2}+U_{roof}} & 0 & \frac{-U_{roof}}{U_{rad}+U_{h2}+U_{roof}} & \frac{-U_{h2}}{U_{rad}+U_{h2}+U_{roof}} \\ 0 & 0 & \frac{-U_{roof}}{U_{roof}+U_{in}} & 0 & \frac{-U_{in}}{U_{roof}+U_{in}} \\ 0 & -K\frac{h_1}{h_1+h_2} & -K\frac{h_2}{h_1+h_2} & 0 & 0 \end{bmatrix}$$

…static

$$\text{with} \quad K = \left[1 - \exp\left(-\frac{(h_1+h_2) D \cdot L}{\dot{m}_{air} \cdot c_{p,air}}\right)\right]$$

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Matrix form:

$$A \cdot x + B \cdot u = 0$$

$$\text{Matrix\_B} = \begin{bmatrix} \frac{-U_o}{U_o + U_{pv}} & \frac{1}{U_o + U_{pv}} & \frac{-\alpha_{pv} \cdot A_{pv}}{U_o + U_{pv}} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-U_{in}}{U_{roof} + U_{in}} \\ -\exp\left[-\frac{(h_1 + h_2) \cdot D \cdot L}{\dot{m}_{air} \cdot c_{p,air}}\right] & 0 & 0 & 0 \end{bmatrix}$$

$$x = inv(A) \cdot B \cdot u = \begin{bmatrix} T_{pv,e} & T_{pv,i} & T_{roof,e} & T_{roof,i} & T_{air} \end{bmatrix} \qquad u = \begin{bmatrix} T_{out} & P_{el} & G & T_{in} \end{bmatrix}$$

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How MatLab solves dynamic equations…

There exist different numerical methods for solving ODEs…

The form of the generic function for numerical integration is:

y = *solver*(odefun, [t0 tf], y0...)

- odefun: *function name…*
- y0: *vector of initial conditions…*
- (t0,tf): *a period of time over which the solution is to be (iteratively) obtained…*
- y: *solution vector (for each step)…*

…at each step the solver applies a particular algorithm to the results of previous steps…
…at the first step, the initial condition, y0, provides the necessary information that allows the integration to proceed…

…dynamic

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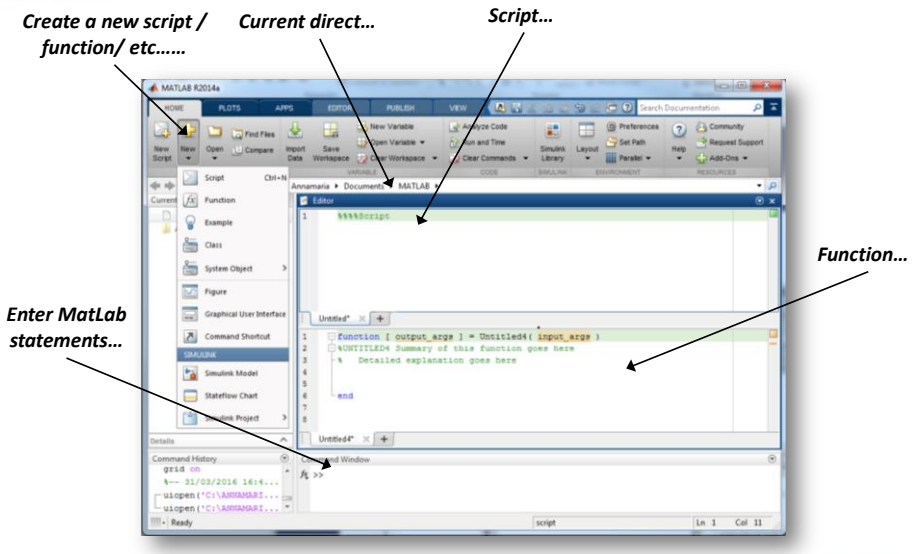

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…our **odefun**

```
Matrix_A = zeros(5,5);
Matrix_A(1,2) = - Upv / (Uo+Upv);                          %% Tpv_i
Matrix_A(2,1) = - Upv / (Upv+Uh1+Urad);                    %% Tpv_e
Matrix_A(2,3) = - Urad / (Upv+Uh1+Urad);                   %% Troof_e
Matrix_A(2,4) = - Urad / (Upv+Uh1+Urad);                   %% Troof_i
Matrix_A(2,5) = - Uh1 / (Upv+Uh1+Urad);                    %% Tair
Matrix_A(3,2) = - Urad / (Urad+Uh2+Uroof);                 %% Tpv_i
Matrix_A(3,4) = - Uroof / (Urad+Uh2+Uroof);                %% Troof_i
Matrix_A(3,5) = - Uh2 / (Urad+Uh2+Uroof);                  %% Tair
Matrix_A(4,3) = - Uroof / (Uroof+Uin);                     %% Troof_e
Matrix_A(4,5) = - Uin / (Uroof+Uin);                       %% Tin
Matrix_A(5,2) = - (1-exp(-((h1+h2)*D*L)/(mdot_air*cp_air))) * h1/(h1+h2);   %% Tpv_i
Matrix_A(5,3) = - (1-exp(-((h1+h2)*D*L)/(mdot_air*cp_air))) * h2/(h1+h2);   %% Troof_e

u_T= [Tout, Pel, G, Tin];
Matrix_B = zeros(5,length(u_T));
Matrix_B(1,1) = - Uo / (Uo+Upv);                            %Tout
Matrix_B(1,2) = +1 / (Uo+Upv);                              %Pel
Matrix_B(1,3) = - abs_pv*A_pv / (Uo+Upv);                   %G
Matrix_B(4,4) = - Uin / (Uroof+Uin);                        %Tin
Matrix_B(5,1) = - exp(-((h1+h2)*D*L)/(mdot_air*cp_air));    %Tout = Tair_in

%%% Matrix_A.*x_T + Matrix_B.*u_T = 0   /   %%% x_T= [Tpv_e, Tpv_i, Troof_e, Troof_i, Tair];
x_T = inv(Matrix_A)*(-Matrix_B)*u_T';
```

```
A=eye(2);
equation(1) = ((Tout - Tenv)/Req_ext + (Tin - Tenv)/Req_int + hr_op*A*(Tsky_WS-Tenv) + A*(abs_op*G_av)) / Cenv;  %Tenv
equation(2) = ((Tenv - Tin)/Req_int + (Tout - Tin)/Req_v + (Troof_i - Tin)/Rroof + Qgain + Qac) / Cinv;          %Tin
B=equation';
dydt=A\B;
```

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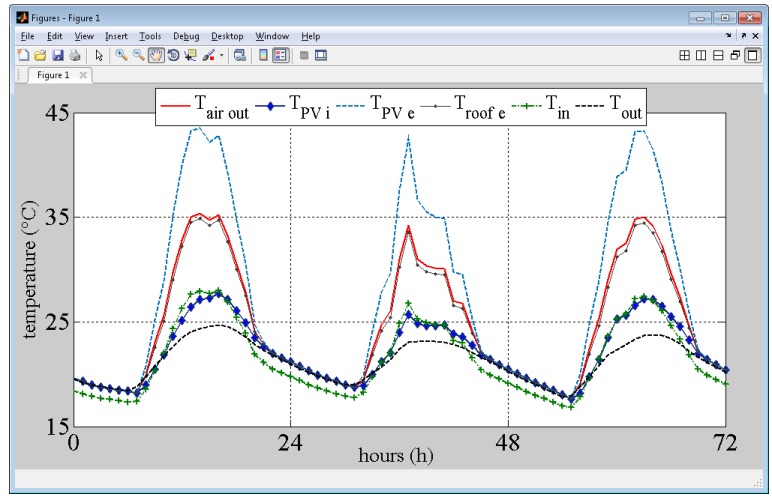
graphical results…



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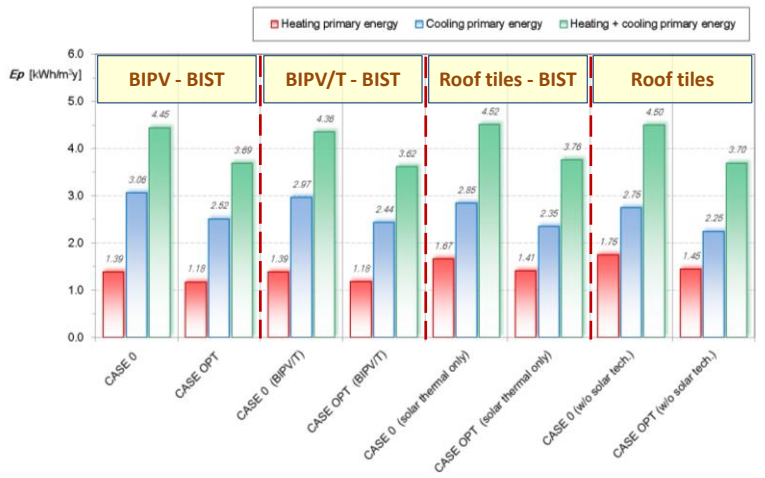

…assess the primary energy demand as a function of the integrated solar technologies…

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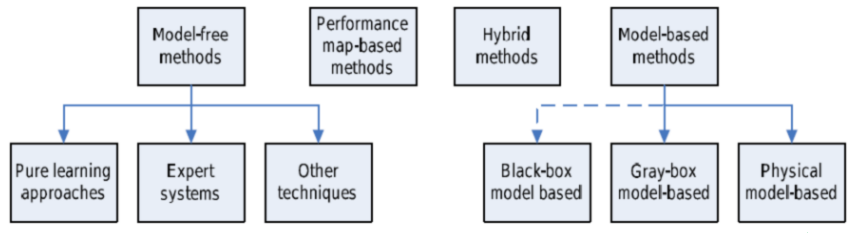
… as a function of the specific question and objective, different models can be derived…



…increasing level of modelling detail

Adapted from Wang and Ma (2008)

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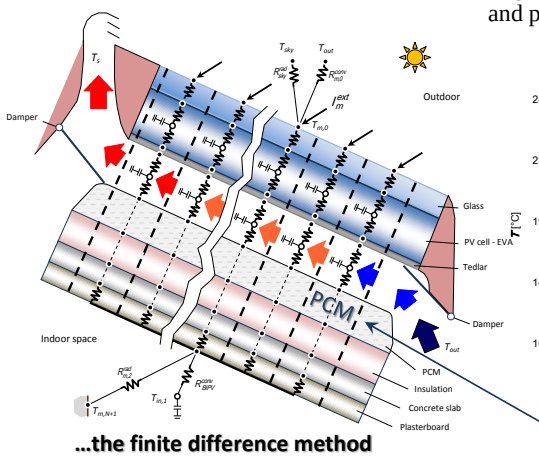
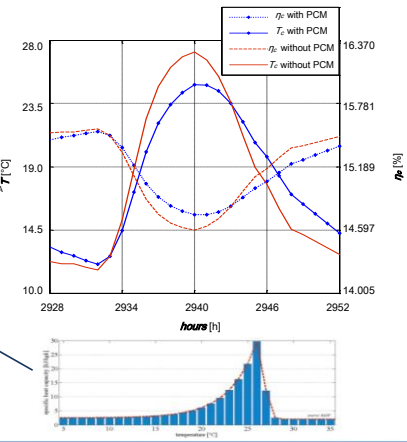
Examples: BIPV - BIPVT – PCM



…the finite difference method together with thermal network…

…to effectively take into account their **integration** in the **building envelope** (active and passive effects) and to perform **whole building level simulations**…



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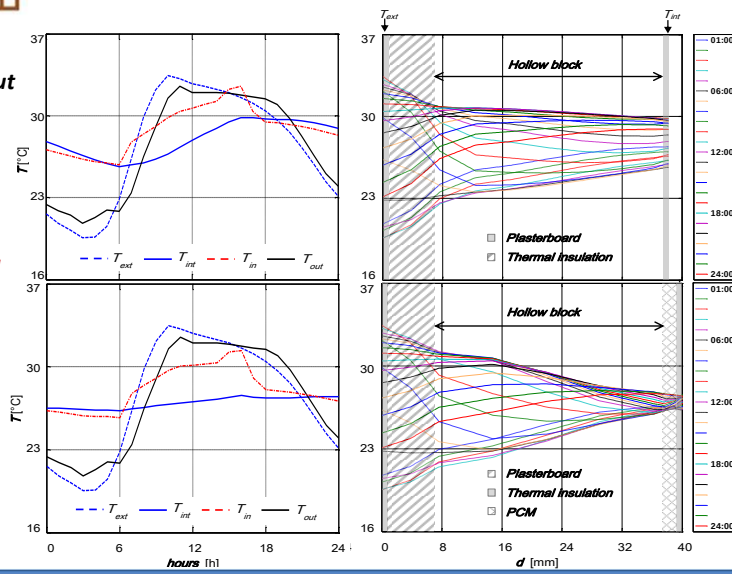
…without PCM

east wall June 13th

…with PCM



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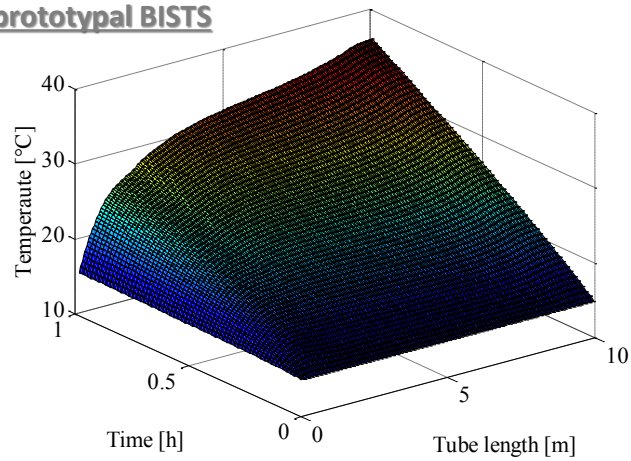
Examples: prototypal BISTS



…evolution of the outlet water temperature v.s. time and length of the absorber tube (serpentine of N nodes) of a prototypal solar collector…

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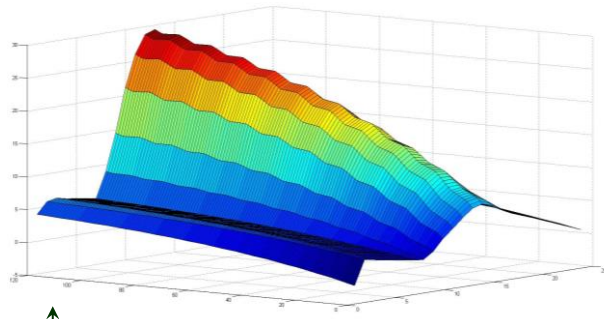
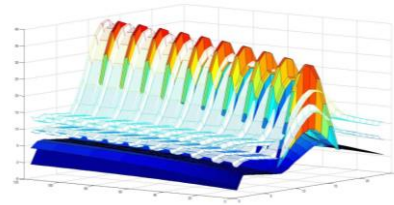


Examples: double façade with photovoltaic and movable shading devices

…temperature of the air flowing through the channel vs. time and nodes (N nodes for each floor)…

…temperature of the nodes of the building elements comprising the building-façade system… →



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Summary…

Importance of modelling - programming environments (e.g. MatLab) - is discussed

How to write a mathematical models (static and/or dynamic) of a BIPVT system in MatLab is presented

The model can be suitably used to also carry out optimization and control analyses

Thank you…

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