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Building and HVAC system simulation with the help of an engineering equation solver

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- Building energy simulation tool for Audit
- Modelling Bases
- Validation of the building model
- Implementation in an equation solver and application
- Conclusion

Motivation for this presentation

- Energy simulation useful from **HVAC system design → audit and retrofit actions**

  → Simulation tools available according to the available information

  → Tools required to be simple, transparent and easy-to-update

  → **How Equation Solvers can help us to do the job ?**

  (EES, © F-Chart Software)

- Focus on a building energy simulation tool developed for benchmarking and audit

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Building energy Simulation for Audit ?

- **Benchmarking**

  Statistics and arbitrary normalization **not always adapted** for benchmarking due to **large diversity of the building stock**

  → Building energy simulation software

  → **“reference” performance**

- **Pre – audit**

  Available **global data** (energy bills) **insufficient** to analyze the performance of the installation

  → **Calibrated** building energy simulation software

  → **dis-aggregation** of energy consumption

- **Detailed Audit**

  Evaluation of Energy Conservation Opportunities

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Modelling Bases

- Hourly simulations

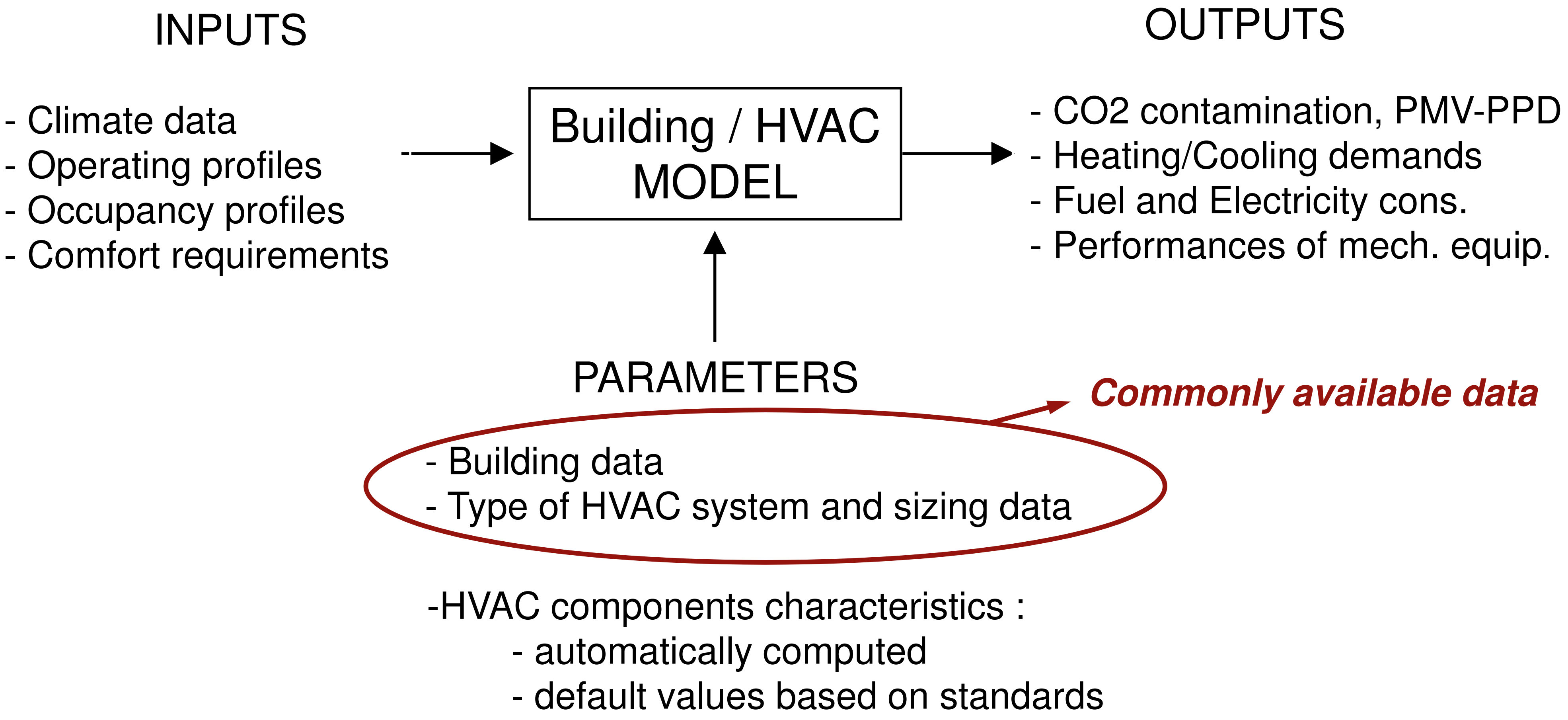
- Simplified models with limited quantity of parameters according to the available information

- Two main parts :

  - **1 Dynamic Building model** adjusted with geometrical data, walls characteristics, orientations,…

  - **1 Static HVAC system model** including Air Handling Unit, Terminal Units, Distribution networks and Heat/Cool production systems

Inputs / Outputs / Parameters



INPUTS

- Climate data
- Operating profiles
- Occupancy profiles
- Comfort requirements

Building / HVAC
MODEL

OUTPUTS

- CO2 contamination, PMV-PPD
- Heating/Cooling demands
- Fuel and Electricity cons.
- Performances of mech. equip.

PARAMETERS

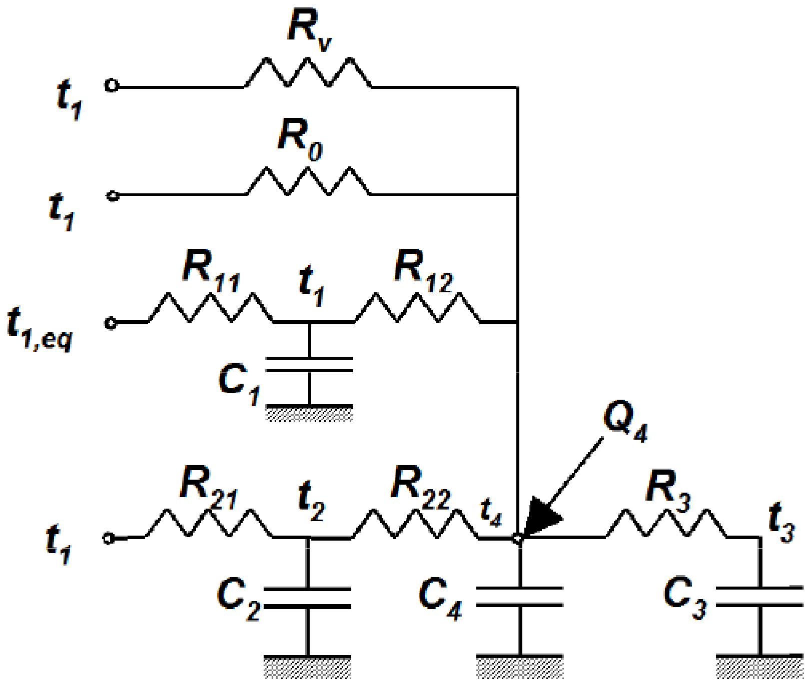
- Building data
- Type of HVAC system and sizing data

Commonly available data

-HVAC components characteristics :
    - automatically computed
    - default values based on standards

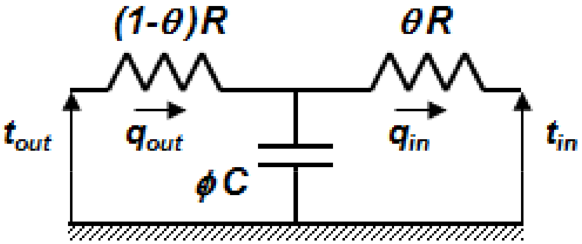
Building zone model

- Lumped RC model developed by Laret (1981)
  - Only 2R1C branches to keep limited quantity of parameters
  - Equation solver well adapted to solve differential equations
- Influences
  - Envelope dynamic behavior
  - Structure dynamic behavior
  - Solar gains
  - Long-wave radiation losses
  - Ventilation and Infiltration
  - Internal gains

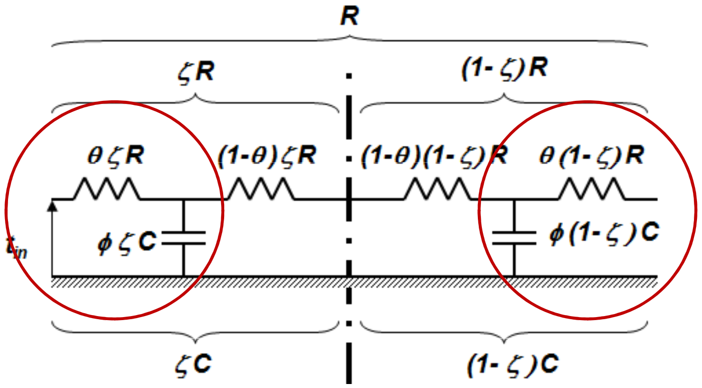


Tuning of the building zone model

- Two types of boundary conditions
  - **Isothermal** (external walls, in contact with outdoor “cold” zones) : 2R1C



  - **Adiabatic** (internal walls, between similar zones) : 3R2C



Null heat flow plane

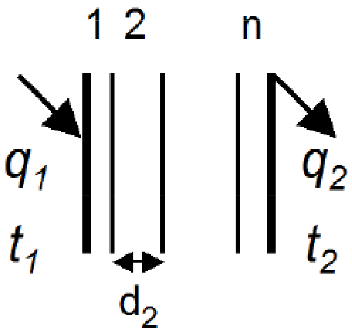
Null heat flow plane :

$$f_d = \prod_{i=1}^{n} \exp\left(-d_i \cdot \sqrt{\frac{\omega}{2\alpha_i}}\right) \rightarrow \zeta$$

→ Walls parameters to compute : R, C, θ, φ and ζ

Wall parameters calculation

- Frequency characteristic analysis for a 24h period sinusoidal solicitation
- Temperature and heat flow variations (complex quantities) are correlated by :



$$\begin{pmatrix}\tilde{t}_1\\ \tilde{q}_1\end{pmatrix} = \begin{pmatrix}A_1 & B_1\\ C_1 & D_1\end{pmatrix}\begin{pmatrix}A_2 & B_2\\ C_2 & D_2\end{pmatrix}\cdots\begin{pmatrix}A_n & B_n\\ C_n & D_n\end{pmatrix}\begin{pmatrix}\tilde{t}_2\\ \tilde{q}_2\end{pmatrix}$$

Complex quantities (function of the material characteristics)

- Wall reverse transfer matrix Q :

$$\begin{pmatrix}\tilde{t}_1\\ \tilde{q}_1\end{pmatrix} = \begin{pmatrix}Q_{11} & Q_{12}\\ Q_{21} & Q_{22}\end{pmatrix}\begin{pmatrix}\tilde{t}_2\\ \tilde{q}_2\end{pmatrix}$$

Wall parameters calculation

- **Isothermal conditions** : modulus of admittance */A_v/* and transmittance */K_v/* are imposed to the 2R1C model

$$\left|\tilde{A}_v\right| = -\left|\frac{Q_{11}}{Q_{12}}\right| \qquad \left|\tilde{K}_v\right| = \left|\frac{1}{Q_{12}}\right|$$

$$\longrightarrow \quad \theta = \sqrt{\frac{U^2 - \left|\tilde{K}_v\right|^2}{\left|\tilde{A}_v\right|^2 - \left|\tilde{K}_v\right|^2}} \qquad \phi = \frac{1}{(1-\theta)\omega RC}\sqrt{\frac{\left|\tilde{A}_v\right|^2}{\left|\tilde{K}_v\right|^2} - 1}$$

- **Adiabatic conditions** : modulus and phase lag of admittance are imposed to the 2R1C model

$$\tilde{A}_v = -\frac{Q_{21}}{Q_{22}} \longrightarrow \theta = \frac{\left|\Re\left(\tilde{A}_v\right)\right|}{R.\left|\tilde{A}_v\right|^2} \qquad \phi = \frac{\left|\tilde{A}_v\right|^2}{\omega.C.\left|\Im\left(\tilde{A}_v\right)\right|}$$

- Each wall described by : $\boxed{R=1/U}$, in W/m^2K, $\boxed{C}$ in J/m^2K, $\boxed{\theta}$ and $\boxed{\phi}$

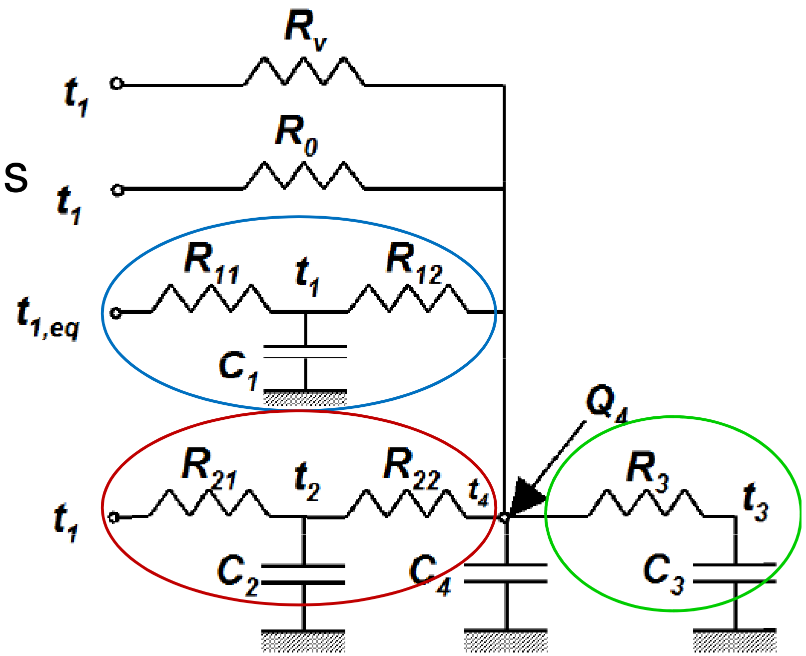
Building zone parameters calculation

- RC network aggregation : Walls admittances and transmittances multiplied by wall areas and summed for each wall category

→ 3 admittance matrixes = 3 branches for each building zone:

  - roof slabs
  - external walls
  - internal walls : floor slabs, partition walls

→ Light and simplified RC network model with limited quantity of parameters



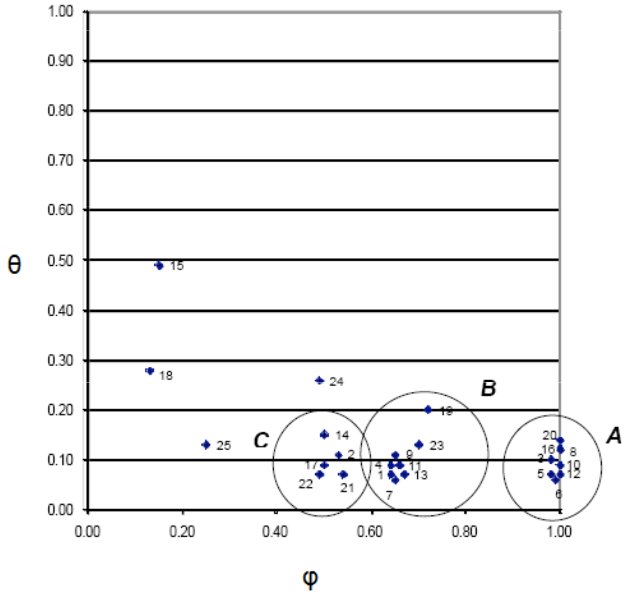
Building zone parameters calculation

- Adjustment parameters θ and φ stay in a limited range for frequent walls compositions

  → walls library with standard values available for the user

  → Definition of walls categories characterized by similar values of the parameters θ, φ and ζ

A : massive wall, strongly ventilated air layer or outdoor insulation
B : massive insulated walls
C : massive wooden structure



Standard values can be used without important loss of accuracy but simplifies greatly the parametrization work for the user (Masy’s PhD thesis)

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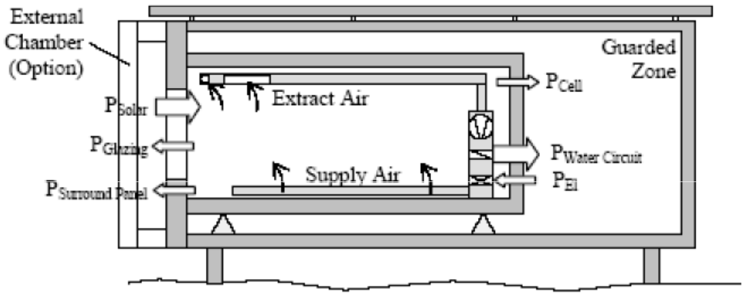
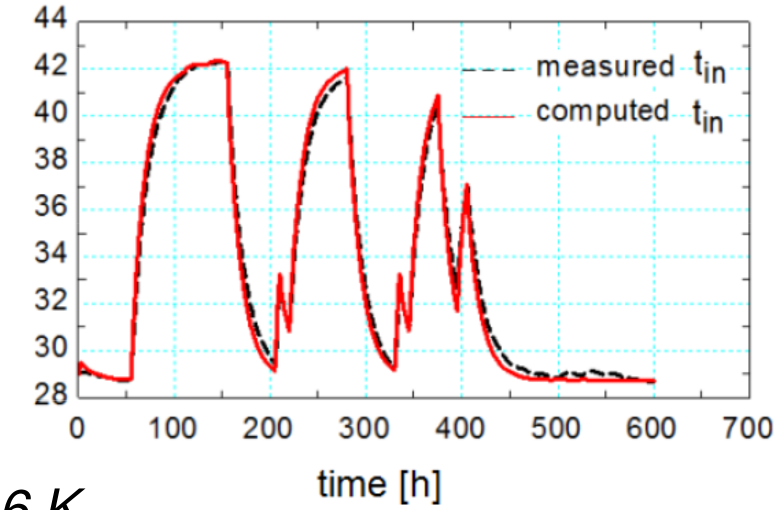
Building model Validation

- Empirical validation (IEA ECBCS Annex 43)
  - *Measured heating power is imposed to the model*
  - *Measured and computed indoor temperature are compared*



(EMPA test cell)



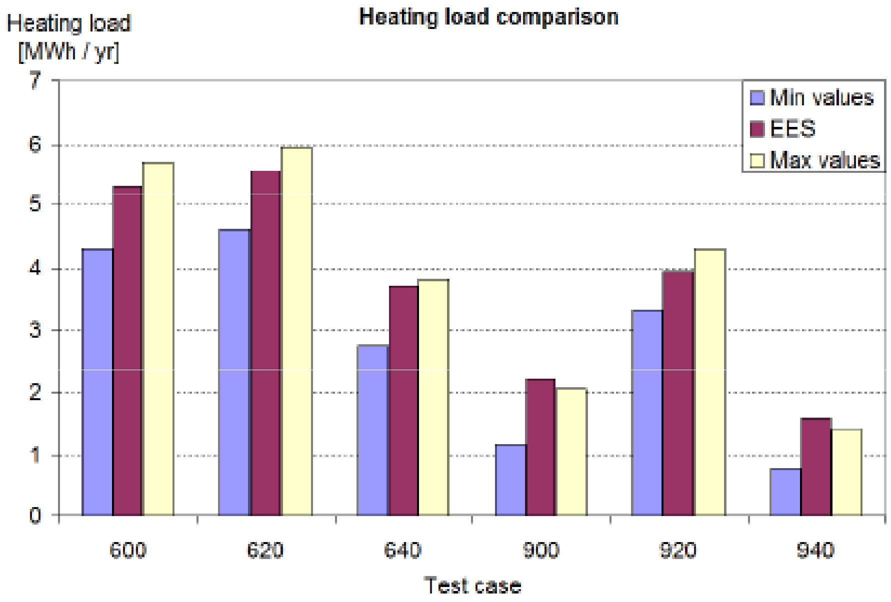
Error RMS : 0.46 K

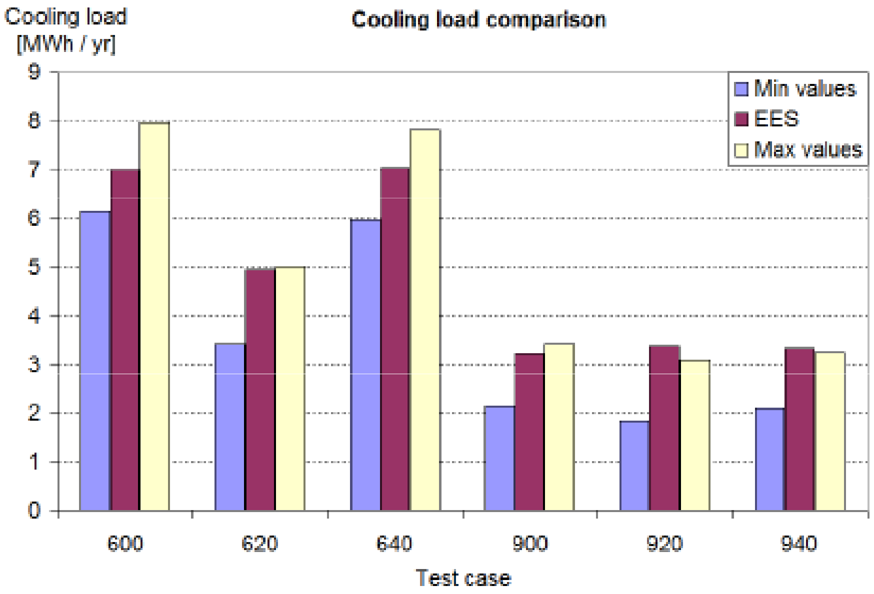
- Analytical validation (response factors convolution process) (Masy, 2008)

Max Error RMS : 0.6 K

Building model Validation

- Comparative validation (IEA BESTEST)

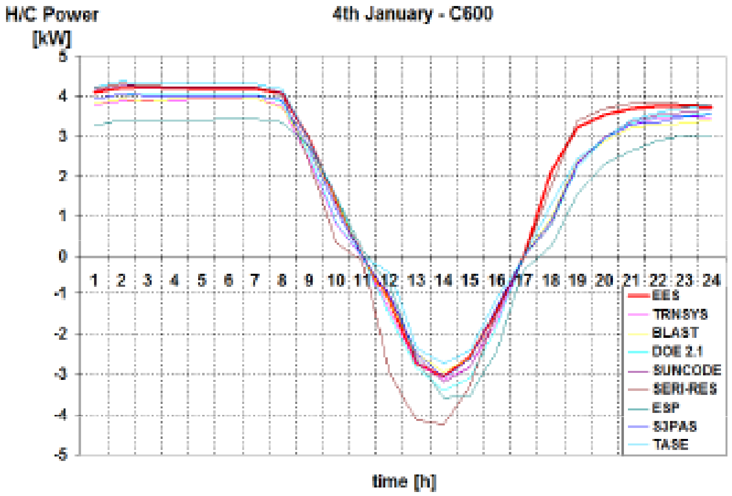




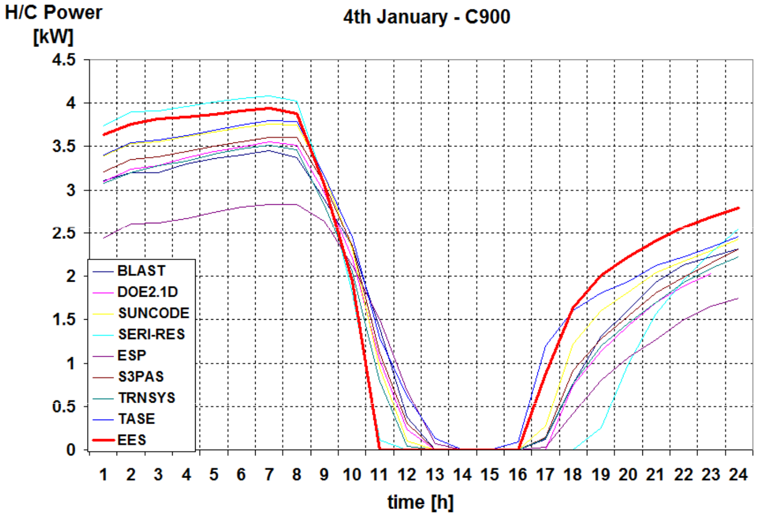
Good results for lightweight cases
Discrepancies for heavyweight cases

Building model Validation

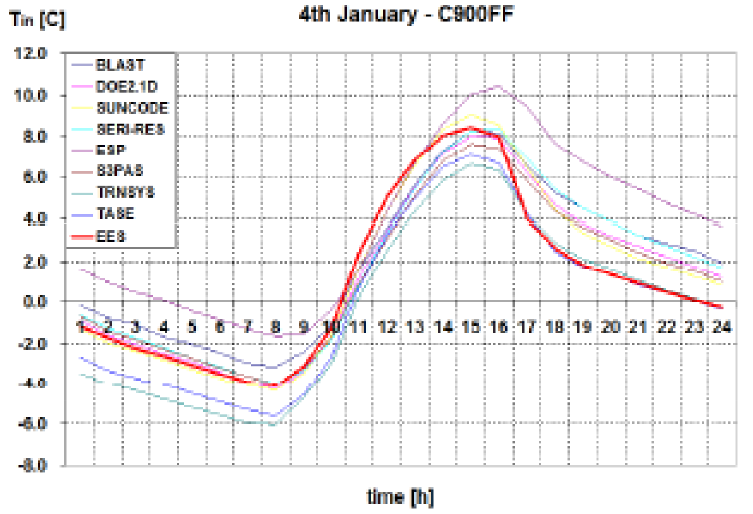
- Comparative validation (IEA BESTEST)



(lightweight)



(heavyweight)



(heavyweight, floating temp.)

Building model Validation

- Simplified dynamic building model
    - Empirical validation : good
    - Analytical validation : good (see Masy, 2008)
    - Comparative validation : quite good

- Discrepancies :
    - Due to low order of the RC network (problems with heavy outdoor insulated walls)
    - Due to imperfect control (proportional only) of the H/C system

→ Sufficient accuracy to be implemented in a simplified building/HVAC simulation tool

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Implementation in an equation solver

- Wall model : 1st order differential equation

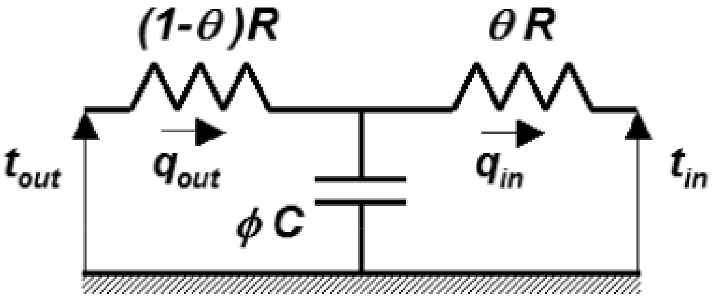
$$\frac{dU}{d\tau_{wall}} = \dot{Q}_{in} + \dot{Q}_{out}$$

$$\dot{Q}_{out} = \frac{t_{out} - t_{wall}}{(1-\theta)\,R}$$

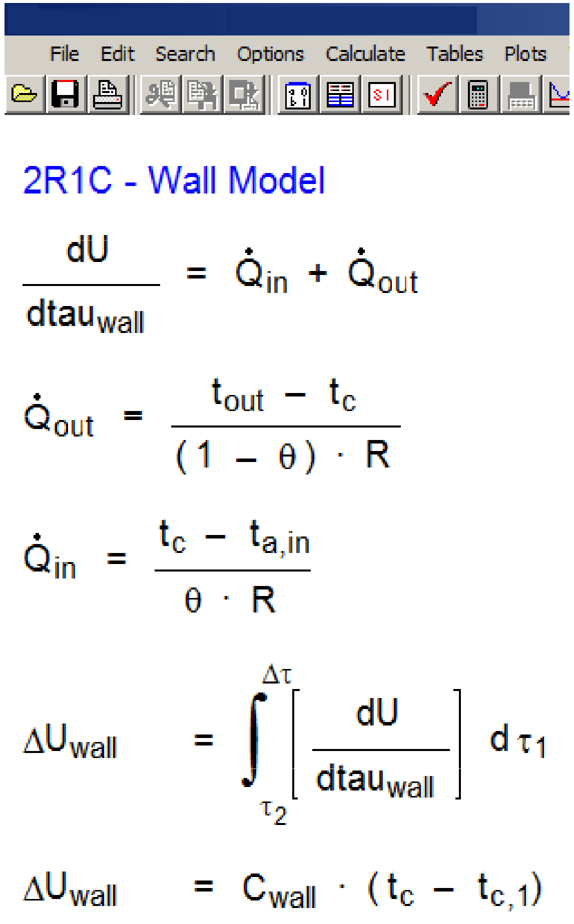
$$\dot{Q}_{in} = \frac{t_{wall} - t_{in}}{\theta\,R}$$

$$\Delta U_{wall} = \int_{\tau 1}^{\tau 2} \frac{dU}{d\tau_{wall}}\, d\tau$$

$$\Delta U_{wall} = C\left(t_{c,wall} - t_{c,wall,1}\right)$$



Implementation



2R1C - Wall Model

$$\frac{dU}{dtau_{wall}} = \dot{Q}_{in} + \dot{Q}_{out}$$

$$\dot{Q}_{out} = \frac{t_{out} - t_c}{(1-\theta)\cdot R}$$

$$\dot{Q}_{in} = \frac{t_c - t_{a,in}}{\theta \cdot R}$$

$$\Delta U_{wall} = \int_{\tau_2}^{\Delta\tau} \left[\frac{dU}{dtau_{wall}}\right] d\,\tau_1$$

$$\Delta U_{wall} = C_{wall}\cdot(t_c - t_{c,1})$$

Building Zone Model

- Sensible Heat Balance → combined convective-radiative Temp. : $T_{a,in,zone}$

Transmission trough walls *Ventilation and Infiltration* *Internal Gains*

$$\frac{dU}{d\tau}_{in} = \dot{Q}_{roof,surf,in} + \dot{Q}_{floor,surf,in} + \dot{Q}_{opaque,frontages,surf,in} + \dot{Q}_{windows} + \dot{H}_{s,vent} + \dot{H}_{s,\inf} + \dot{Q}_{s,in}$$

- CO2 Mass Balance → CO2 contamination : $X_{CO2,in,zone}$

infiltration/exfiltration

$$\frac{dM}{d\tau}_{CO2,in} = \dot{M}_{CO2,vent} + \dot{M}_{CO2,\inf} + \dot{M}_{CO2,in}$$

ventilation *internal production*

- Water Mass Balance → Indoor humidity ratio: $W_{in,zone}$

infiltration/exfiltration

$$\frac{dM}{d\tau}_{w,in} = \dot{M}_{w,vent} + \dot{M}_{w,\inf} + \dot{M}_{w,in}$$

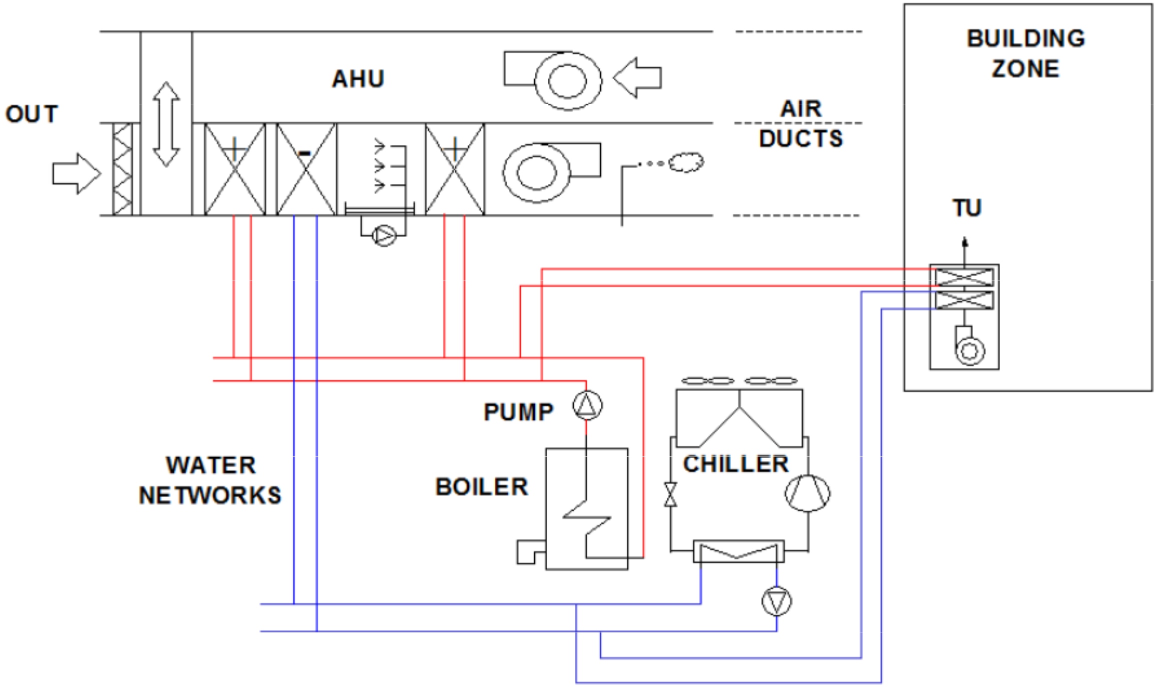
ventilation *internal production*

HVAC System Model

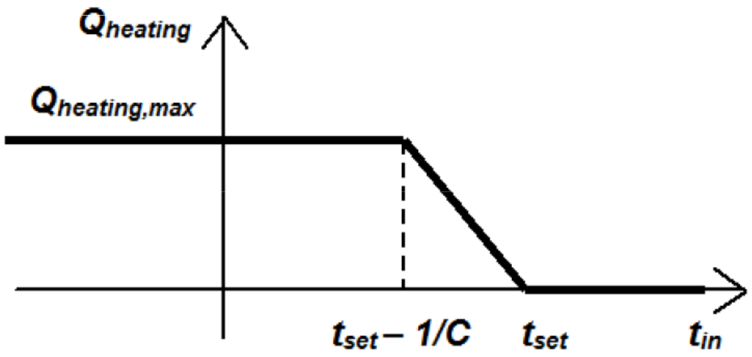
- Dynamic mono-zone building model ←→ complete steady-state HVAC system model:
    - Air Handling Unit
    - Heating/Cooling Terminal Units
    - Air and Water distribution networks
    - Plant
- HVAC Components aggregated into “global” components
- HVAC components simplified models derived from reference models (ASHRAE HVAC toolkits 1 and 2)

(See other papers for details about the HVAC system model)

HVAC System Model



(proportional control)



$$X_{control} = MIN\left(1, MAX\left(0, C_{control} * \left(t_{sepoint} - t\right)\right)\right)$$

Implementation in an Equation Solver

- Full transparency of the model :

  Software, User guide and model description are included : 3 in 1

- Easy continuous improvement and development of the software (adding of new HVAC components, …)

- Well adapted to create and use simplified models using limited quantity of parameters and to solve differential equations

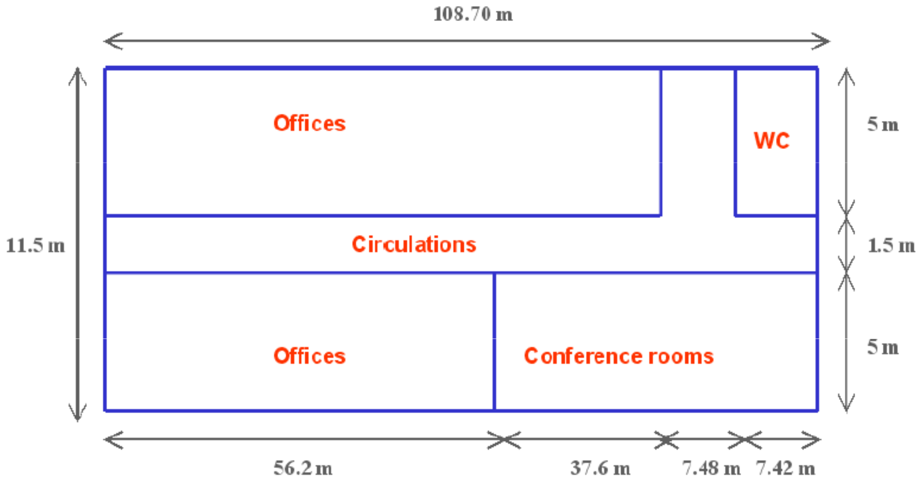
- Longer computation time than other softwares

  (about 20 minutes for a 8760 hours simulation of a building and its HVAC system)

- Convergence problems may be encountered when using too strict control laws

Commercial Building Auditing Tool

- Application to a fictitious building, representative of the french building stock (IEA ECBCS Annex 48)
  - 15000 m^2 (12 storeys)
  - CAV system + FCU
  - offices and meeting rooms
- Comparison between simplified monozone tool (EES) and detailed multi zone tool (TRNSYS)



	Heating kWh/m^2	Cooling kWh/m^2
EES – mono-zone	53.7	32.8
TRNSYS - multi-zone	50.5	29.3
Relative Error - %	6.3 %	12 %

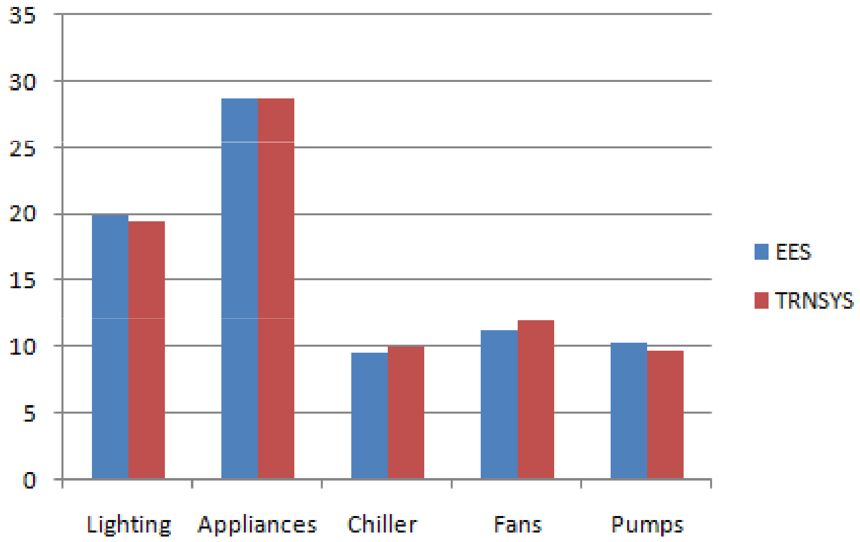
(Sensible building demands; ideal local heating/cooling system)

Commercial Building Auditing Tool

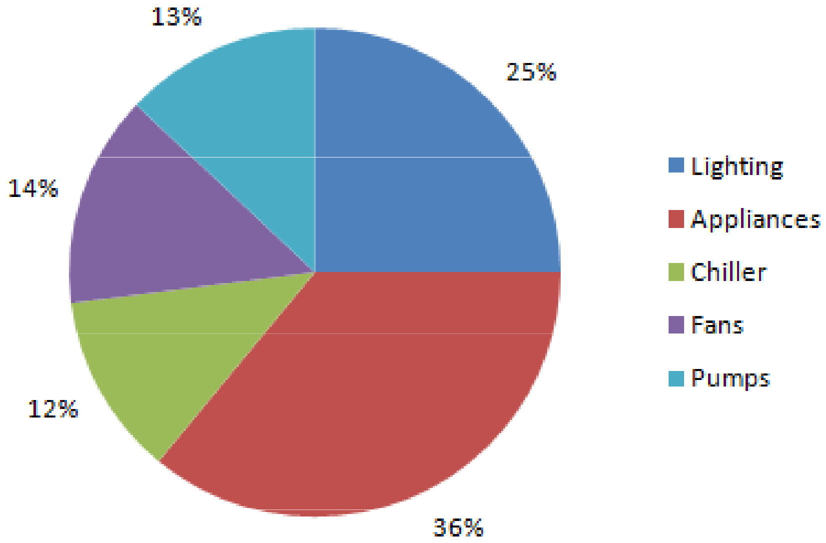
- Fuel Consumption

Trnsys	EES
60.8 kWh/m²/yr	63.7 kWh/m²/yr

- System electricity demands



(Electricity consumption, in kWh/m²/yr)



(Electricity consumption distribution)

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Conclusion

- Simplified lumped building model
  → Limited quantity of parameters
  → used with a “walls compositions library”

- Building zone model coupled to a complete HVAC system model

- Simulation tool implemented in an Equation Solver
  - Equation solver well adapted to the use of simplified models
  - Simplified lumped building model → Eq. Solver well adapted to solve differential equations
  - Simplified HVAC components models → easily connected in Eq. Solver to run complete HVAC system simulation

- Different versions of the tool are available at www.labothap.ulg.ac.be

Thank you for your attention