International Building Physics Toolbox

General report

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Preface

A calculating tool for thermal system analyses in building physics, that takes interaction between building structure, building services, climate and the users into account, is of great interest both for the researchers and the designers in this area. In order to take the advantage of the graphical user interface, a unique library of software packages related to the basic building components, like layered wall structures with material data, boundary and surface conditions, ventilated space, windows, heat sources, HVAC components, etc. is made in Simulink, at the Department of Building physics, at the Chalmers University of Technology in Sweden, (Hagentoft, 2000).

During the same time, another building physics department from the Department of Civil Engineering from the Technical University of Denmark has developed a similar calculating tool, also in Simulink. Working with similar problems and using the same modeling tool, has brought an idea of joining the work of these two research groups. And even more, an idea of establishing a public available library of building elements that provide HAM system analysis in building physics.

The first step was to define the common platform in modeling, which would enable developing and exchanging models between the partners. For this purpose, we defined some basic blocks each representing one of the basic building constructions like walls, windows, ventilated space, etc, and the same data flow between them. For simplicity, only heat transfer was concidered. We also defined a common exercise for inter-model comparison.

The first results were very promising. Each partner developed its own library, with different blocks (although with the similar names), but the agreed data structure was strictly obeyed. By this, we succeeded in exchanging the blocks without any problems, just by dragging the desired block from one library and placing it into the model from another. The simulation results from the common exercise were also in a very good agreement.

All our ideas and results from this common work are presented in this document. At the same time, this document also defines guidelines for any future contribution to the library, including both models and the documentation of these. We believe that we are on the right way in establishing the International Simulink Building Physics Toolbox, and that this document will motivate other researchers to join us.

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1. International Building Physics Toolbox

The International Building Physics Toolbox (IBPT) is a library of blocks, specially constructed for the thermal system analysis in building physics. There are two main blocks, representing the most frequent objects of interest: a building envelope *construction* (walls, windows), as a layered structure of different building materials, and a *thermal zone* (ventilated space), which is enclosed by the building envelope. Component models provide detailed calculations of the thermal state of each subcomponent in the structure, according to the surrounding conditions to which it is exposed. The thermal state of the zone is determined by the heat gains through the building envelope, (HVAC) *systems* and internal *gains*, additional components presented by the model of the same name. Direct coupling between building envelope and surrounding air (outdoors/indoors climate, ventilated space) is accomplished by *outdoor and indoor surface conditions* – models for heat balance at the wall boundaries. Our goal was to provide the blocks that will enable thermal system analyses of certain kind, schematically presented in Figure 1.

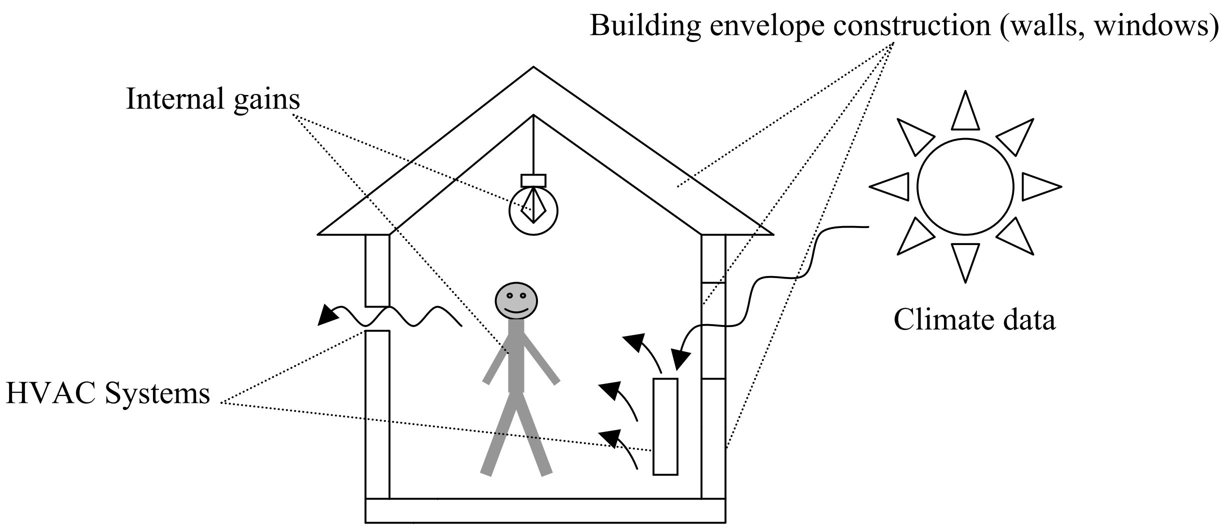


Figure 1: House as a thermal system

1.1 Library structure

Blocks are grouped into five sub-libraries according to their function. The library window displays the library icons and names, (Figure 2):

Construction library contains blocks that represent *elements* of the *building* envelope, like wall and window.

Zones library contains blocks that represent air space enclosed in the building envelope, like room air. In the zones, radiation exchange between surfaces can also be included.

Systems library contains blocks that represent HVAC equipment applied to the zone.

Helpers library contains blocks that are necessary for building elements construction and climate data manipulation.

Gains library contains blocks that represent internal gains applied to the zone.

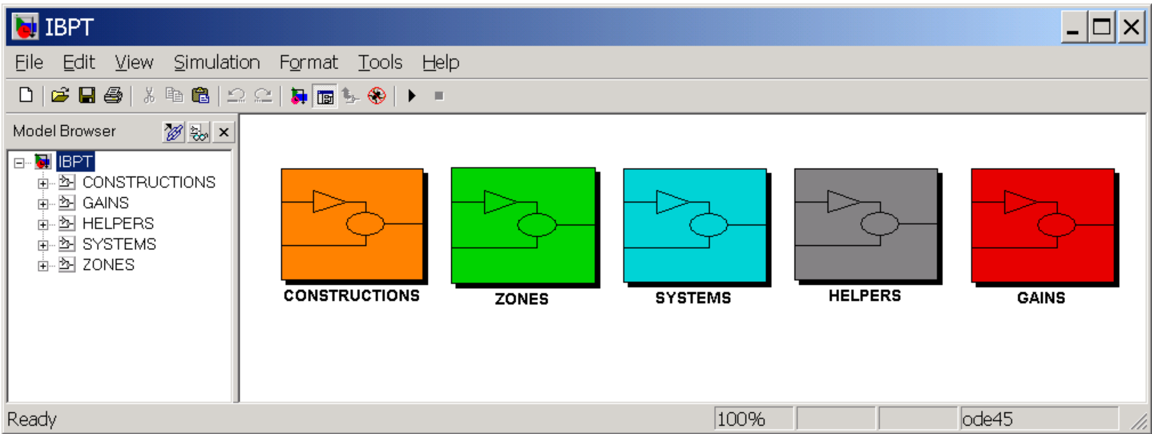


Figure 2: The library window

Library blocks are developed by each of the partners: DTU and CTH. Blocks may have similar or equal mask and name, but they are based on different mathematical model. Thus, besides the first grouping according to the function, they are also grouped according to the creator, Figure 3. Each creator provides documentation with detailed block description, where the mathematical model, among others, is described, see [2] and [3].

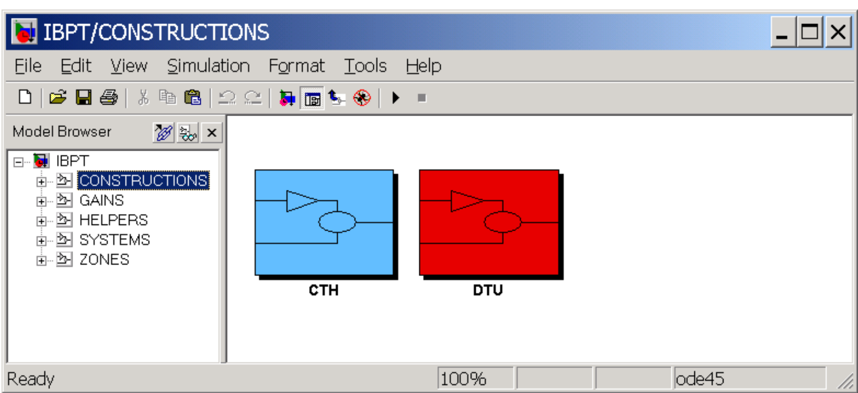


Figure 3: Blocks organisation according the creator.

Library enables users to copy blocks into their models and automatically update the copied blocks when the source blocks change. Using library allows user to ensure that their models automatically include the most recent version of these blocks.

In [4], a user’s manual is provided for first time users of the toolbox. The manual includes a brief introduction to the Simulink, but is mostly concerned about the assembly of a simple building model, which serves as an introduction to the general use and functionality of the toolbox. The manual cannot, however, be used for developing new blocks, this information can be found in this report and in [2] and [3].

1.2 Block documentation

Each author provides documentation for the blocks placed in the library. The documentation gives instructions how to use the blocks and what are the mathematical models that are based on. Following sections should be included in this documentation, in the specified order:

Description
Block diagram
Input to the block
Output from the block
Block mask
Variables
Mathematical model
Simulink model
Miscellaneous: connection to the neighbouring layers, scooping the results, etc
Validation

For more details see some of the already written documentations [2] or [3].

1.3 Rules for naming and sizing the blocks

Each block has the name, input and output ports.

Block name is written on the bottom of the block icon, with font type “Ariel”, size 12. A name is given according to the block function. After the name comes the name of the creator, using the space and slash sign like “ / DTU”.

Names and order of input and output ports are defined in Chapter 2.4. Here are some examples:

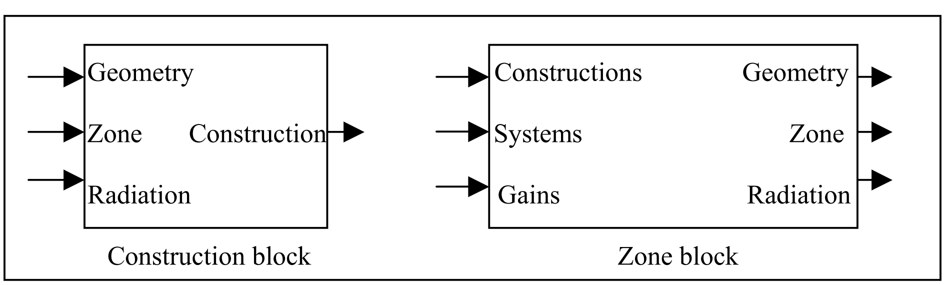


Figure 4: Names and order for input and output ports, following the general rule.

If an input and output port have the same name, the prefix “To” is added to the name of the output port in order to avoid possible confusion, see Figure 7.

The size of the block is proposed according to the number of input and output ports. The size is expressed in pixels, and can be seen by activating the grid in the model window:

```
set_param('IBPT','showgrid','on')
set_param('IBPT','gridspacing','25')
```

Blocks with one input/output: 125x50 pixels
Block with two inputs/outputs: 125x75 pixels
Block with three inputs /outputs: 125x100 pixels

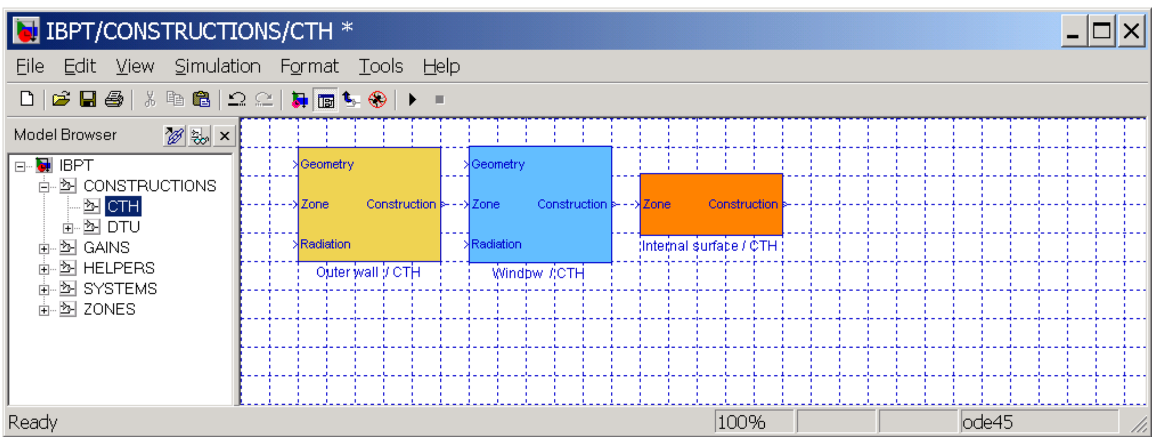


Figure 5: The block size

The Zone block is excluded from this rule, due to the Matrix concatenation blocks, so its size is proposed like 150x250 pixels.

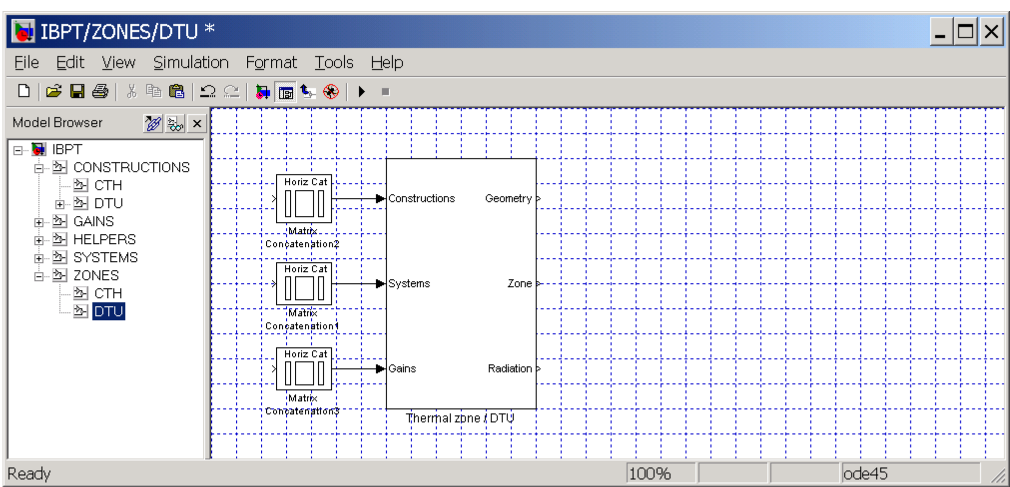


Figure 6: The size of the Zone block

These rules in block size, names and orders of input and output signals enable simplicity in exchanging blocks between different authors. It should be strictly followed everywhere, except for the blocks of *helpers* library, where we expect somewhat lower frequency of exchange. Here is one example, on the Figure 7.

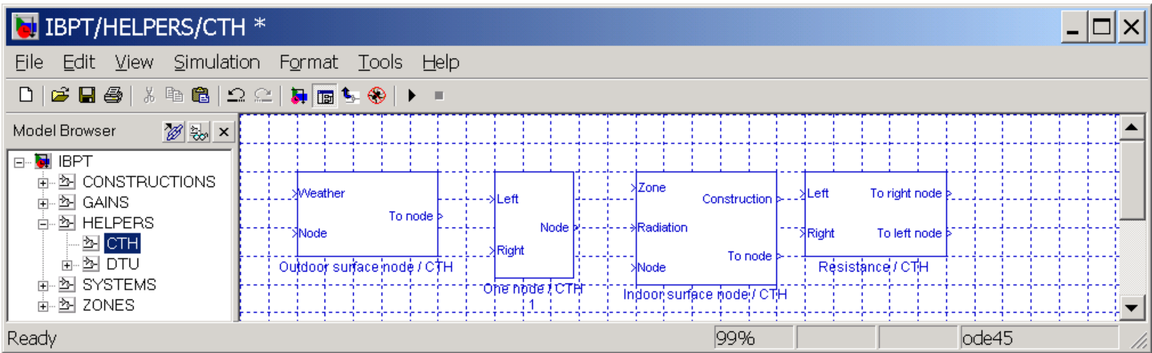


Figure 7: The size of the blocks from *helpers* library.

2. Data arrays

In order to enable block exchange between different constructors / libraries, the communicating signals and their order in the arrays are strictly defined and definite. Here is the list of the main signals, all organized as the data arrays. If some signals are not active in the simulation, it is sufficient to assign the ground or zero signals at their place.

2.1 Weather data file

Climate data for certain location are given as hourly values during one year together with information of longitude, latitude and local standard time for that location.

Climate data are stored in a file called *weather.mat*, which is an ordinary data file (for example in ASCII format) but saved in Matlab "*.mat" form (binary format). The following table describes the parameters, their order and units. There are 8760 time steps (rows) and 12 columns. This signal is the only hidden one during simulation (see also [1]) in order to simplify the calculating scheme.

Table 1: Weather data file

Column number:	Output number in Simulink	Description	Unit
1	-	Time	s
2	1	Air temperature	10 °C
3	2	Dew point temperature	10 °C
4	3	Global radiation on horizontal surface	W/m^2
5	4	Diffuse radiation on horizontal surface	W/m^2
6	5	Normal direct radiation	W/m^2
7	6	Incident long wave radiation	W/m^2
8	7	Illuminance, global	lux
9	8	Illuminance, diffuse	lux
10	9	Illuminance, direct	lux
11	10	Wind direction	deg
12	11	Wind speed	10 m/s

2.2 Main communication arrays

Table 2: Surface weather data array

Symbol	Description	Unit
I_{dir}	Direct solar radiation	W/m^2
I_{dif}	Diffuse solar radiation	W/m^2
θ	Incidence angle of solar radiation	deg
T_{air}	Air temperature	^oC
v_s	Wind speed	m/s
φ_{air}	Relative humidity	[0-1]
I_{lw}	Longwave radiation from surroundings	W/m^2
G_{rain}	Rain on surface	$kg/m^2 \cdot s$
P_{air}	Air pressure	Pa

Table 3: Construction array

Symbol	Description	Unit
R_c	Convective thermal surface resistance	m^2K/W
T_s	Surface temperature	^oC
R_p	Moisture surface resistance	$Pa \cdot s \cdot m^2/kg$
p_s	Surface vapour pressure	Pa
R_a	Air flow resistance	$m^3/(s\ Pa)$
P_a	Air pressure	Pa
Q_{sun}	Transmitted solar energy	W/m^2
ε	Surface emissivity	-
T_{air}	Inlet temperature of air flow	^oC
φ_{air}	Relative humidity of air flow	-
Snr	Surface number	-

Table 4: System array

Symbol	Description	Unit
R_c	Convective thermal surface resistance	m^2K/W
T_s	Surface temperature	^oC
R_p	Moisture surface resistance	$Pa \cdot s \cdot m^2/kg$
p_s	Surface vapour pressure	Pa
R_a	Air flow resistance	$m^3/(s\ Pa)$
P_a	Air pressure	Pa
Q_{sun}	Transmitted solar energy	W/m^2
ε	Surface emissivity	-
T_{air}	Inlet temperature of air flow	^oC
φ_{air}	Relative humidity of air flow	-

Table 5 Geometry array

Symbol	Description	Unit
α	Orientation	deg
β	Tilt	deg
A	Area	m^2

Table 6: Zone array

Symbol	Description	Unit
T_a	Air temperature	^oC
P_a	Air pressure	Pa
φ_a	Relative humidity	-

Table 7: Radiation array

Symbol	Description	Unit
Q_{rad}	Net radiation to surface	W/m^2

Table 8: Gain array

Symbol	Description	Unit
Q_c	Convective gain	W
Q_r	Radiative gain	W
G	Moisture gain	kg/s

2.3 Internal communication arrays

There are some communication signals that are omitted from the general list and defined by the authors. An example is the signal between outdoor surface conditions block and material layer named “Node”, Figure 7. These signals are for internal communication, on the level where we do not expect block exchange. They are defined in the block documentation and have the lowest order of appearance.

2.4 Rules for signal appearance on the model scheme

The order of the signals at the input and output ports of the blocks and their names are given in the following Table 9.

Table 9: Order of appearance and name of the signals

Order	Signal type	Name
1	Surface weather data array	Weather
2	Construction array	Construction
3	Geometry array	Geometry
4	Zone array	Zone
5	Radiation array	Radiation
6	System array	System
7	Gain array	Gain
8	Internal array	Node, etc

2.5 Signals concatenation

All listed signals are 1-D vectors. The library blocks are mainly built in such a way to accept or output one 1-D signal through the each input or output port (like the blocks from the Helpers, Constructions, Systems and Gains libraries).

In the case where it is necessary to input more than one 1-D signal through the one input port, the "Matrix concatenation" block is used. This block makes the matrix of all attached 1-D signals concatenating them horizontally or vertically. With the signal selector blocks, matrix elements can be further easily extracted. Some of the blocks from the Zone library are built in such a way (see for example Figure 6), and given together with the matrix concatenation blocks.

3. Material library

Together with the block library comes the material library, with all material properties of interest and used by the models in the library.

The material library is created in the form of **structures**. Structures are multidimensional Matlab arrays with "data containers" called fields. Each field has certain name and can contain any kind of data: text, scalar or array/matrix. Here is an example:

```
data(1).name='insulation'
data(1).dry_density=100
data(1).lambda_dry=0.04
data(1).heat_capacity=1000
data(1).absorptivity=0.9
data(1).absorption_RH=[0.05 0.015 0.025 ...]
data(1).absorption_U=[0.001 0.002 0.008 ...]
```

Each material from the library is described by the same set of data, but with the different index (data(2)). Note, that it is not possible to use structure name "material" as this is an in-built Matlab function.

```
data(2).name='glass'
data(2).dry_density=2400
…
```

These structures called "data()" are then saved to a Matlab file, e.g. *DATABASE.m*. In order to access this structure from Simulink, it must be loaded either in the Matlab Workspace or by the block mask initialization to the local Workspace.

Keeping the same structure and especially field names, any user can create his/her own material library. In order to distinguish between different material libraries constructed by different users, it is useful to place some reference in the library name like: CTH_DATABASE, DTU_DATABASE, as well as in the structure names like:

```
CTH(1).name='insulation'
CTH (1).dry_density=100
CTH (1).lambda_dry=0.04
```

An overview of the reserved filed names is shown in the Table 10. It should be stressed that these field names are definite for the particular use. Any other material property can be added, just with another describing name. This allows users and developers to use their preferable material parameter presentations matching their models.

Notice, that in Matlab tables, x-values have to be monotonically increasing, and that all the variables are given in SI-units.

Table 10: The list of material parameters in the material database for Simulink simulation.

Fieldname	Parameter	Unit	Example
name	material name	-	Concrete
dry_density	dry density of the material	kg/m³	2400
porosity	porosity	-	0.204
lambda_dry	thermal conductivity of the dry material	W/m·K	1.5
lambda_T	thermal conductivity factor dependent on temperature	W/m·K²	0
lambda_U	thermal conductivity factor dependent on moisture content by weight	W/m·K	36
lambda_W	thermal conductivity factor dependent on moisture content by volume	$W\cdot m^2/kg\cdot K$	0.015
heat_capacity	specific heat capacity of the dry material	J/kg·K	800
U_critical	critical moisture content by weight	kg/kg	0.04
W_critical	critical moisture content by volume	kg/m^3	96
U_capillary	capillary moisture content by weight	kg/kg	0.062
W_capillary	capillary moisture content by volume	kg/m³	148.8
U_vacuum	vacuum moisture content by weight	kg/kg	0.085
delta_RH	RH entries for vapor permeability	-	[0 0.6 0.98]
delta_p_RH	vapor permeability f(RH)	kg/(s·Pa·m)	[2.5e-12 2.5e-12 1.0e-11]
delta_U	moisture content by weight entries for vapor permeability	kg/kg	[0.048 0.085]
delta_p_U	vapor permeability f(U)	kg/(s·Pa·m)	[1.0e-11 1.0e-16]
delta_W	moisture content by volume entries for vapor permeability	kg/m³	[115.2 204]
delta_p_W	vapor permeability f(W)	kg/(s·Pa·m)	[1.0e-11 1.0e-16]
absorption_RH	RH entries for absorption isotherm	-	
absorption_U	moisture content by weight entries for absorption isotherm	kg/kg	
desorption_RH	RH entries for desorption isotherm	-	
desorption_U	moisture content by weight entries for desorption isotherm	kg/kg	
sorption_RH	RH entries for sorption isotherm (mean value)	-	[0 0.2525 0.449 0.65 0.8 0.8985 0.9815]
sorption_U	moisture content by weight entries for sorption isotherm (mean value)	kg/kg	[0 0.0089 0.0116 0.0174 0.0262 0.0335 0.0444]
sorption_W	moisture content by volume entries for sorption isotherm (mean value)	kg/m³	[0 21.36 27.84 41.76 62.88 80.4 106.56]
slope_sorption_RH	RH entries for slope of the sorption isotherm	-	
slope_sorption_ksi	slope of the sorption isotherm	kg/m³	
wet_suction_U	moisture content by weight entries for suction (wetting)	kg/kg	
wet_suction_lnP	logarithmic suction pressure (wetting)	Pa	
dry_suction_U	moisture content by weight entries for suction (drying)	kg/kg	
dry_suction_lnP	logarithmic suction pressure (drying)	Pa	
suction_U	moisture content by weight entries for suction	kg/kg	[0.0442 0.0454 0.0544 0.0597 0.0620]
suction_lnP	logarithmic suction pressure	Pa	[14.7860 14 10 6 -10]
suction_W	moisture content by volume entries for suction	kg/m³	[106.08 108.96 130.56 143.28 148.8]

Fieldname	Parameter	Unit	Example
suction_Psuc	suction pressure	Pa	[2639236 1202604 22026 403 0]
WAC	water absorption coefficient	$kg/m^2h^{0.5}$	0.018
hyd_cond_U	moisture content by weight entries for hydraulic conductivity	kg/kg	[0.0400 0.0620 0.0850]
hyd_cond_W	moisture content by volume entries for hydraulic conductivity	kg/m^3	[96 148.8 204]
hyd_cond_K	hydraulic conductivity	kg/(s·Pa·m)	[1.1000e-014 6.2500e-013 6.2500e-013]
air_permeability	air permeability	m^2	0
absorptivity	radiative absorptivity	-	0.8
emissivity	radiative emissivity	-	0.8
transmittance	solar transmittance	-	0

4. The common exercise: an example of a thermal system analysis for a ventilated space; results from different solutions and validation.

We consider heat losses and gains to a room, which is exposed to the certain climate data during one year. The room has only one outer wall and one window, both facing the south. During the whole year, the room is heated by the heating system with the constant heat supply and ventilated with the outdoor air with a constant ventilating rate. The room geometry is shown on Figure 8.

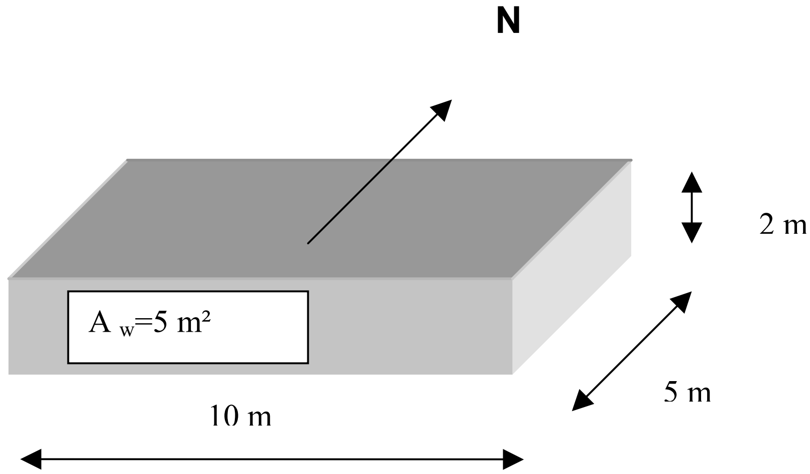


Figure 8: Room geometry

4.1 Description of the building components

Wall:
Orientation: South

Heat conductivity $\lambda = 0.04$ W/mK
Heat capacity $\rho c = 10^5$ J/m³K
Thickness d = 0.2 m
Emissivity $\varepsilon = 0.9$
Air leakage = 0

Window:
Heat resistance $R_{glass} = 1/1.5$ m²K/W
Area A = 5m²
Solar transmittance $\tau = 0.75$

Room:
"Mass" of the zone (air and furniture):
m_{zone}= 500 kg
Average heat capacity c_{zone}= 800 J/kgK

Sources:
Moisture source $G_{zone} = 0$
Radiative heat source $Q_r = 0$
Convective heat source Q_c = 500W

Ventilation
Air change rate n = 0.5 h^{-1}
Solar transmittance $\tau = 0.75$

4.2 Climate data and boundary conditions

Weather data are taken from the Danish design reference year (DRY).
Outdoor convective heat transfer coefficient is $h_{c,out}$=20 W/m^{2}K.
Indoor convective heat transfer coefficient is $h_{c,in}$=3 W/m^{2}K.
For simplicity, all internal surfaces (excluding the window and outer wall) have the same temperature, equal to the room air temperature.

4.3 Simulink model

Simulink models for the exercise, made by teams from DTU and CTH are shown on Figures 9 and 10 respectively. On this top-level models are almost equal, partly because the exercise is simple and partly because the agreed structure of the blocks and data arrays defines them exclusively.

The "contents" of the blocks – the mathematical model – are in part quite different (see [2] and [3] for information on the actual contents of the blocks). This difference becomes visible when studying the results in the next section.

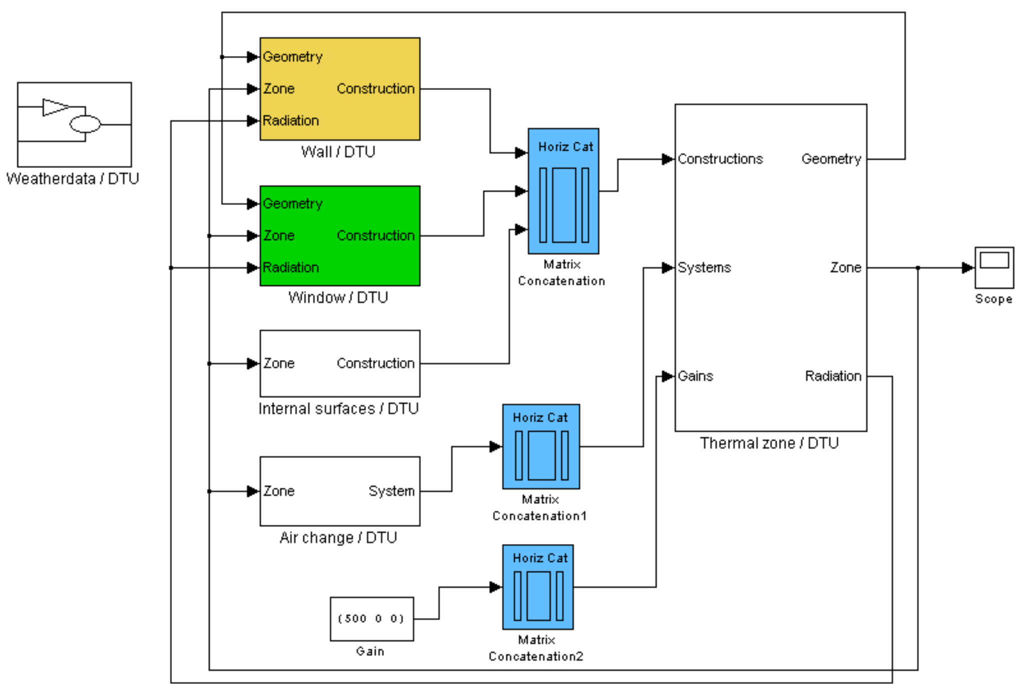


Figure 9: DTU Simulink model for the common exercise.

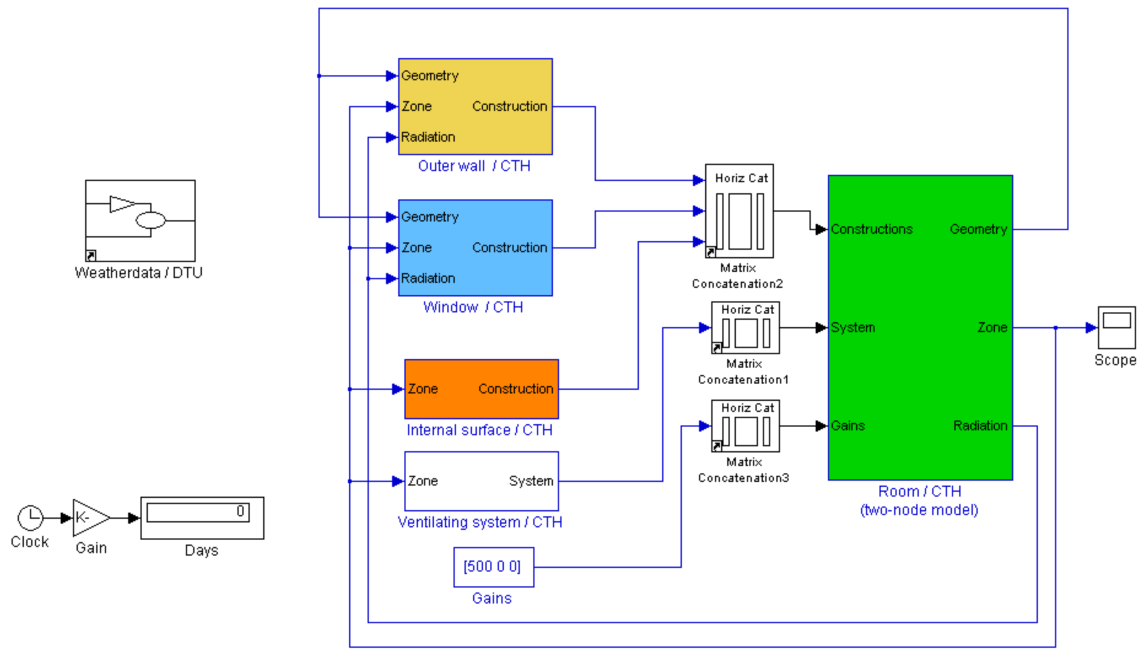


Figure 10: CTH Simulink model for the common exercise.

4.4 Results

The results are given as the yearly temperature variation in the room air temperature T_{room} [ºC], Figures 11 and 12, and transmitted solar energy through the window $Q_{transmitted}$ [W], Figure 13.

The total yearly net heat flow due to transmitted solar energy and the heat losses through the outer wall and window are given in the following Table:

Table 11: Results of the calculation

	CTH	DTU
Yearly transmitted solar energy [kWh]:	682	682
Yearly heat loss through the outer wall [kWh]:	287	236
Yearly heat loss through the window [kWh]:	650	594

Figure14 presents results of the room air temperature calculations from both partners in enlarged time scale in some representative intervals throughout the year.

Finally, Figure 15 shows the differences in the calculated room air temperatures.

The temperature level of the results might seem unrealistically high, but is mostly due to the supplied heat ("Gain"), constantly throughout the whole year.

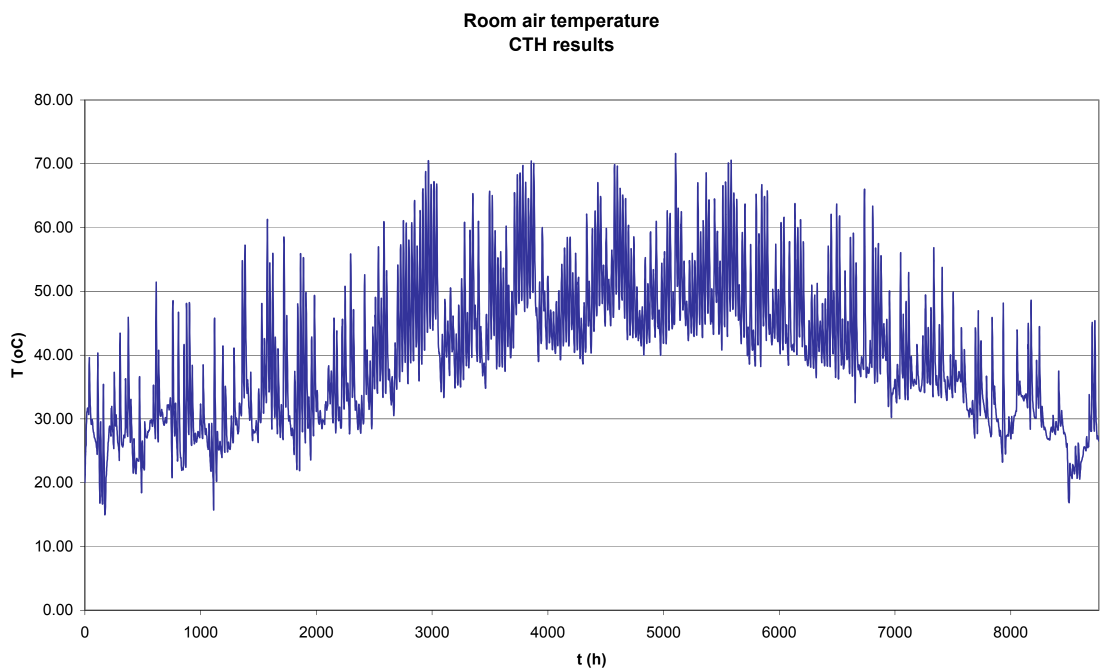


Figure 11: Calculated room air temperature, CTH results

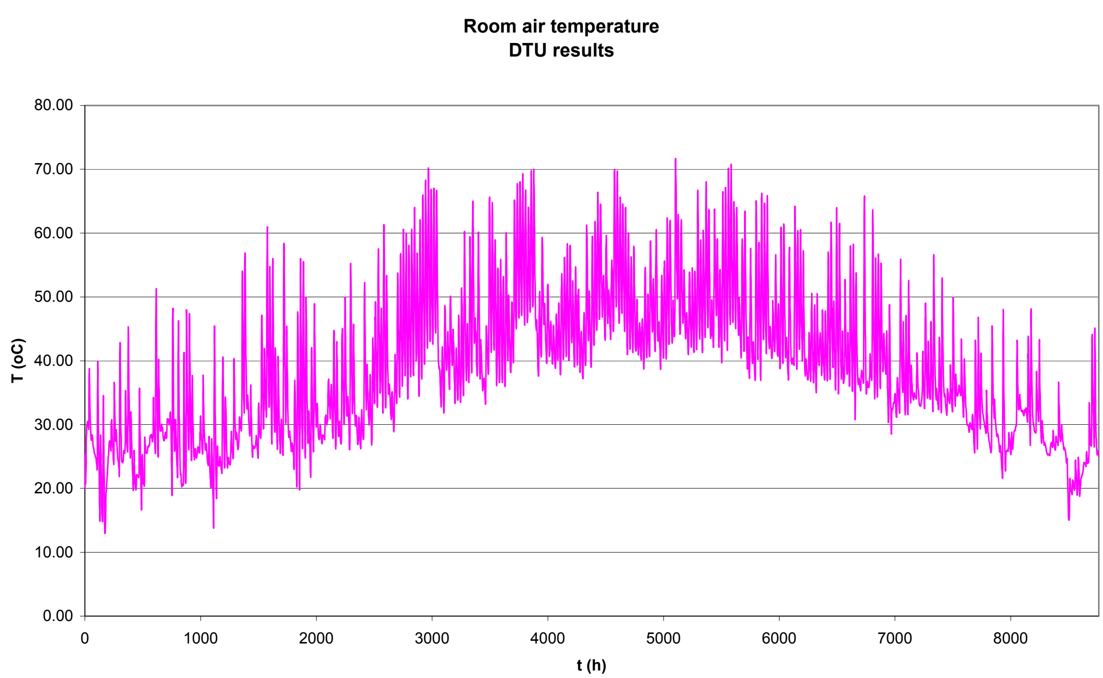


Figure 12: Calculated room air temperature, DTU results

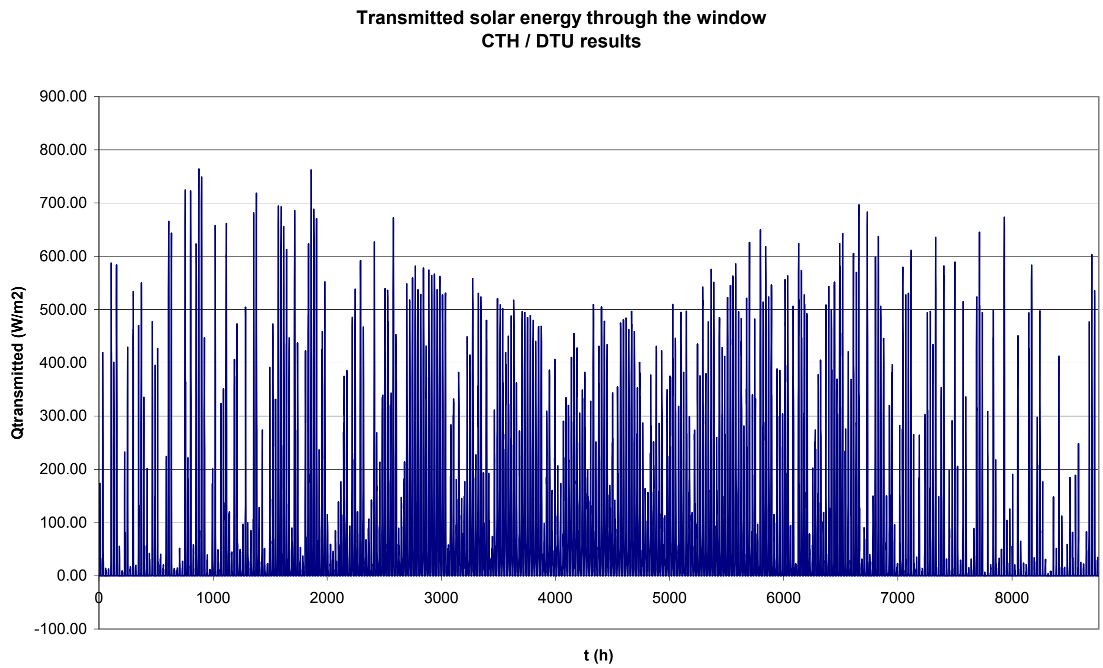
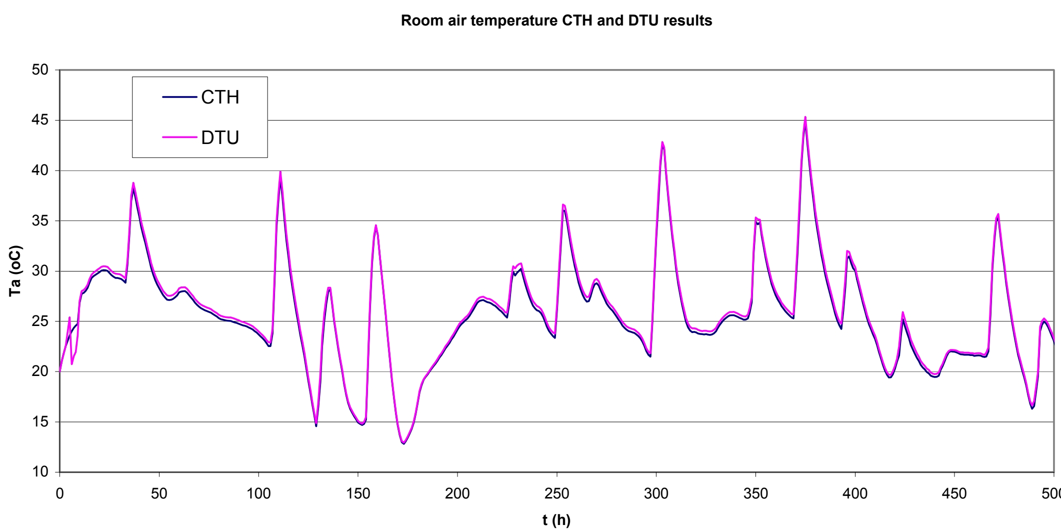
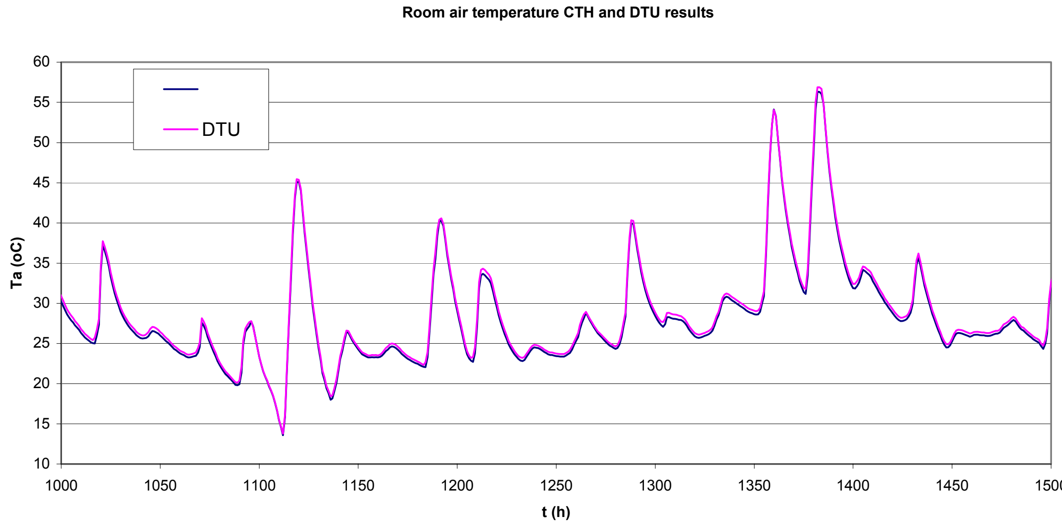
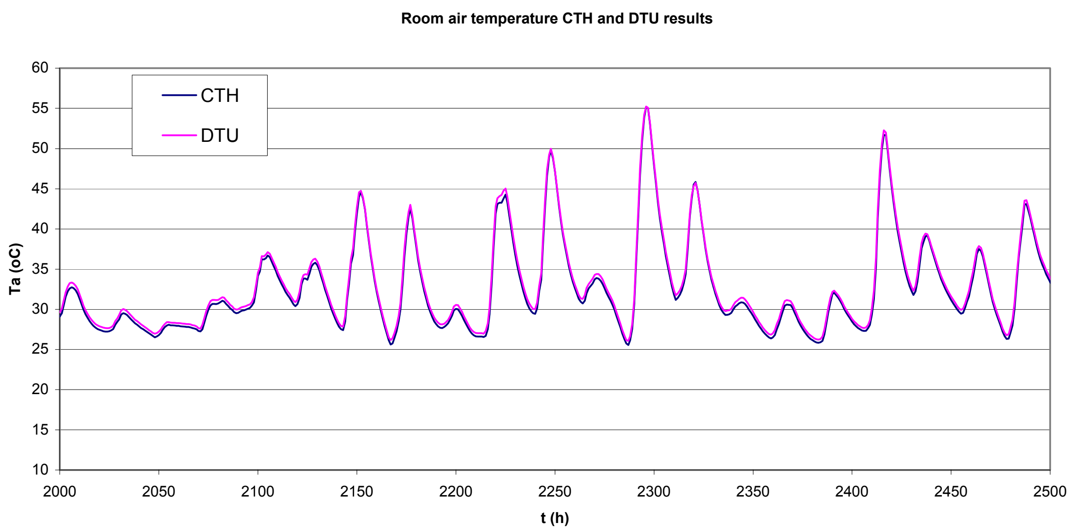


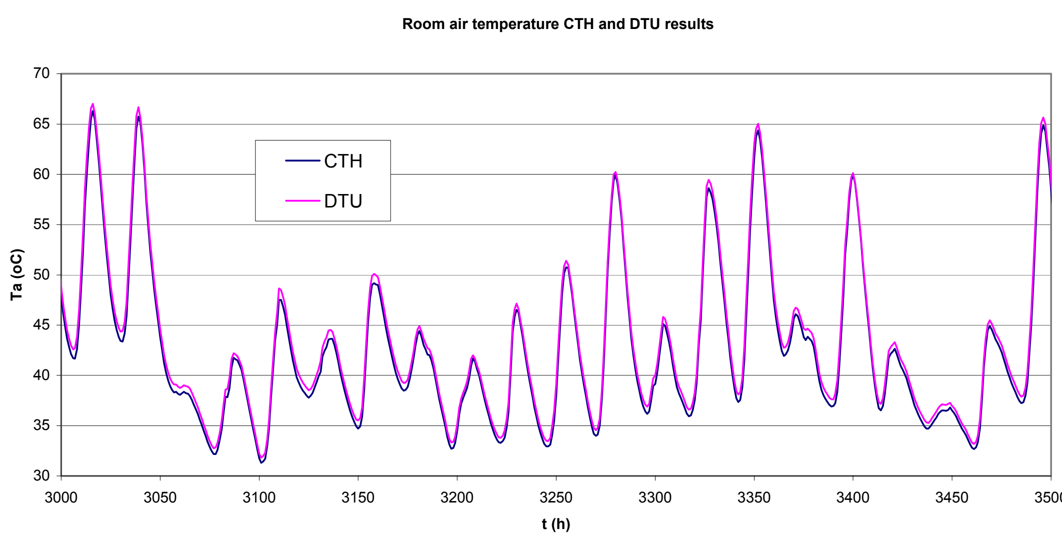
Figure 13: Transmitted solar energy through the window, CTH and DTU results.

Following figures present results of the room air temperature calculations from both partners in enlarged time scale, throughout the year.

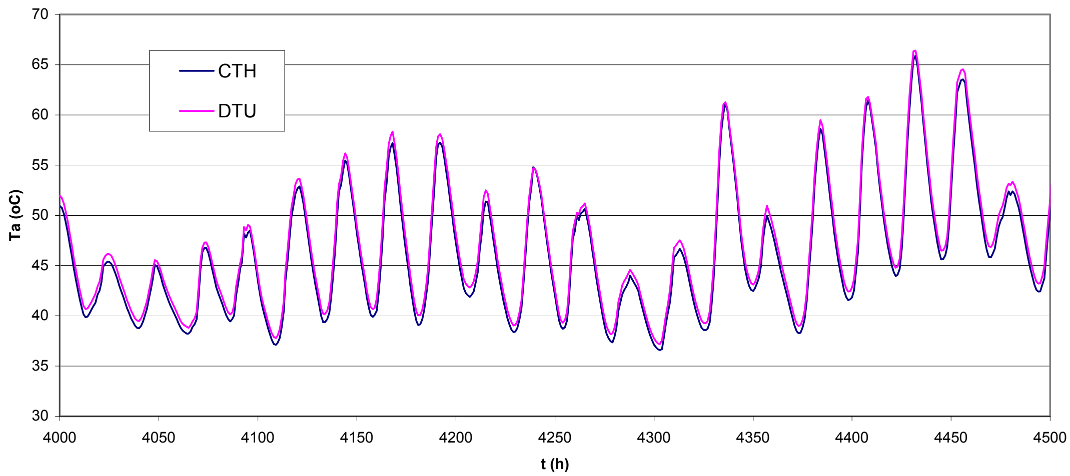



Room air temperature CTH and DTU results
DTU
Ta (oC)
t (h)

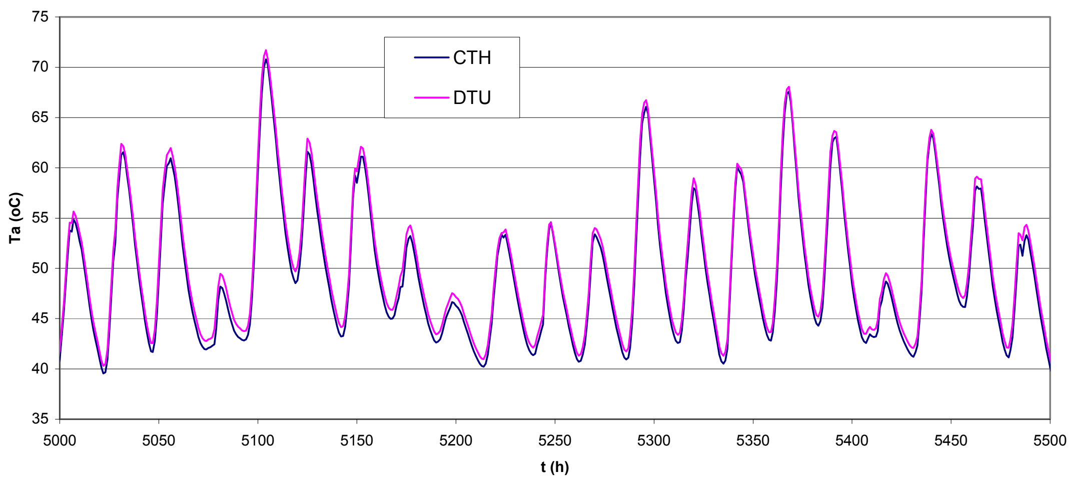

Room air temperature CTH and DTU results
CTH
DTU
Ta (oC)
t (h)


Room air temperature CTH and DTU results
CTH
DTU
Ta (oC)
t (h)

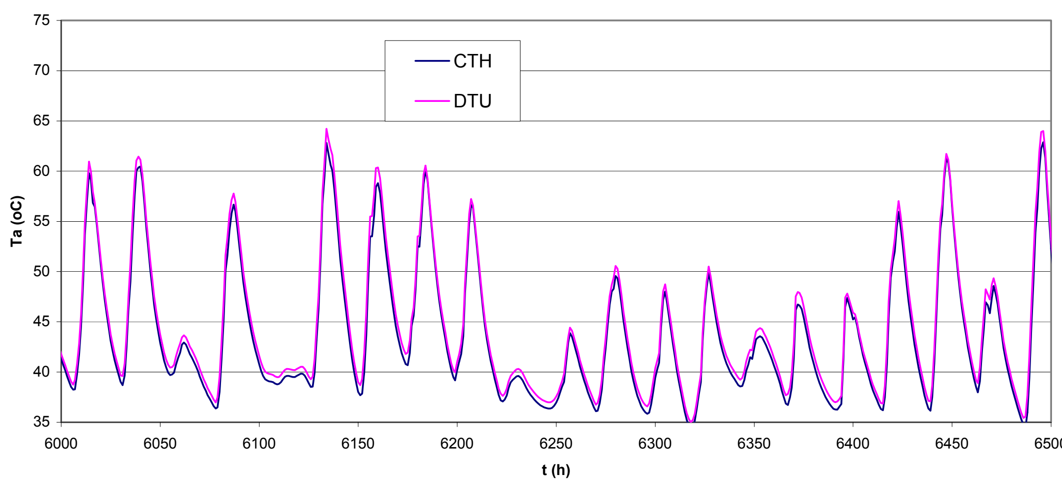
Room air temperature CTH and DTU results



Room air temperature CTH and DTU results



Room air temperature CTH and DTU results



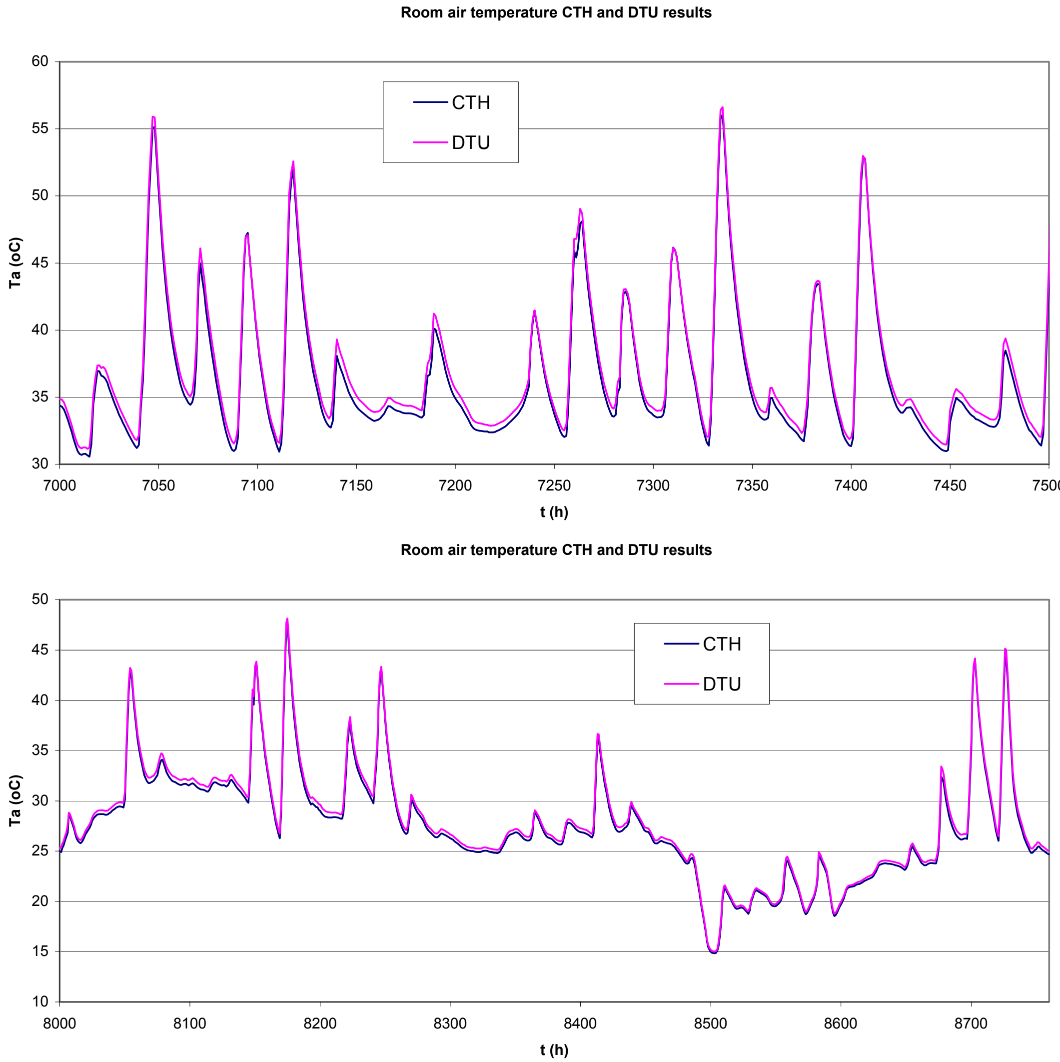


Figure 14: Calculated room air temperature, comparison of results for different periods.

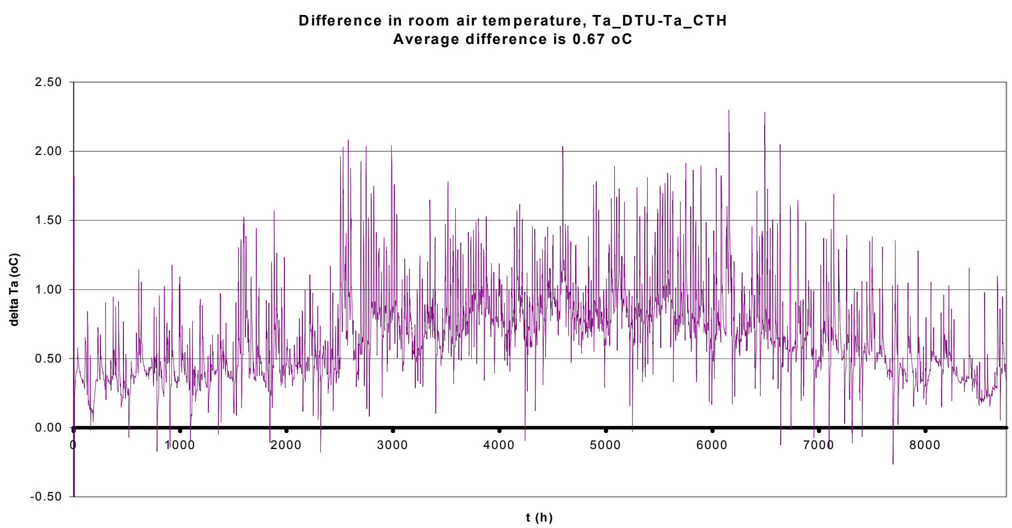


Figure 15: Differences in the calculated room air temperature through a whole year.

The reason of this deviation is to be found in the different mathematical models for the zones. This is tested with a following model, Figure 16. The same exercise is performed, with CTH model as the basis, but both the wall and the window area are split into two equal parts and each part is presented by the corresponding block of the each partner.

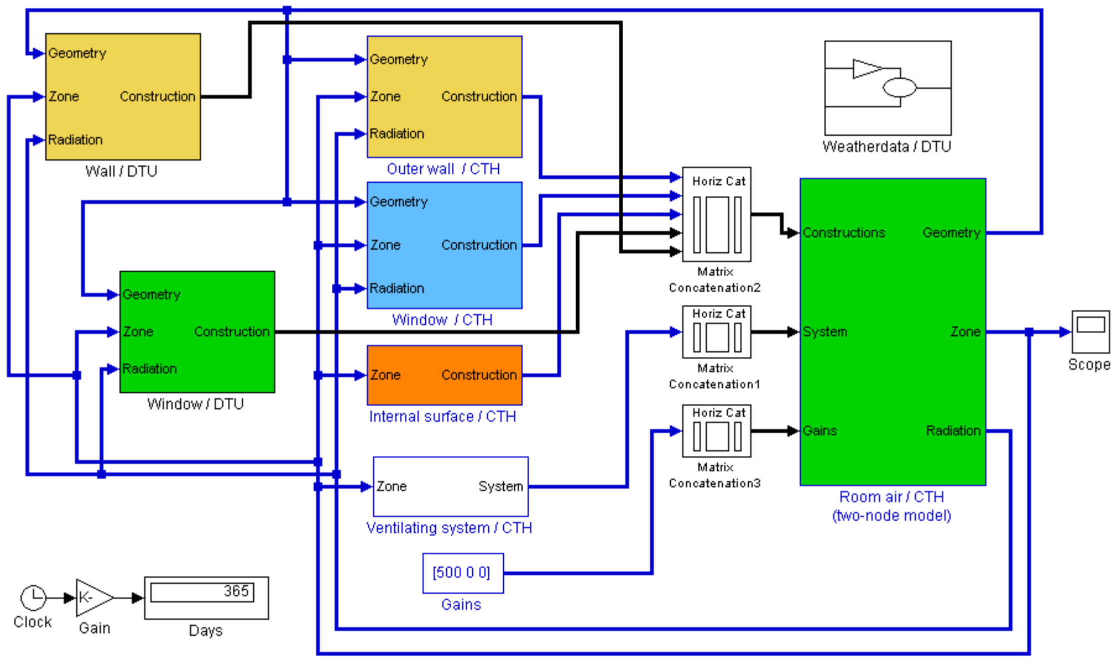


Figure 16: Testing of the outer wall and window blocks. An example of the block exchanging.

In this model, where all walls and windows are attached to the same zone, we achieved to apply the same internal climate data to the each. The net heat losses through the each component are presented in the following Table:

Table 12: Results of the model comparison

	CTH models	DTU models	Sum
Yearly transmitted solar energy [kWh]:	341	341	682
Yearly heat loss through the outer wall [kWh]:	144	144	288
Yearly heat loss through the window [kWh]:	325	325	650

The sum of the heat losses through the each par of constructions is presented in the last column. These results correspond to the CTH results, presented in the Table 11. They confirm our previous assumption, that results are different due to the different mathematical models for the zone blocks.

This testing is at the same time an illustration of the block exchanging possibilities.

4.5 Conclusion

It was possible to design a common platform for modelling building physics problems. By using the agreed structure, two research teams succeeded in developing models that give almost identical results. Models developed by another team can communicate with each other, allowing research teams to exchange blocks and hereby also expertise.

5. References

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