PRESENTATION OF THE INTERNATIONAL BUILDING PHYSICS TOOLBOX FOR SIMULINK

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ABSTRACT

The international building physics toolbox (IBPT) is a software library specially constructed for HAM system analysis in building physics. The toolbox is constructed as a modular structure of the standard building elements using the graphical programming language Simulink. Two research groups have participated in this project. In order to enable the development of the toolbox, a common modelling platform was defined: a set of unique communication signals, material database and documentation protocol. The IBPT is open source and publicly available on the Internet. Any researcher and student can use, expand, and develop the contents of the toolbox. This paper presents the structure and the backbone of the library. Three examples are given to visualize the possibilities of the toolbox.

INTRODUCTION

The numerical modelling of heat, air and moisture (HAM) flows in buildings is an essential part of studying these phenomena – it might be as a part of research work, building design or for educational purposes. Examples of HAM models can be found in Hens (1996), Wit (2000) and Hagentoft (2002a).

A host of commercially available computer tools models already exist for modelling single components or whole buildings. For modelling whole buildings, there are models for the hourly energy balance programs (in some cases also including moisture) Bsim[1], ESP-r[2], EnergyPlus[3], and more. While these tools are fully appropriate for designing standard buildings, they are not suitable for modelling innovative building elements such as building integrated heating and cooling systems, ventilated glass facades and solar walls, as these have not been defined in the program. A different approach is the use of modular simulation tools, represented i.e. by TRNSYS[4] and SPARK[5]. In Strand et al. (2002), the differences in the two types of tools are discussed. Here it was found that the major shortcomings of building energy simulation programs have so far been the inability to accurately model HVAC systems that are not "standard". This argumentation can easily be expanded to include advanced building elements. The modular models, on the other hand, have the advantage that components and systems can be modelled as the need appears.

Should a detailed and transparent tool be usable by a large number of people working individually to develop models, it must be modular. In addition, transparency of the existing components is essential, if the user/developer wishes to implement any modifications. A transparent, modular and open source system for modelling heat and moisture flows in buildings should therefore be a user-friendly tool that can be expanded as needed in the future.

The above-mentioned concerns have given rise to a need to develop an open and freely available building physics toolbox among the Authors. The start of the International Building Physics Toobox (IBPT) was laid by two groups of researchers working independently of each other with developing building physics models in Simulink. For both groups, the reason for starting to use Simulink as the development environment was a need to being able to model, in great detail, the processes of heat, air and moisture transfer. In both groups the reason for choosing Simulink, which is part of the Matlab package[6], was a large degree of flexibility, modular structure, transparency of the models and ease of use in the modelling process.

Simulink has already previously been used by other research communities (SIMBAD[7] and CARNOT[8]), but the models have either not been open source, free of cost or have not been directly applicable to building physics modelling.

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[1] www.bsim.dk
[2] www.esru.strath.ac.uk/programs/ESP-r.htm
[3] www.eren.doe.gov/buildings/energy_tools/ energyplus

[4] sel.me.wisc.edu/trnsys
[5] simulationresearch.lbl.gov
[6] www.mathworks.com
[7] evl.cstb.fr
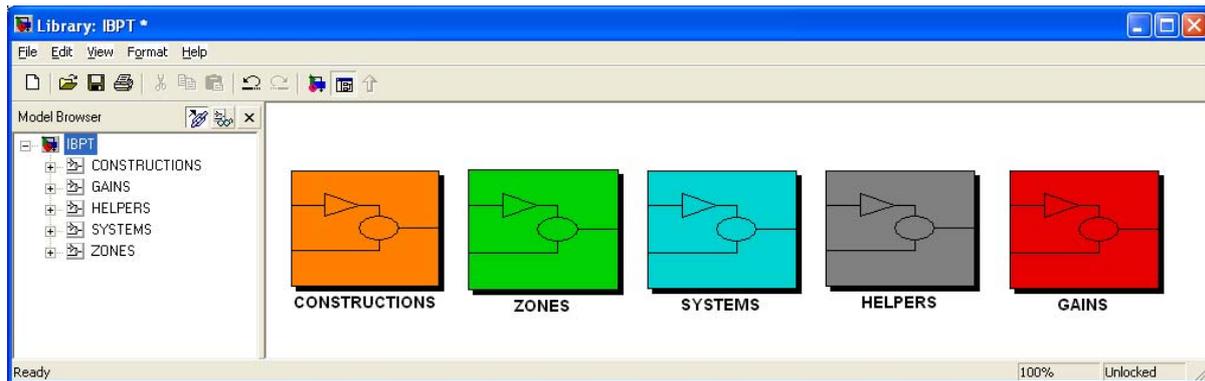[8] www.sij.fh-aachen.de/projekt_energiesysteme/ carnot_1.shtml

Figure 1 Main window of the International Building Physics Toolbox

The modular structure in Simulink - using systems and subsystems - makes it easier to maintain an overview of the models, and new models can just as easily be added to the pool of existing models. Another advantage of using Simulink is the graphical programming language based on blocks with different properties such as arithmetic functions, input/output, data handling, transfer functions, state space models and more. Furthermore, Simulink has built-in state of the art ordinary differential equation (ODE) solvers, which are automatically configured at run-time of the model. Therefore, only the physical model needs to be implemented, and not the solver. Further, models can be created using a number of different approaches. These include assembling models directly in Simulink using the standard blocks, Matlab m-files, S-functions, and Femlab[9] models using one-, two-, or three-dimensional finite element calculations. This wide variety of modelling techniques with different advantages and disadvantages means, that the optimal choice can always be made with respect to the task.

The graphical approach also makes it easy to show the very complex interaction between the different parts of the model. In addition, people who are not used to programming can easily get started building their own models or altering existing ones. Therefore, the toolbox also represents a good way to teach building physics.

Comparing IBPT to other modular building energy simulation programs (i.e. TRNSYS, SPARK and EnergyPlus), a few notes can be made. (1) IBPT does not require the same level of detailed programming knowledge (but advanced programming is possible), (2) it can use Simulink's built in solvers (but new solvers can be added by the user), (3) a large degree of integration using the Matlab package can be achieved and as described below (4) all programming code is freely available from the website.

The vision behind the development of the IBPT is to create a website (http://www.ibpt.org) with a set of

block models for modelling building physics. On the website, the blocks are freely available for download.

A 'block' is a common term for the basic elements used during the modelling process. Five categories of blocks have been defined. They are:

– constructions (e.g. walls and windows)
– zones (e.g. room models)
– systems (e.g. HVAC systems)
– helpers (e.g. handling of weather data)
– gains (e.g. internal heat gains).

These five categories are organized in a Simulink block library as shown in Figure 1.

New blocks can be added by the users, thereby ensuring the development of the contents of the toolbox.

The cornerstone of the IBPT is made up of the definition of a set of data arrays for exchange of data between blocks. A total of seven different arrays have been defined. The use of these data arrays ensures that the blocks can communicate with each other – even if different people have developed the blocks independently of each other!

Besides the data arrays, two more key elements exist. They are: a key for the documentation of the blocks and a database of material properties. This can be found in Sasic (2002) and Nielsen et al. (2002). On the website, a description of the functionality of each of the blocks is available. Also, a detailed description (Rode et al., 2002) of the interface between the blocks can be downloaded, so new blocks can be created and be in compliance with the existing blocks from the toolbox.

Different blocks can have different levels of details and processes. Some construction blocks may model only heat transfer while others may have both heat, air and moisture transfer. Also, the blocks can use different modelling techniques and have different accuracy in the modelling.

In this paper, the International Building Physics Toolbox (IBPT) for Simulink is presented. The paper describes the work that has led to the present state of

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[9] www.comsol.com

the toolbox and the background for the choices that have been made.

TOOLBOX

As described above, the IBPT consists of three cornerstones, which are: (1) the set of seven data arrays, (2) a material database and (3) the requirements for describing and documenting the blocks.

Initially however, the blocks presently existing in the toolbox are briefly presented

BLOCKS IN THE TOOLBOX

In the first version of the IBPT, which is presently available for download, a limited number of blocks are available. These include a zone model, input of weather data, ventilation and inner walls, outer walls and windows. These blocks can be used to perform simple energy balance calculations on simple rooms. Below in the examples, the development of two new blocks is described.

An example of a block is shown in Figure 2. The block accepts three input arrays and returns one output array. All data exchange between blocks is in the form of arrays, which contains a predefined set of data.

DATA ARRAYS

Seven data arrays have been defined for the data exchange between the blocks in the models. The arrays have been given the following names:

– Surface weather data array
– Construction array
– System array
– Geometry array
– Zone array
– Radiation array
– Gain array

Each of the arrays includes the necessary physical states and properties at the interfaces of the boundaries between the blocks. This way the data exchange between the blocks can always be handled using the pre-defined arrays, regardless of the level
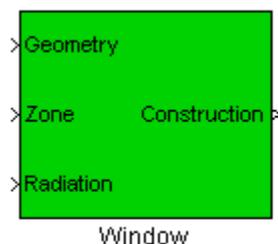

Figure 2 Example of block used in toolbox. In this case a window.

Table 1 Construction array

Symbol	Description	Unit
R_c	Convective thermal surface resistance	m² K/W
T_s	Surface temperature	°C
R_p	Moisture surface resistance	Pa s m²/kg
p_s	Surface vapour pressure	Pa
R_a	Air flow resistance	m³/(s Pa)
P_a	Air pressure	Pa
Q_{sun}	Transmitted solar energy	W/m²
ε	Surface emissivity	-
T_{air}	Inlet temperature of air flow	°C
φ_{air}	Relative humidity of air flow	-
Snr	Surface number	-

of detail used in the models. An example of the data the arrays is the construction array shown in Table 1. The construction array is the output from a construction element (wall, window), and it includes the conditions at the surface along with data for transmitted solar energy and air flow through the construction. This array covers both opaque, translucent and transparent constructions, and constructions with air gaps or openings

The reason for using the predefined arrays is that the output from any type of component is known, concerning type and order of data in the array. Therefore, when creating new models, the type of input and output from other blocks is already known. The blocks just need to be connected, and they will be able to communicate with each other. This approach will inevitably give arrays where one or more of the data positions in the array are not activated. However, at the same time the same array can be used from all components of the actual type regardless of the model.

From Table 1, it can be seen that some choices have been made with respect to which data should be exchanged. As an example, the convective thermal surface resistance has been defined to be an output from the construction – and not an input from the zone array. Therefore, the calculation of the convective thermal surface resistance must be performed in the construction block. Of course, this could also have been done in the zone model. This example illustrates the type of choices and considerations involved in the design process of the communication arrays.

In case it should be necessary to include further data in the exchange between blocks (i.e. if a control system variable depends on a given parameter which is not included in the pre-defined arrays), this can be done by using a user-defined array.

MATERIAL DATABASE

The material parameters are arranged in a material library 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).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, e.g. (data(2)). These structures called "data()" are saved to a Matlab file, e.g. *DATABASE.mat*. In order to access this structure from Simulink, the file must be loaded either in the Matlab Workspace or by the block mask initialisation to the local Workspace. Now there is an access to the structure, which can be used in the model as any other variable. The different materials can be given an index in the block mask by using a pop-up menu and after choosing the material; all the material parameters in this block are valid only for the material chosen.

Keeping the same structure, and especially field names, any user can create his/her own material library. It should be stressed, anyway, that a range of field names are already definite for particular uses. 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.

DOCUMENTATION

Each block in the toolbox is documented according to the following paradigm:

- Description – a short description of the use of the block
- Block diagram – the "front page" of the block as it appears in the toolbox
- Input to the block – which arrays does it require as inputs?
- Output from the block – which arrays does it output?
- Block mask – here different properties for the block can be set. E.g. the insulation thickness in a wall
- Variables – variables used in the mathematical model
- Mathematical model – a documentation of the mathematical model used
- Simulink model – the implemented model
- Miscellaneous – connection to the neighbouring blocks, logging of results, etc

- Validation – if a block has been validated, this must be included. The validation can be a comparison to hand calculations and/or measurements

This documentation is important in the use of the IBPT, as it is here the model is described with respect to the level of detail (what is included and what has been left out). The documentation is also a help file for the user in case of difficulties in using the block.

EXAMPLES

Three examples are given on the use and flexibility of the IBPT. Example 1 shows the implementation of an outer wall with heat, air and moisture transport, which is directly modelled using Simulink blocks. In Example 2, a floor heating system is modelled. This is done using an S-function. Finally, in Example 3, a room model including the blocks from the two first examples is created. It should be noticed, that the blocks in the two examples have been created by different research groups. They have been built in accordance with the requirements of the IBPT, and are thereby able to work together in the room model.

Notice that where the numerical model in Example 1 has been validated, this is not the case for the models presented in Example 2 and 3. Work is in progress to validate the models used here.

EXAMPLE 1: WALL

The wall is treated as a multi-layered structure of different materials in direct contact or connected through a ventilated or non-ventilated air gap. 1D heat, air and moisture (HAM) transfer through the wall is solved numerically using the control volume method.

An example of a numerical procedure and Simulink model for a simple, one material external wall is given in Figure 3. The block icon named as "External wall" corresponds to the numerical scheme given on the right, where the space discretization is obtained by dividing the total wall thickness into five control volumes. Each volume is presented by separate Simulink blocks that are connected following the numerical scheme. The complete Simulink model of the considered wall is shown in Figure 3: one External surface node, three One nodes (used internally in the material) and one Internal surface node.

The layer of the considered material is modelled as a porous structure, consisting of the skeleton of the main (dry) material and pores filled with moisture and air. The output of the system gives temperature, water vapour partial pressure and moisture content of the volume – it's hygrothermal state. Material and geometrical data of the volume are placed either in the model or in a material data file, from which they are called during simulation.
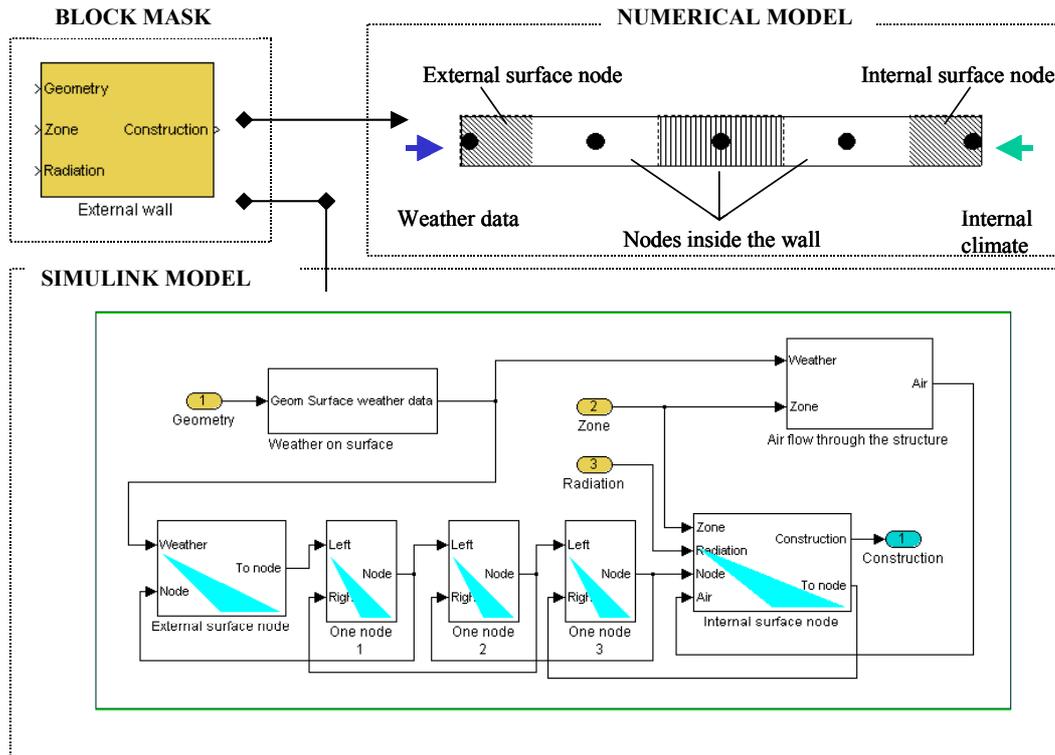
Figure 3 Model of wall with heat, air and moisture transport

External and internal surface nodes describe the surface transfer coefficient between the wall and surrounding air. The model assumes that the external wall surface is exposed to convective heat and moisture exchange with outdoors air, incident solar radiation, long wave radiation, transfer of latent heat, air and rain. Internal wall surface is exposed to convective heat and moisture exchange and transfer of latent heat with inner air, and long wave radiation exchange with other surfaces.

VALIDATION OF THE WALL MODEL

The HAM wall block is validated through the inter-model comparison performed within the HAMSTAD project, which was initiated in order to develop a platform for assessment of computational modelling of HAM transport mechanism in building physics. In this project, five benchmark tests were defined. Details are provided in the project report (Hagentoft, 2002b).

Some results for one of the benchmarks, which covers heat, air and moisture transfer, are given in Figure 4. The benchmark deals with an air transfer through a single material layer. Moisture transfer is caused mainly by the airflow through the layer, and by the moisture and temperature gradients across the layer. The left hand side of the layer is vapour tight, but air-open.

Validation of the HAM room model (like the one in Figure 6) with the measurements taken on the real object is the work in process.

EXAMPLE 2: FLOOR HEATING MODULE

Another approach to creating models in Simulink is to use so-called S-functions. An S-function is "a computer language description of a Simulink Block" (MathWorks, 2002). The S-function can be written in C, C++, Fortran, Matlab or Ada. The advantage of using an S-function is the fast execution, which due to the special syntax can communicate directly with Simulink's equations solvers, much in the same way
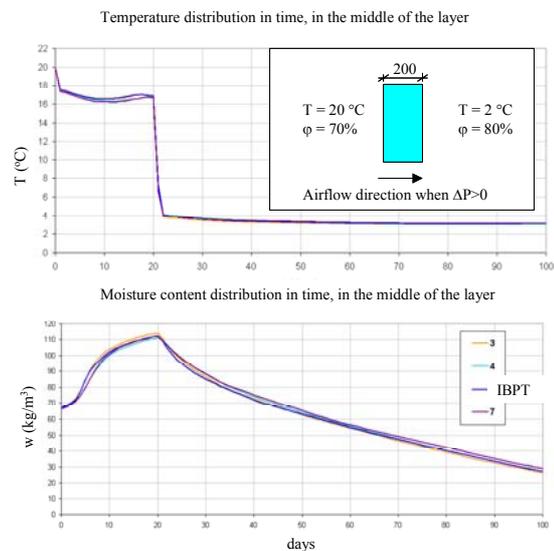

Figure 4 Validation results for the IBPT HAM wall block. Comparison with different solutions
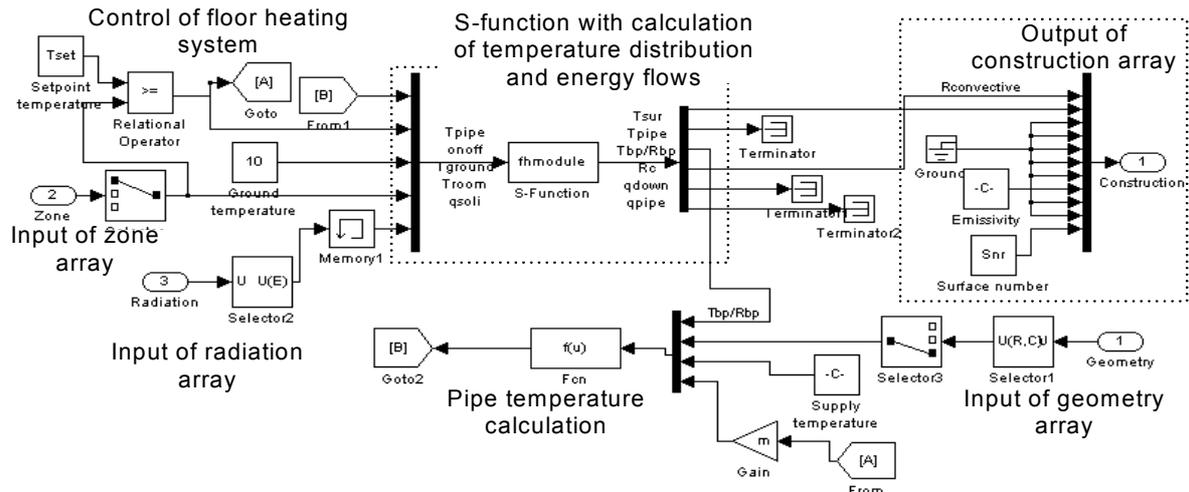
Figure 5 Floor heating block. The numerical model of the floor heating system is placed in the S-function called 'fhmodule', placed in the middle of the block.

as the built-in Simulink blocks do.

A section of the floor around a floor heating pipe has been modelled and implemented into an S-function. The model is described in detail in Weitzmann (2002), and in Weitzmann et al (2002), where the same model was used in the form of a Matlab m-function.

The implementation of the floor heating module includes a two-dimensional finite control volume calculation of the temperature distribution and energy flows in the floor. Notice that in the floor model, the temperature and energy flows are calculated within the model and not by the built-in Simulink solver. However, this is not a problem for Simulink as it only passes the parameters to and from the S-

function and therefore does not have problems accepting the calculated values from the S-function

The model, includes both radiation and convection exchange with the room. The pipe temperature is calculated based on the heat flow through the floor heating pipe boundary. The control system is a simple on-off type based on the room air temperature.

The model of the floor heating block can be seen in Figure 5. The temperature distribution and energy flows are calculated in the block called 'fhmodule', which is the S-function. The block is set to have a discrete sampling time, where, the output from the block is assumed constant between the samples. This approach has been used because a finite control
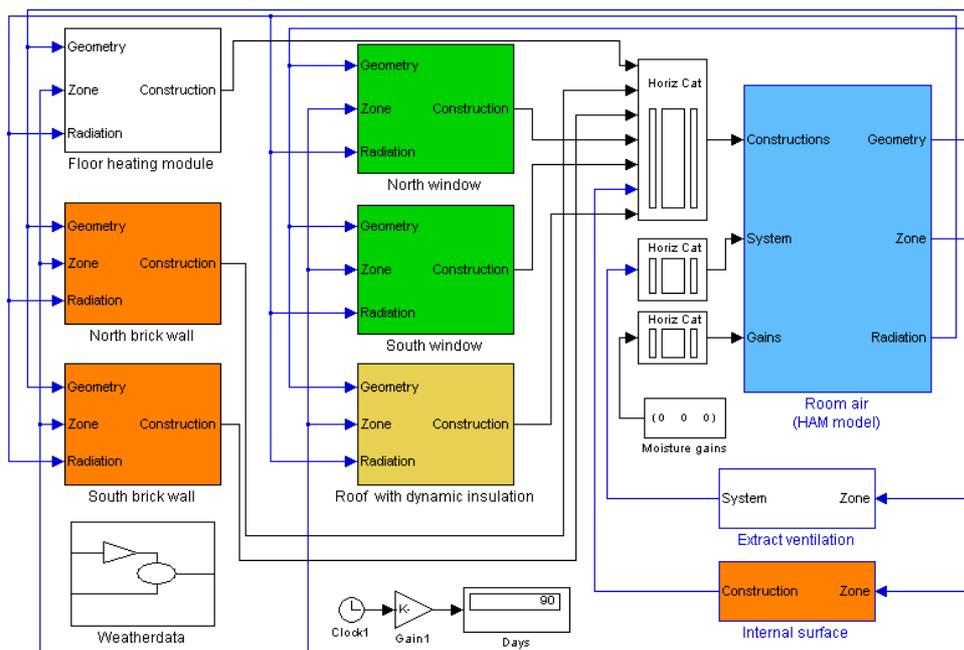

Figure 6 Room model with HAM walls and floor with floor heating. The other blocks have been taken directly from the toolbox

volume method requires a fixed discrete timestep. Notice also, how the construction output array is assembled in the upper right of the figure. Here most of the values have been grounded (signal equal to zero). The fact that they have been included is that the other blocks expect a construction array with 11 values.

EXAMPLE 3: ENTIRE ROOM MODEL

The two blocks shown so far are used in a complete room model where the remaining blocks have been taken from the toolbox.

The temperature, relative humidity and air pressure of the ventilated space is calculated accounting for the heat and moisture gains through the building envelope, internal sources and HVAC equipment placed in the space. All geometrical data like areas, orientations and tilts of the attached construction elements are given as input to the room air block.

The room model assumes well mixed air (one air node), and calculates long wave radiation between the internal surfaces.

The room air model, the constructions and HVAC equipment are represented by different Simulink block models, shown in Figure 6. The number of attached elements is not limited, as well as the number of additional zones. Structural details, materials, meteorological data and applied equipment are designed in such details to represent the reality in a credible way.

Some of the results from this simulation are presented in Figure 7. They illustrate the sensitivity of the model regarding the surrounding and working conditions.

CONCLUSION

In this paper, the International Building Physics Toolbox is presented and a few examples of the usability are shown.

The modular approach together with the definition of the communication arrays gives a versatile and easy-to-use environment for creating building physics models. The toolbox is open source and the blocks that make up the modelling elements are freely available from the website www.ibpt.org. Therefore, there is no need to start over when creating models. Also, anyone is free to contribute their models, as long as they are in compliance with the requirements concerning data exchange and documentation.

So far, the IBPT only contains fairly simple models containing only heat transfer. But as shown in the paper, more advanced models including air and moisture and building integrated heating systems can also be included. Furthermore, there are many different ways of modelling the blocks in the toolbox. In the paper, two were shown: One using only the graphical environment of Simulink and the other using S-functions. Other possibilities of modelling can be found in Femlab and the other toolboxes available in Matlab. In addition, there is no need to worry about the solver, as Matlab has an extensive list of state-of-the-art ODE-solvers available.

Simulink and Matlab also have many advanced features for post processing of the results from the simulation, as it can be seen from the figures in the text above.

The graphical programming environment is useful for teaching building physics as the interaction between different parts of the model can easily be visualized.
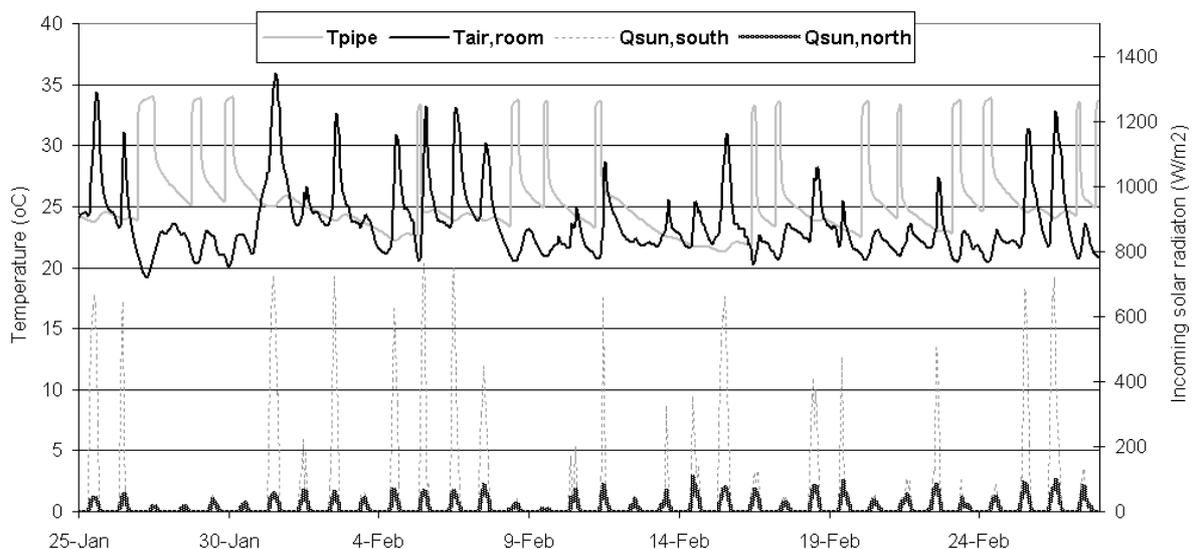

Figure 7 Results from simulation of the example model

One initial concern about the development of the toolbox where different people develop models independently of each other was that it would not work, and that Simulink would refuse to do simulations. This has been proven wrong, because of the strict definition of the communication arrays.

A few drawbacks should also be mentioned. The calculation time is not impressive and cannot compete with native code in other programming languages such as Fortran, C or C++. However, the implementation time is much quicker. Finally, the availability of Matlab should also be mentioned as a problem, as the program is very expensive.

To sum up, the IBPT represents an open and user friendly way of modelling building physics processes. If a researcher (or student) wishes to investigate a certain part of a building and see how it interacts with the entire building – for instance a solar wall, she does not need to create the entire model of the building from scratch. She can focus on the modelling of the solar wall and get the rest from the existing blocks in the IBPT. She can then choose a set of blocks with the level of detail in modelling that she is interested in including into the investigation. When the development and investigation of the solar wall has been completed and documented according to the requirements, she is welcome to upload the block to the website where it will become part of the toolbox and thereby freely available by other researchers and students! In this way, it is hoped that the toolbox over time, will develop into a full modelling tool with open source and fully documented code for the modelling of building physics processes.

Finally, the authors of this paper therefore invite anyone who is interested to participate in the further development of the IBPT. All information on the use of the toolbox and further development of the blocks can be found on the website.

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