Simulink modelling tool for HAM-system analyses in building physics

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1. INTRODUCTION

A calculation tool for HAM (heat, air and moisture) 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 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 and moisture sources, HVAC components, etc. is made in Simulink. All models are made as block diagrams and are easily assembled in a complex system through the well-defined communication signals and ports. Simulations are run under both steady-state and transient real outdoor and indoor climatic conditions.

2. BUILDING PHYSICS TOOLBOX

BFTools is the library of models, specially constructed for HAM-system analyses in building physics. There are two main models, representing the most frequent objects of interest: a *wall*, as a layered structure of different building materials, and a *ventilated space,* which is enclosed by the building envelope. Wall models provide detailed calculations of hygrothermal state of each component in the structure, according to the surrounding boundary conditions to which it is exposed. The hygrothermal condition of the ventilated space determines by the heat and moisture gains through the building envelope (walls), and through the *windows*, *HVAC-system* and *internal gains*, additional components presented by the model of the same name. Direct coupling between the wall and the surrounding air (internal/external climate, ventilated space) is accomplished by *internal and external surface conditions* – models for heat and moisture balance at the wall boundaries.

2.1 Heat, air and moisture balance in the wall

The wall is treated as a multi-layered structure of different materials in direct contact or through the ventilated or non-ventilated air gap. The calculation of one-dimensional heat, air and moisture transfer through the wall is governed by the following model equations[1] (Hagentoft, 2001):

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[1] There are three types of BFTools libraries, classified as 1, 2 and 3. The first, BFTools1, contains models that cover only heat transfer. The second library, BFTools2, contains models for heat, air and water vapour transfer through the structure. The third library, BFTools3, offers models with heat, air and moisture transfer through the structure, concerning both vapour and liquid transfer. Modelling equations presented here relate to the models from the BFTools3 library.

heat transfer by conduction and convection:

$$q = -\lambda(w,T)\frac{\partial T}{\partial x} + \sum_{a,v} g_k c_{pk} T + g_v \cdot r_e,$$ (1)

vapour transfer by diffusion and convection:

$$g_v = -\delta_p(\varphi,T)\frac{\partial p}{\partial x} + g_a \cdot x,$$ (2)

liquid moisture transfer:

$$g_w = K\frac{\partial P_{suc}}{\partial x},$$ (3)

air flow through the structure:

$$g_a = const.$$ (4)

To exemplify the numerical process, the heat conduction procedure is presented in more details below. The numerical procedure is based on a finite volume method, with thermal/moisture capacity of the layer (volume) localized in the middle, Figure 1, left. The heat conductance between the node and the surfaces of the layer is K (W/K), and the conductance between the surfaces to the neighbour temperature nodes to the left and to the right are denoted K_l and K_r respectively.
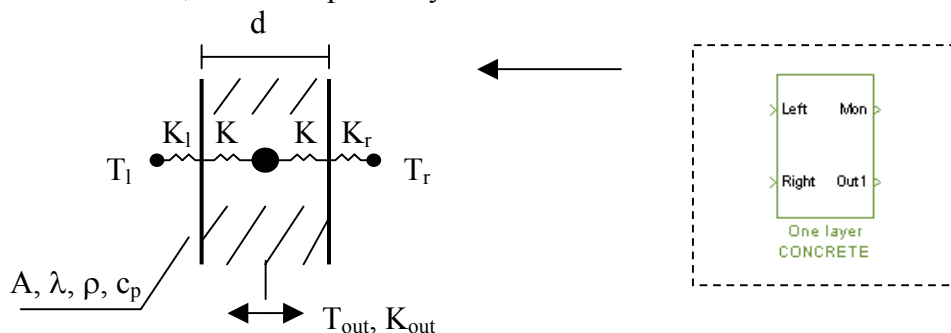

Figure 1:   Left: One calculating node in a finite volume method, with the lumped heat capacity in the middle of the volume. Right: Simulink model for one control volume of the considered material.

The conductance K is defined as $K = A \cdot \lambda/(d/2)$, where A is the surface area, d is the thickness of the layer and λ is the thermal conductivity of the material. Input signals to the block are temperatures and conductances of neighbouring nodes T_l, K_l, T_r, K_r while the output signal contains information about the node T, K. These data for each node are organized as vectors of type *(KT,K)*, carrying the product $K \cdot T$ on the first place, and the conductance K on the second. Assuming that the surface temperatures of the layer are known, T_{sl} and T_{sr}, the ordinary differential equation for the layer becomes:

$$C\frac{dT}{dt} = K \cdot (T_{sl} - T) + K \cdot (T_{sr} - T)$$ (5)

The equation says that the temperature change per time unit is balanced by the heat flow rate from the left and from the right. In the local steady-state condition between the layer and the neighbouring nodes, surface temperatures are calculated as

$$T_{sl} = \frac{K \cdot T + K_l \cdot T_l}{K + K_l} \quad \text{and} \quad T_{sr} = \frac{K \cdot T + K_r \cdot T_r}{K + K_r}$$ (6)

A corresponding finite volume model is used for moisture balance.

A Simulink model for one calculating node (one control volume of a certain material) is presented on Figure 1, right. This block solves the system of coupled equations (1)-(4). The solution 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.

The model of a complex wall structure is obtained by connecting the desired number of one node models, like in Figure 2. The squared block icon for Timber frame wall hides the structure from the picture below - the Simulink model of a wall consists of, from outside to inside: wooden layer, insulation, wooden layer and gypsum board. Two additional blocks – external and internal surface conditions blocks describe the surface transfer coefficient between the wall and surrounding air.

2.2 Boundary conditions at the wall surfaces
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. All outdoor thermal influences are lumped into equivalent outdoor air temperature, (Hagentoft 2001).

Internal wall surfaces are exposed to convective heat and moisture exchange and transfer of latent heat with inner air, and long wave radiation exchange with other surfaces. As for the external boundary, all these influences are lumped into an equivalent indoor air temperature.

2.3 Heat and moisture balance of the ventilated space
The temperature and relative humidity 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. Heat balance model assumes (Wit at al., 1987):
- uniform air temperature,
- all radiation is distributed in such a way that all surfaces absorb the same amount per unit of surface area
- the surface coefficients for convection and radiation are the same for all surfaces.

The room air model and each of the wall or HVAC equipment component have their own Simulink block model, as it is presented in Figure 3. The blocks exchange information organised as vectors or signals of a prescribed structure. These signals are presented as connected lines between the blocks.

3. EXAMPLES OF THE HAM-SYSTEM ANALYSIS USING BUILDING PHYSICS TOOLBOX
The case study: a room with an outer wall (type: timber framed insulation) facing south with one window, flat roof (type: same as outer wall) and floor on the ground (type: insulated concrete slab on the ground), as it is presented in the Figure 3. Other specifications can be found in Tables (1-3).

The results of one year operating cycle of this space, with the specified building envelope and heat and moisture loads are presented in Figures 4-7. The external climate data are representative for Gothenburg, Sweden. The walls which are not included in calculations are regarded as heat and moisture non-active.

All presented results can be seen during the simulation, on the Simulink's Scope block (see monitors in Figure 2 and 3), as a graph "value in time".
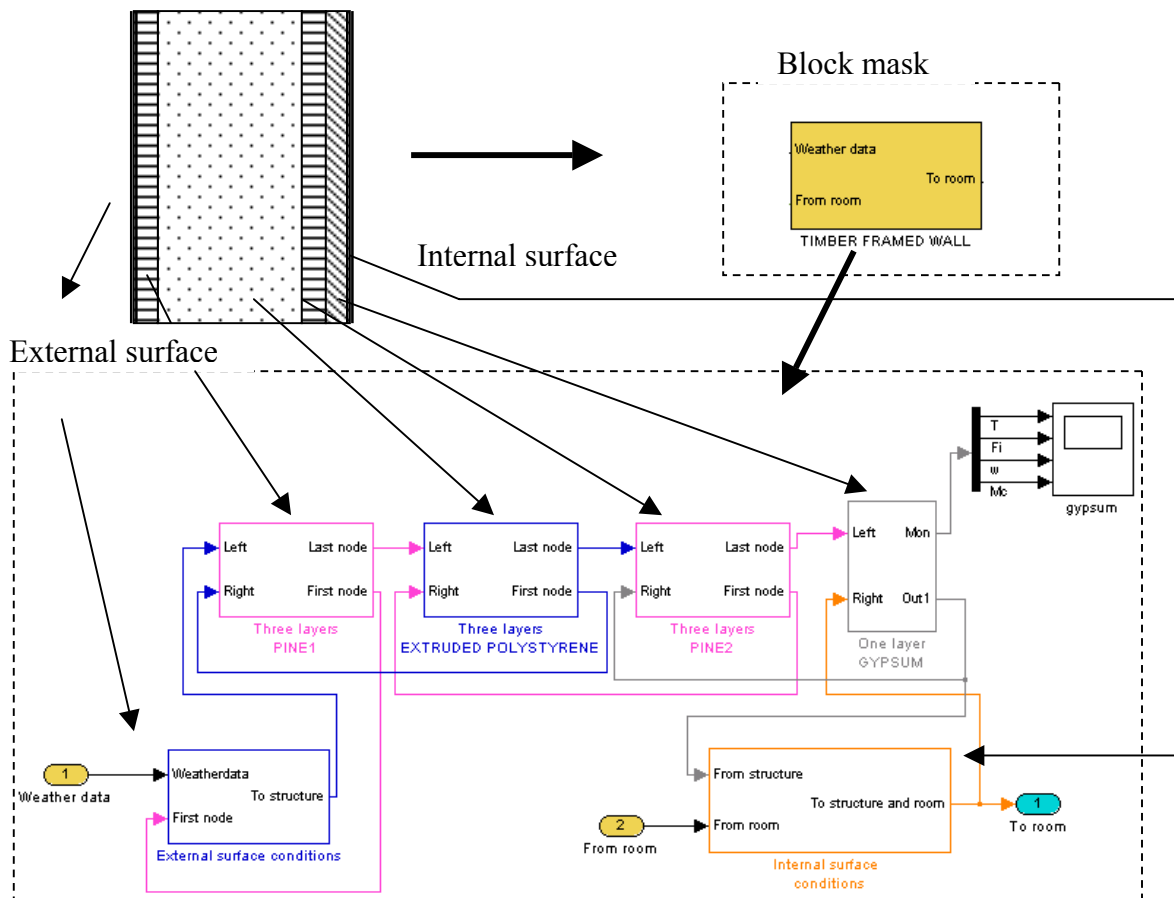

Figure 2:   Simulink model for a complex wall structure.

Table 1:   Input parameters for the case study: room geometry.

Component	Area	Structure			Initial values
Outer wall (without window area) and Roof	10 m^2	Wooden layer	Pine	0.044	20°C, 60%
		Insulation	Extruded polystyrene	0.2	
		Wooden layer	Pine	0.044	
	25 m^2	Gypsum board	Gypsum	0.013	
Floor	25 m^2	Soil	Bed rock	1	10°C, 100%
		Insulation	Rock wool RW 36	0.2	20°C, 60%
		Concrete	c/w=0.4	0.15	20°C, 60%
Window	2.5m^2				U=1.5W/m^{2}K
Total room area :	100 m^2				
Total volume:	62.5 m^3 (5x5x2.5m)				20°C, 60%

Table 2:   Input parameters for the case study: transfer coefficients.

Transfer coefficient	Surface	Value
Heat transfer coefficient	External / internal surface	20 / 7 W/m^{2}K
Vapor transfer coefficient	External / internal surface	2e-8 / 1e-7 s/m
Solar radiation absorptivity	Outer wall	0.7
	Roof, window	0.5

Table 3:   Input parameters for the case study: heat and moisture gains.

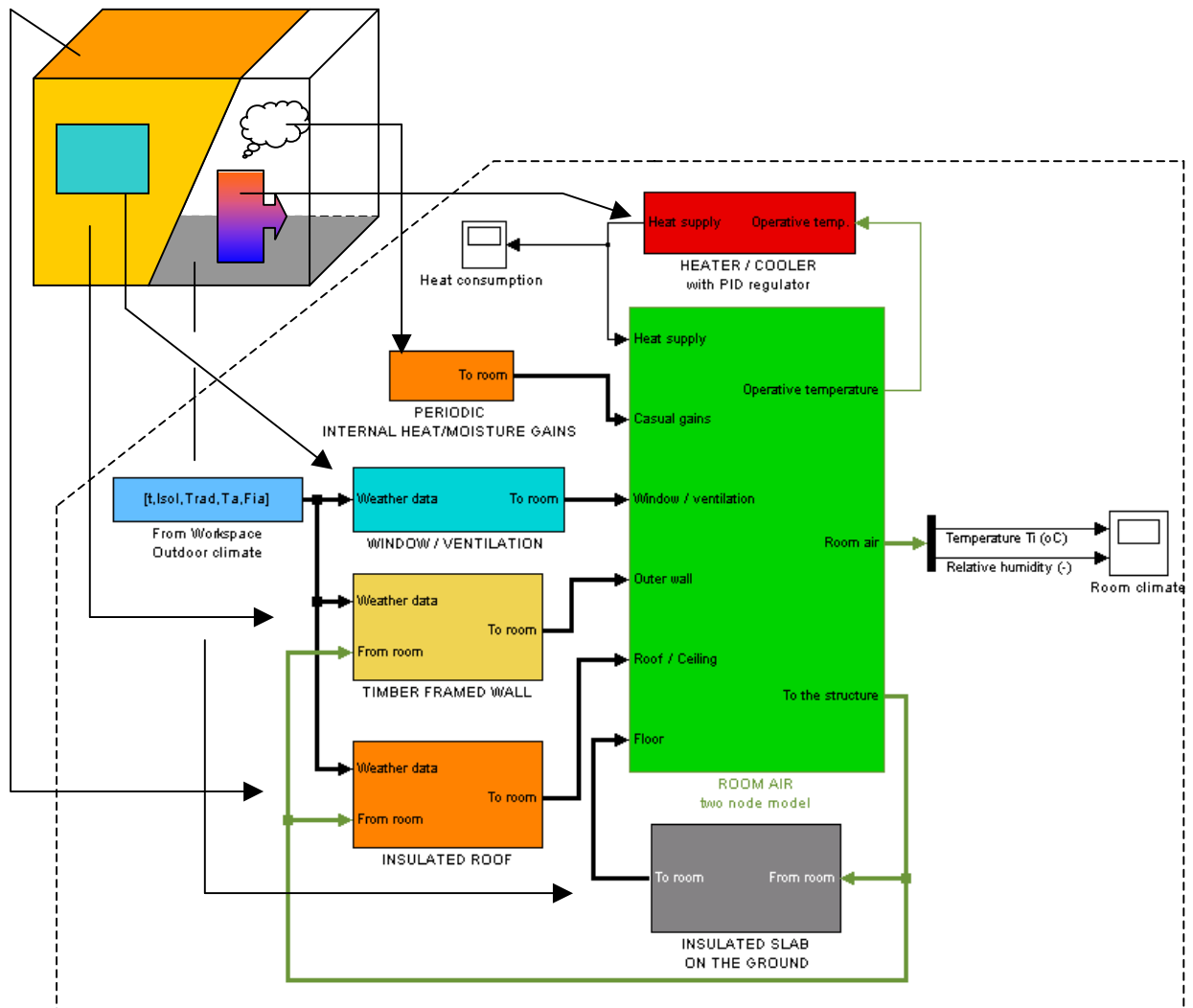| Source	Operating mode	Range
Ventilation	First calculation: 0.2 1/h, Second calculation: 0.5 1/h	12.5 m^3/h 31.25 m^3/h
Heat supply	Variable, Tset=20°C, ΔT=2°C, P-controlled in the same way for both ventilation regimes	Q=0-2000 W,
Internal heat gains	Periodically varying, operating cycle 24h,	Q=0-100 W,
Internal moisture gains	Constant	100g/h

Figure 3:   Simulink model for ventilated space.

4. CONCLUSION

BFTools library offers a tool for analysing complex structures of interests. Each model from the library is transparent and can be disassembled to the very basic pieces like symbols for mathematical calculations, and will therefore not representing a black box for the user. The library itself is open for models made by other users - the only condition is to obey the signal structure, see (Sasic, 2002).

Using the advantage of Simulinks graphical interface, huge amount of work relating to formulating equations in a language or a program is avoided and an attention is focused to the

physical problem. This is already experienced through the courses given to the students and researchers.
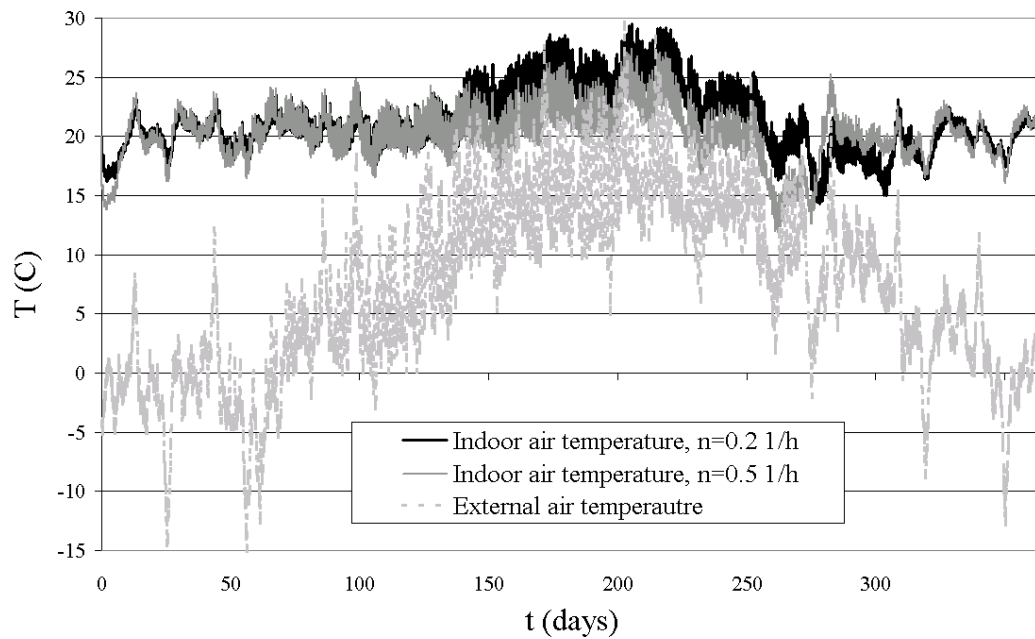

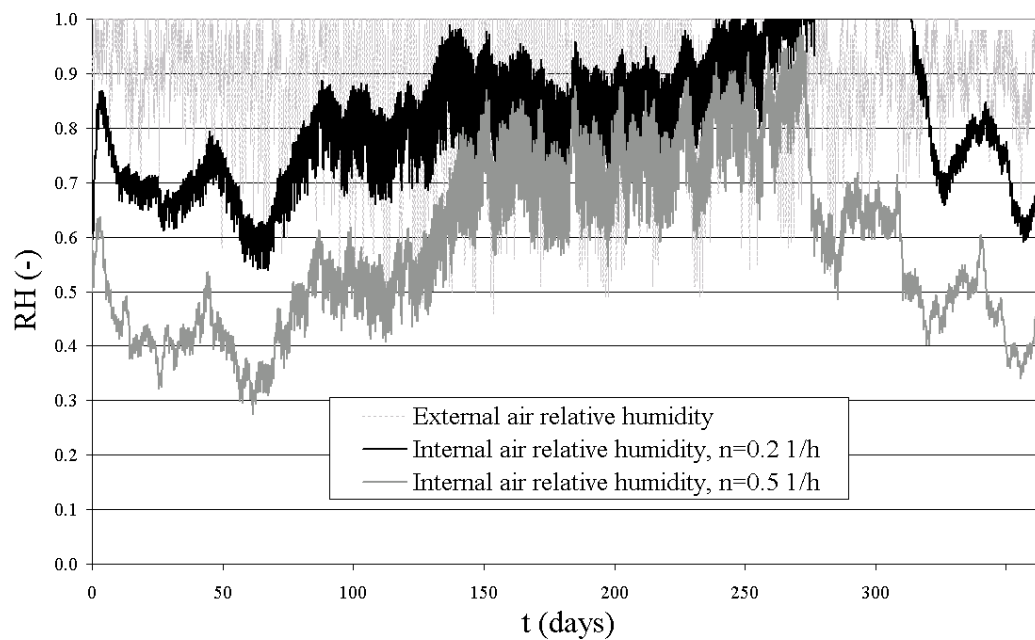Figure 4:   Room air temperature for two ventilation loads and external air temperature.

Figure 5:   Room air relative humidity for two ventilation loads and relative humidity of external air.

It is up to the user to decide which modelling equations should be used for the analyses. Models from the library can be used as black boxes, as the start point, and later adjusted to the desired model. No matter how complex the problem is, the solution will be obtained in a relatively short time (i.e. 15 min for the simulation presented here) and without any

difficulties connected to the numerical stability of the chosen procedure. This is accomplished by the set of numerical solvers built in Simulink, providing the numerically stable calculations no matter how coarse the disretisation scheme is.
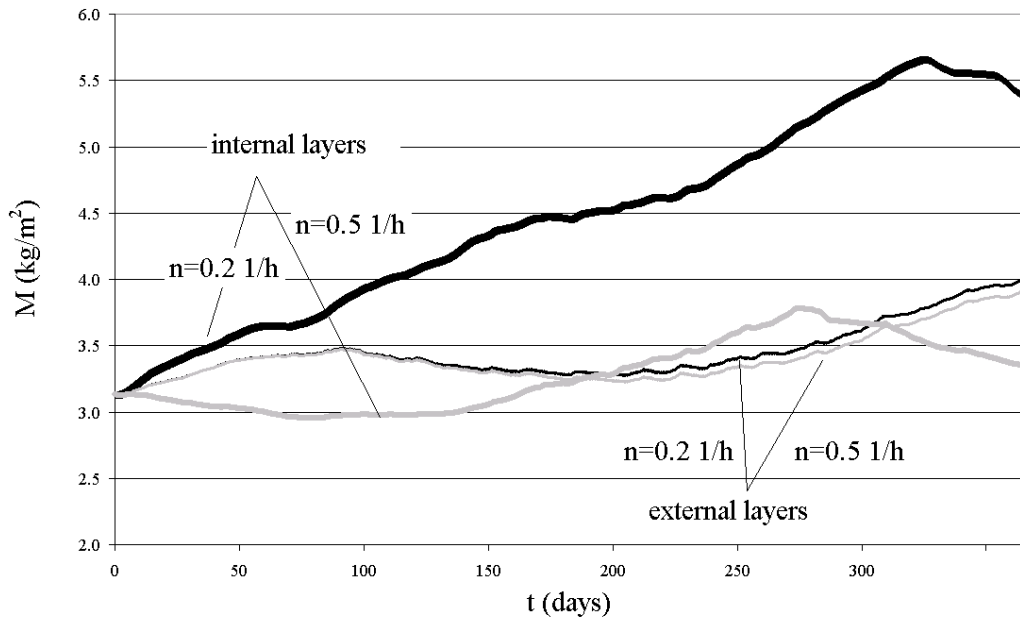

Figure 6:   Moisture content in the insulation layer of the outer wall for the two ventilation loads.
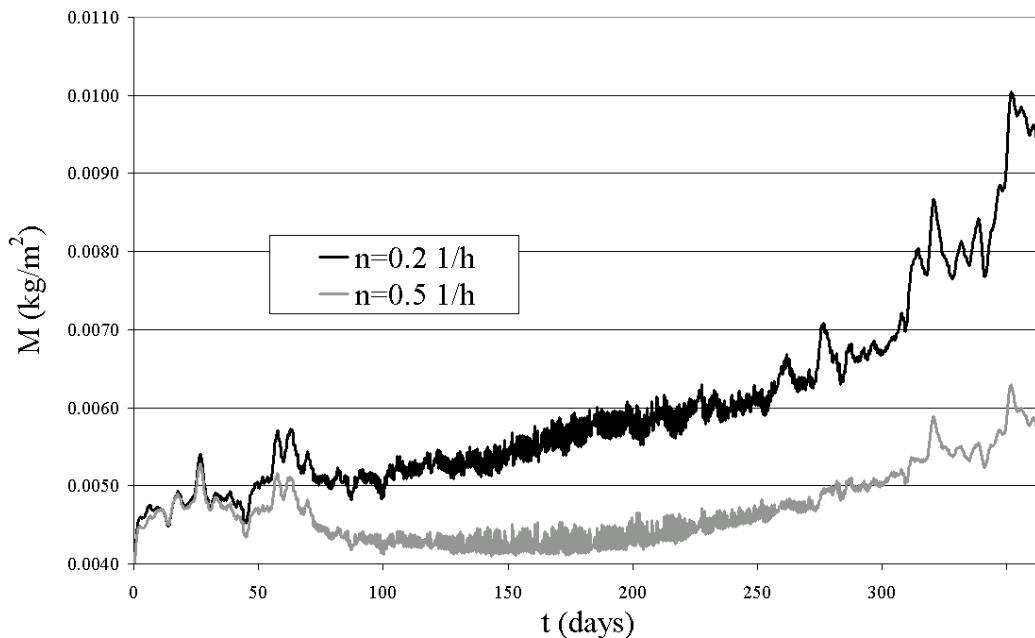

Figure 7:   Moisture content in the external and internal wooden layer of the roof for two ventilation loads.
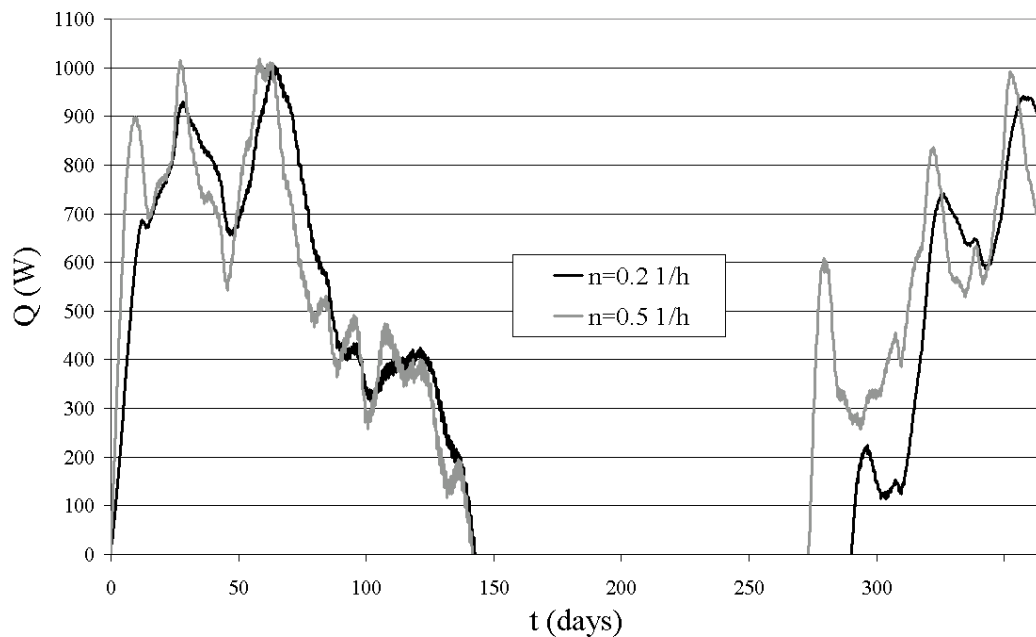
Figure 8:   Heat input from the heating system (HVA) for two ventilation loads.

5. REFERENCES

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