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# The Whole Model Validation for HAM-Tools—Case Study: Hygrothermal Conditions in a Cold Attic under Different Ventilation Regimes

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## ABSTRACT

*HAM-Tools is a software library specially constructed for hygrothermal system analysis in building physics. The software is developed as a modular structure of standard building elements and systems using a graphical programming environment. Due to its modular structure and transparency, each of the existing components can be easily changed and adjusted to specific user demands. In order to assess the software's ability to predict the building hygrothermal response under given climatic and operating conditions, validation tests against measurements have been performed. As a case study, temperature and relative humidity of a cold ventilated attic space in real operating conditions was selected. Validation results are presented as a comparison between measurements and calculations. Parametric sensitivity analyses were performed and necessary adjustments for the missing input parameters have been fully documented. The code has shown a high degree of reliability, both in a qualitative and a quantitative way.*

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## INTRODUCTION

The work presented here concerns the validation of a whole building simulation tool. The program, HAM-Tools, has been developed as a research and educational tool for building physics applications. It is designed to provide a better understanding of the whole building heat, air, and moisture response in operating conditions, thus obtaining information about the effects that a certain design has on indoor environment, energy consumption, and durability of the enclosure.

As a case study for the validation of the program, air temperature and relative humidity of a cold ventilated attic space in real operating conditions was selected. Validation is performed by comparing the output of the simulations with data collected from the real model. This test exemplifies to what extent the program can predict the selected target.

This work aims also to exemplify the complexity of the validation test, which is mostly related to availability and completeness of input data for the problem. By now, there is only one official verification test for the whole building energy simulation tools—the BESTEST (Judkoff and Neymark

1995), based on intermodel comparison. Similar tests or empirical validation procedures for programs that include moisture transfer analyses on a building as a whole are not publicly available. Further development in building simulation tools capability is focusing on problems of hygrothermal performance of whole buildings (IEA-EXCO Annex 41, 2003). This means that there is a need for such validation procedures, which will probably be more expressed in the near future.

## ABOUT HAM-Tools

HAM-Tools is a building simulation software program. “HAM” stands for *Heat, Air, and Moisture* transport processes in a building and building envelope that can be simulated by this program, and “Tools” describes its modular structure. The program is designed using a graphical programming environment and is composed as a library of block diagrams, where each block represents a certain building part of interest (Sasic 2004). Blocks are grouped according to their functionality into five categories:

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1. constructions (external / internal walls and windows)
2. zones (air volume of the room)
3. systems (HVAC systems)
4. helpers (handling of weather data)
5. gains (internal heat and moisture gains)

The program provides one-dimensional calculations of the HAM transport processes in a building enclosure and assumes well mixed air in air zones. By using the system of well-defined data signals (Rode et al. 2002), blocks or tools may be combined in a more complex calculating procedure, leading to a prototype of a building as a system (see Figure 3). A unique signal structure and material database definition are the “backbone” for a separated and leveled development of the components. A graphical approach enables a clear overview of the complex interaction between different parts of the model.

Material and weather data are also joint parts of the library, providing variations in design and climatic conditions. As a part of International Building Physics Toolbox (IBPT 2002), HAM-Tools is an open research tool and publicly available for free downloading. Any researcher can use, expand, and develop the contents of the library.

## SCOPE AND SUBJECT OF THE HAM-Tools ATTIC MODEL VALIDATION

The aim of this validation is to estimate the program’s ability and accuracy in predicting the internal climatic conditions of the investigated attic by comparing the results of calculation (attic air temperature and relative humidity) with the data from the attic in use.

Until now, only the HAM-Tools wall block has been validated through the intermodel comparison performed within the HAMSTAD project (Heat Air and Moisture Standardization). The project was initiated by the European Union (2000-2002) in order to develop a platform for the assessment of the computational modeling of a one-dimensional HAM transport mechanism in building physics. In this project, five benchmark tests were defined together with the set of material and climatic data. Up to eight different computational codes participated in the project, originating from several European countries, Israel, and Canada. Details are provided in the project report (Hagentoft 2002).

The HAM-Tools attic model involves the running of several different blocks at once: wall, zone, and system models, as well as the handling of climatic and material data. Thus, this validation represents the validation of the whole building model, i.e., its heat, air, and moisture response to specified climatic conditions.

## PROBLEM DESCRIPTION

A “cold attic” is an attic with a thermally well-insulated floor structure. In Sweden, the insulation thickness is 384 mm, on average, for a single-family house (between 220-500 mm according to Energimyndigheten [2001]). Thus, the heat lost

from the dwelling/office below the attic is kept to a minimum and the attic remains cold throughout the winter, with the temperature close to that of outdoors.

Over the years of such practice, cold attics have encountered problems of mold growth due to the certain temperature and relative humidity range combinations and the duration of such periods. A number of investigations have been done on this topic looking for the cause and the remedy for the problem (see, for example, Hukka and Viitanen [1999]).

One such research project (Samuelson 1995) was organized by the Swedish National Testing and Research Institute in 1994-1995. The aim of the project was to investigate the influence of the ventilation rates and the moisture buffering effect of the insulation on the indoor climate of the cold attic by measurements taken on the spot. The data collected in this project have been used here for HAM-Tools attic model validation.

## Construction Details of the Experimental Attic

The experimental attic is constructed above a flat-roof office building. The entire space is divided into eight equal sections, adjacent to each other in a single line. An additional ventilated space is built under the attic floor in order to stop any transfer of the warm air from offices to the attic, which is accomplished by exhaust ventilation in this section.

The attic is 30 m long and 10 m wide, with 30° pitched roof. The whole floor is insulated with 500 mm thick loose-fill insulation. Internal sections are separated from each other by the walls made of 50 mm loose-fill insulation (mineral wool) wrapped in plastic foil. There is a walking path along the whole attic, 1.2 m wide, made of chipboard. The roof is covered with concrete tiles on the outer side.

Six internal sections marked as A-F (Figure 1) were used for the measurements, while two sides served as protection zones. Sections differ in ventilation regime, floor insulating material, and some other construction details, according to the following scheme:

- Ventilation regimes:
  - A and B mechanically ventilated, 2 ACH
  - C and D not ventilated
  - E and F naturally ventilated, but no other specifications about ventilation rates are given
- Insulation materials:
  - A, C, and E mineral wool
  - B, D, and F cellulose
- Internal layer of the roof construction:
  - A reinforced PE foil
  - B-F 12 mm thick plywood plate

Air temperature and relative humidity were measured outdoors in six internal spaces and in the protecting zone below the insulation. Data were recorded as two-hourly mean values. Apart from these, insolation, wind speed, and wind direction were recorded as mean hourly values.

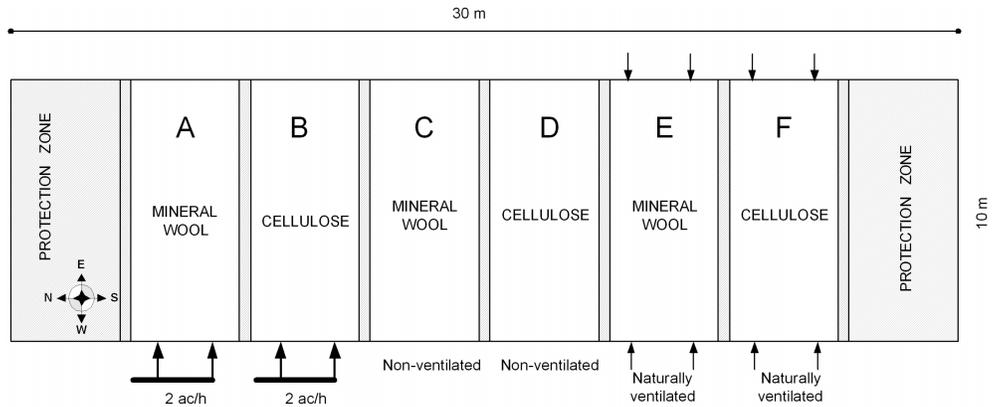


Figure 1 The plan of the investigated attic.

Table 1. Initial Values

Initial Temperature and Relative Humidity						
	A	B	C	D	E	F
Temperature (°C)	9.4	9.7	9.7	9.5	10.2	9.2
Relative humidity in construction elements and air zone (%)	81	78	75	72	85	76
Relative humidity in insulation (%)	61	58	55	52	65	56

## INPUT DATA

### Initial Conditions

Measurements are available from October 1, 1994. Temperature and relative humidity in air zones (of the attic, outdoors, and in the protection zone below the attic) are available from that moment, but not the corresponding states in construction elements. The problem is “path-dependent,” and initial hygrothermal states have a significant influence on calculation results. In Samuelson (1995), mean air temperature and relative humidity of the attic air in all six compartments are given for September and October 1994. Based on these values, initial temperature and relative humidity in construction elements and air zones are chosen to be equal to the mean of the mean values for September and October (Table 1). Initial relative humidity in the insulation (and for each section) is approximated to 20% less than in other construction elements (roof, walking path), in order to compensate for an excessive amount of moisture that is released after establishing the real temperature gradients in this layer. This parameter is discussed more in the “Sensitivity Analysis” section.

### Boundary Conditions

Indoor and outdoor temperature and relative humidity in the air have been measured with the two-hour time sequence. These data have been used in simulations as step functions (no interpolation has been performed within the time sequence).

Solar radiation intensity data for the site are available as hourly measured global radiation intensity on a 45° tilted and south-oriented plane. The roof sides are, however, east- and west-oriented and 30° tilted and, thus, they get less amount of insolation than measured. The necessary transformation of the measured data to the input data for the simulation is done in the following way.

Using the computer program Meteonorm (2000), monthly average values of the global radiation for a 45° tilted and south-oriented surface,  $Glob\_S\_45$ , are generated, and also data for 30° tilted, east- and west-oriented surfaces,  $Glob\_E\_30$  and  $Glob\_W\_30$  (Table 2). The data relate to the nearest site (the town of Gothenburg), which is about 50 km from the measuring location.

The following relations are established and calculated for each month:

$$ratio\ E = \left( \frac{Glob\_E\_30}{Glob\_S\_45} \right)_{Meteonorm} \quad (1)$$

$$ratio\ W = \left( \frac{Glob\_W\_30}{Glob\_S\_45} \right)_{Meteonorm}$$

Parameters “ratio E” and “ratio W” enclose, in a simplified way, differences between angles of incidence of the sun on the surface of the measuring device and the roof. The alternative is to perform detailed calculations of the angle of incidence and backward transformation of measured global radiation data. Since this angle does not change much during

**Table 2. Monthly Averaged Values for Global Radiation on the Differently Oriented and Tilted Surface\***

Global Radiation on Tilted Plain, kWh/m <sup>2</sup>						
	Oct	Nov	Dec	Jan	Feb	Mar
Glob_S_45	66	39	21	26	43	72
Glob_W_30	37	17	8	12	24	51
Glob_E_30	39	17	9	12	26	51
ratio W	0.56	0.44	0.38	0.46	0.56	0.71
ratio E	0.59	0.44	0.43	0.46	0.60	0.71

\* (Data Generated by Meteonom)

**Table 3. Modeled Monthly Averaged Values for the Global Radiation on the Attic Roof**

Global Radiation on Tilted Plain, kWh/m <sup>2</sup>						
	Oct	Nov	Dec	Jan	Feb	Mar
GlobS45°_meas	72	38	31	40	43	80
GlobW30°_calc	40	17	12	18	24	57
GlobE30°_calc	42	17	13	18	26	57
missing data in h and % of the total time	-	-	186 h (25%)	300 h (40%)	155 h (23%)	445 h (60%)

one month, the presented transformation is accepted as accurate enough.

Multiplying measured (hourly) values of the global radiation, *Glob\_S\_45\_meas* with these parameters, the modeled (also hourly) values for the global insolation on roof slopes, *Glob\_E\_30\_calc* and *Glob\_W\_30\_calc*, are obtained.

$$\begin{aligned} Glob\_E\_30\_calc &= ratio\ E \cdot Glob\_S\_45\_meas \\ Glob\_W\_30\_calc &= ratio\ W \cdot Glob\_S\_45\_meas \end{aligned} \quad (2)$$

The ratio number is constant during a specific month (Table 3). These data were used in simulations with a one-hour time sequence and applied as step functions (no interpolation within the sequence).

Longwave radiation exchange with surroundings is modeled as the longwave heat exchange between the roof external surfaces and the sky. Since the measurements on the longwave radiation have not been performed, the following “sky temperature” model has been set in the calculations. First, the clear day is defined as the day when the maximum solar radiation (the one recorded on the 45° inclined surface) exceeds 300 W/m<sup>2</sup>. The sky temperature during the clear day,  $T_{sky,clear}^h$ , has been calculated from the “clear sky model” (see, for example, Hagentoft [2001]).

$$T_{sky}^h = 1.2 \cdot T_{out} - 14, \quad \text{for horizontal surface} \quad (3)$$

$$T_{sky}^v = 1.1 \cdot T_{out} - 5 \quad \text{for vertical surface} \quad (4)$$

where  $T_{out}$  is the external air temperature. The corresponding sky temperature for the 30° inclined surface is calculated as

the linear interpolation of these two:

$$T_{sky,clear} = \frac{1}{3}(T_{sky}^v - T_{sky}^h) + T_{sky}^h = 1.17 \cdot T_{out} - 11 \quad (5)$$

During cloudy days, when the maximum solar radiation is less than 50 W/m<sup>2</sup>, the sky temperature is taken to be equal to the air temperature.

$$T_{sky,cloudy} = T_{out} \quad (6)$$

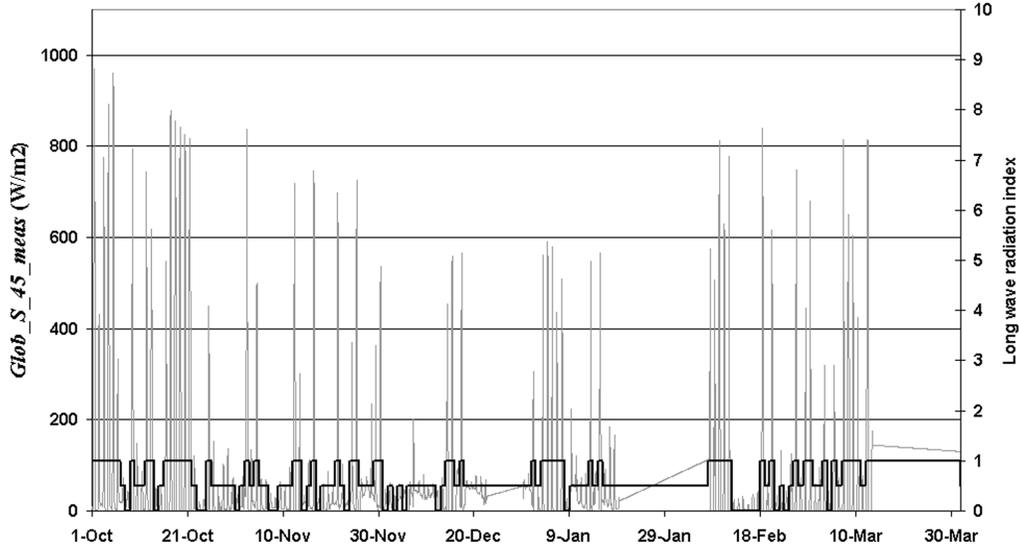
For the half-cloudy periods, e.g., when the maximum solar radiation is between 50 and 300 W/m<sup>2</sup>, the sky temperature is calculated as the average between the clear and the cloudy one.

$$T_{sky,half-cloudy} = 0.5 \cdot (T_{cloudy} + T_{sky,clear}) \quad (7)$$

These periods are indicated within the program by the longwave radiation index, which has the value 1 for the clear day, 0.5 for the half-cloudy, and 0 for the cloudy one. Depending on the value of this index, Equations 5, 6, or 7 are alternatively used for the estimation of the sky temperature. Figure 2 shows the distribution of this index over the simulation period together with the measured insolation. The documentation about the library blocks provides the additional information for the longwave radiation model (Sasic Kalagasidis 2004).

### Ventilation Airflow

Attics are usually not completely airtight and some corrections (increments) in the airflow due to the wind have been taken into account as follows (Larsson 1995, 1996):



**Figure 2** Global radiation intensity (measured) and longwave radiation index (modeled).

$$\begin{array}{lll}
 2 + 0.3 \cdot v & \text{ACH,} & \text{sections A and B} \\
 0.2 + 0.3 \cdot v & \text{ACH} & \text{sections C and D} \\
 2 + 0.8 \cdot v & \text{ACH,} & \text{sections E and F}
 \end{array} \quad (8)$$

where  $v$  is the wind speed measured at the spot. No other restrictions due to the wind angle have been introduced in this model. The wind contributions as well as the flows for the naturally ventilated sections are modeled to give the best possible agreement with the measurements. Model sensitivity toward the ventilation flow rates is further discussed in what follows.

### Surface Transfer Coefficients

The convective heat transfer coefficient on the external side of the roof,  $h_{c,ext}$  (W/m<sup>2</sup>K), is calculated according to Sanders (1996).

$$\begin{array}{ll}
 h_{c,ext} = 5.82 + 3.96 \cdot v & v \leq 5 \text{ m/s} \\
 h_{c,ext} = 7.68 \cdot v^{0.75} & v > 5 \text{ m/s}
 \end{array} \quad (9)$$

where  $v$  is the measured wind speed at the spot. The average wind speed for the simulated period is 2.2 m/s, which gives the average external heat transfer coefficient of 14.5 W/m<sup>2</sup>K. Heat transfer coefficients for internal surfaces are 3 W/m<sup>2</sup>K for the convective and 6 W/m<sup>2</sup>K for the radiative heat exchange, respectively.

Moisture transfer coefficients are  $2e-7$  kg/m s Pa for outdoor surfaces and  $3e-8$  kg/m s Pa for indoor surfaces.

### HAM-Tools ATTIC MODEL DETAILS

The numerical model of the attic is constructed using the standard blocks from the HAM-Tools library. Blocks are

connected in a system (the attic) over data arrays, as presented in Figure 3.

Temperature, relative humidity, and air pressure of the attic space are calculated by the “Room air” block, accounting for the heat, air, and moisture gains through the attic enclosure (roofing and insulated floor) and ventilation system. The room model assumes well-mixed air (one air node).

Blocks “W roof 30o” and “E roof 30o” represent the roof sides (Figure 3). Sections B, C, D, E, and F have the same construction, composed of (from external side): 15 mm thick concrete tiles, plastic foil, and 12 mm plywood board. The roof construction for section A is somewhat different: 15 mm concrete tiles and 2 mm reinforced plastic foil.

The floor (12 mm plywood board on the bottom side, plastic foil, and 500 mm insulation) is modeled with the block “Loose fill insulation” (Figure 3). The floor part covered with a walking path (the block ‘Loose fill insulation+walking path’) has, in addition, an air layer (still air, 20 mm) and a plywood board (12 mm).

Airflow through the attic is modeled by blocks “Ventilation Air In” and “Ventilation Air Out.” Weather data, i.e., temperature, relative humidity, insolation, and longwave radiation, are read and processed within the block “Humid climate SP oct-mar.”

### RESULTS OF SIMULATIONS

Results of the simulations of the attic indoor climate (the air temperature and the relative humidity) versus the measured ones for each section and for the period of six months in a row are given as

- variations in time,
- mean monthly values, and
- hourly values of relative humidity, sorted in descending order for each month.

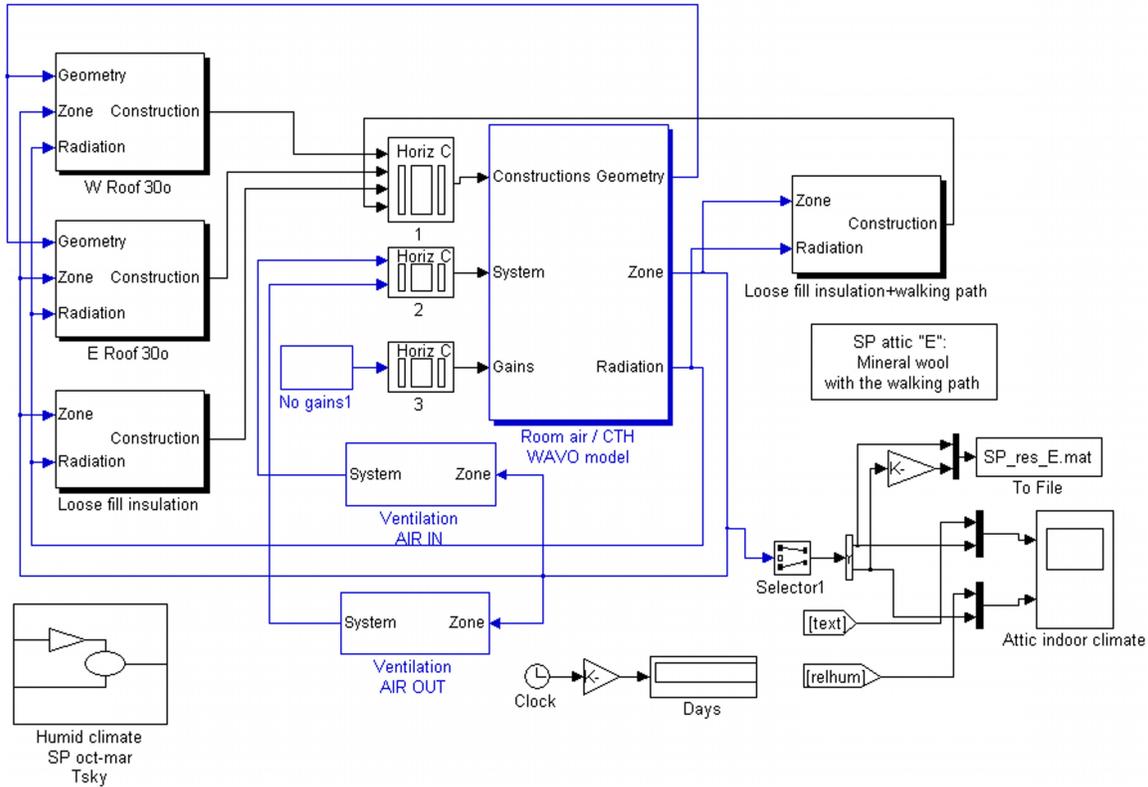


Figure 3 The HAM-Tools model of the attic (section E).

**Variations in Time.** There are altogether 12 figures representing the variations in time of the temperature and the relative humidity for each compartment (Sasic Kalagasidis 2003). Since it is not possible to give an illustration for each case and in every detail, a selection of these is presented in Figure 4. Results are related to the indoor climate in all sections for the whole simulation period from October to March. Results for section E, which will be used later as an example for the discussion, are given using a magnified scale in Figure 5, temperature results, and Figure 6, results for the relative humidity. The absolute differences between measured and calculated values for this case are given at the bottom of Figures 5 and 6, respectively.

In all cases, calculated values of both temperature and relative humidity are in good agreement with measured ones—they show the same trend and response. A general description of the discrepancies between calculated and measured data is summarized here:

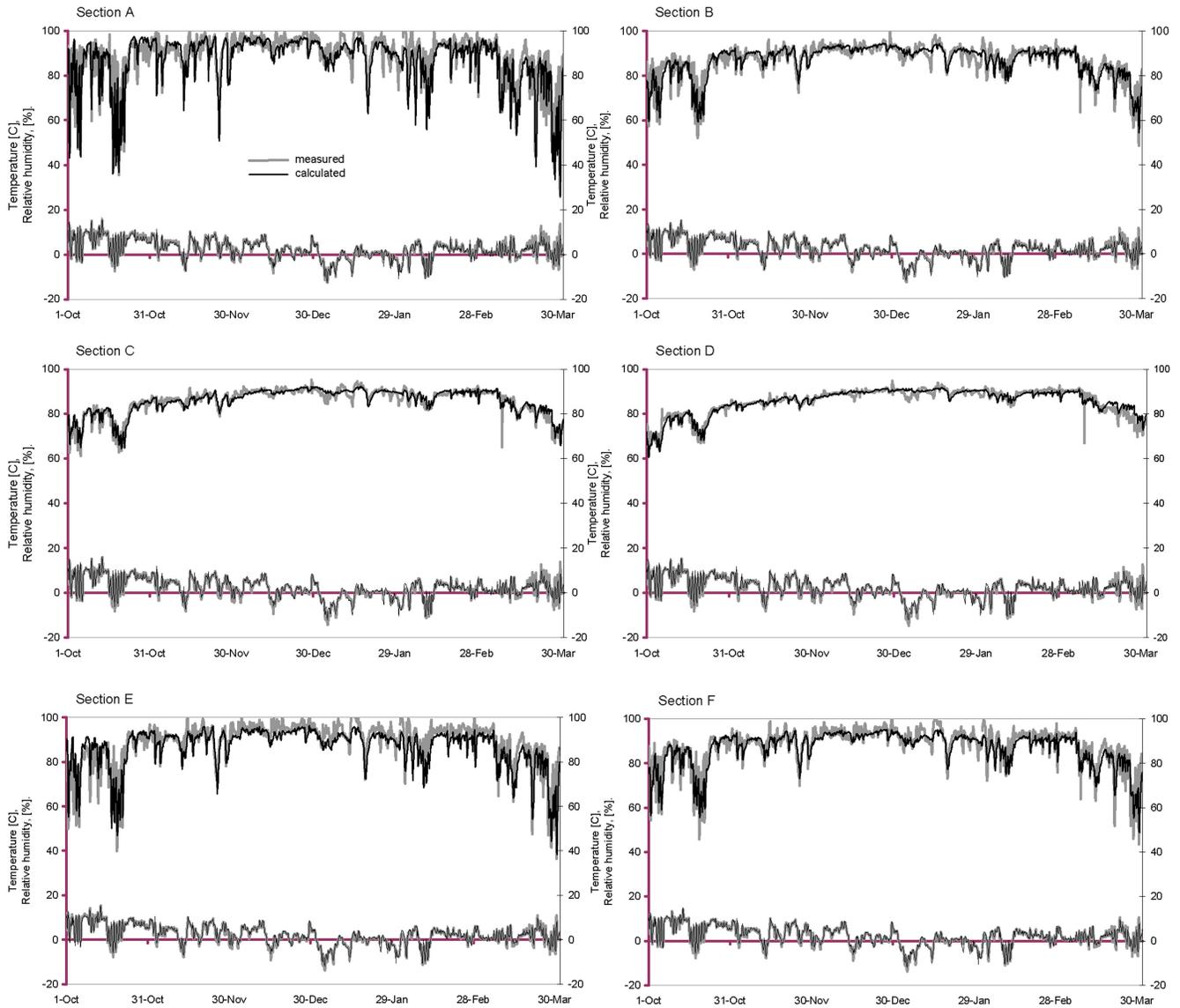
- Temperature results. During the sunny periods and the “clear sky nights,” differences in temperature tend to be bigger, reaching the values of 5-7 degrees (Figure 5). These differences are characteristic for all compartments during the same periods.
- Relative humidity results depend a lot on the ventilation rate and the insulation applied. For nonventilated attics,

C and D, results are in an excellent agreement. Discrepancies become more significant as the ventilation airflow rate increases:

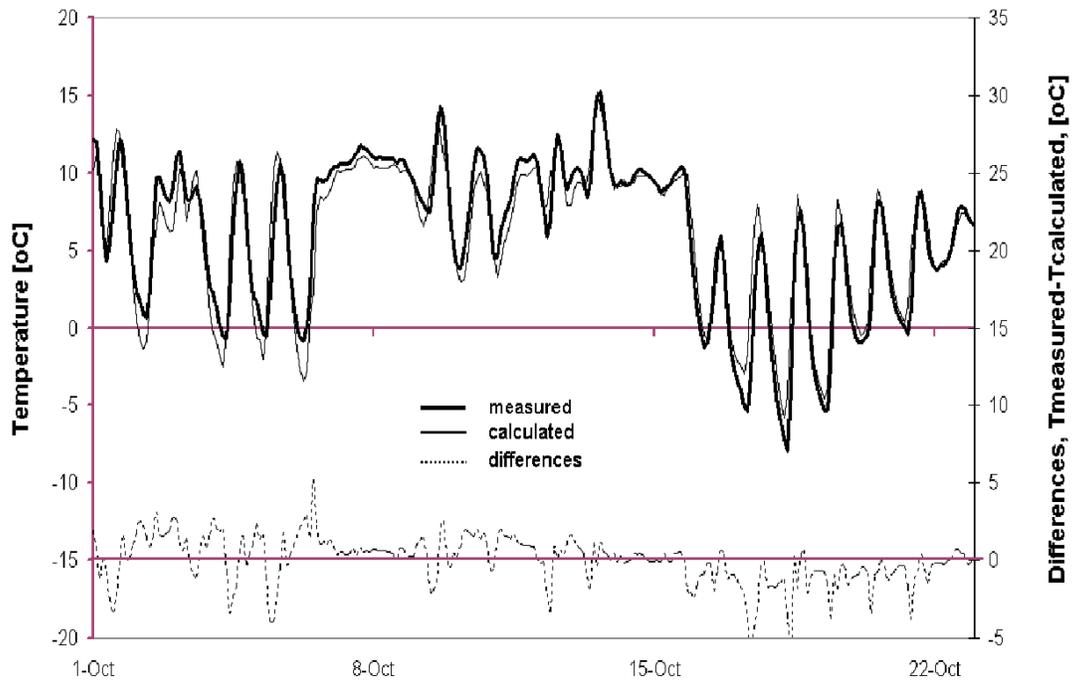
- somewhat smaller for the ones with cellulose and larger for the ones with mineral wool;
- smaller in compartments with lower ventilation rate, as in section B, compared to the naturally ventilated section F, and the largest for section A—the section with the smallest thermal and moisture mass. Sensitivity analysis regarding the ventilation airflow is discussed in the following section.

**Mean values of the temperature and the relative humidity** for each section and for six months in a row (October - March) are presented in Figures 7 and 8. The general conclusion is that the calculated values are in a good agreement with the measured ones, showing slightly warmer climate in all compartments (up to 0.4°C) and slightly dryer in the ventilated ones (up to 4%).

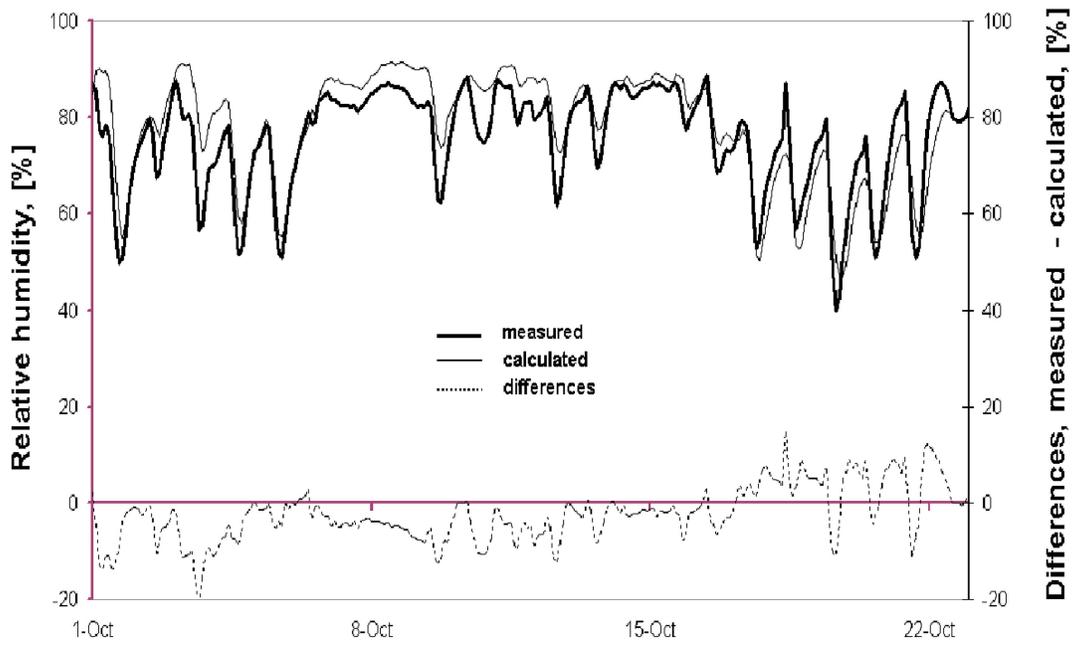
**Measured and calculated results for the relative humidity in descending order.** Again, the E section is used as an illustration. Results for the relative humidity, sorted in descending order, are given in Figure 9 for all six months. The measured data are denoted with a dark line and the calculated ones with the gray line. If the curve is horizontal or close to



**Figure 4** Results for all sections. Calculated air temperature and relative humidity versus measured ones.



**Figure 5** Results for the E section in October: calculated air temperature versus the measured one and the absolute difference between the two.



**Figure 6** Results for the E section in October: calculated air relative humidity versus the measured one and the absolute difference between the two.

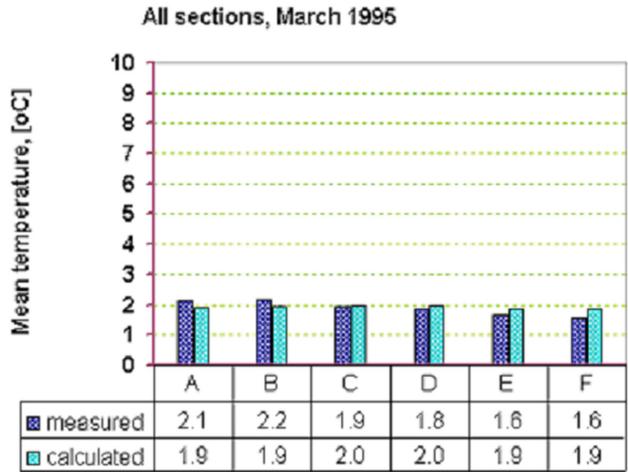
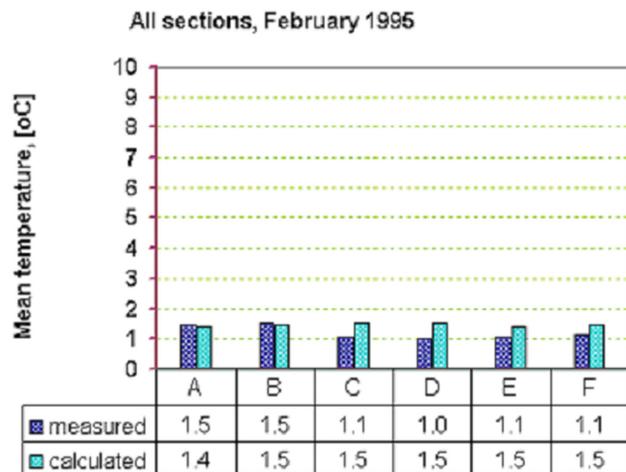
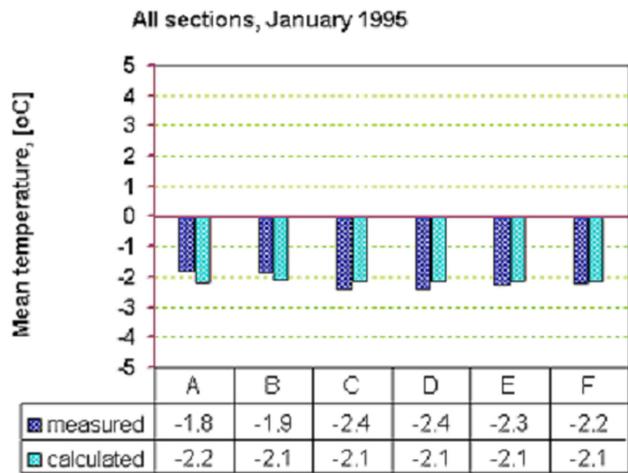
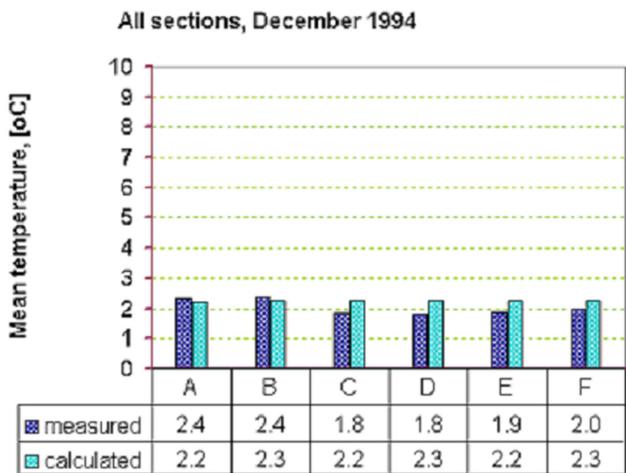
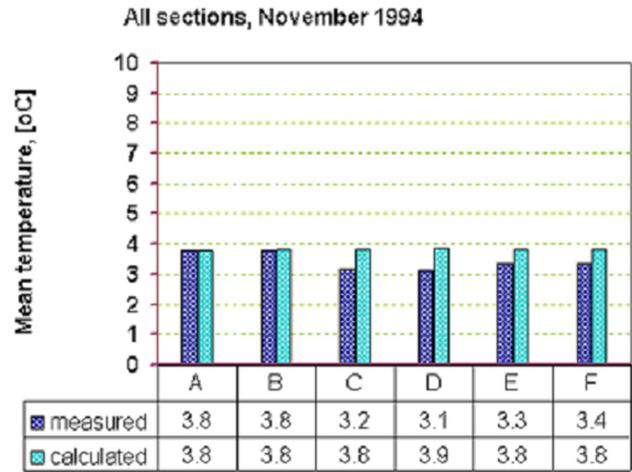
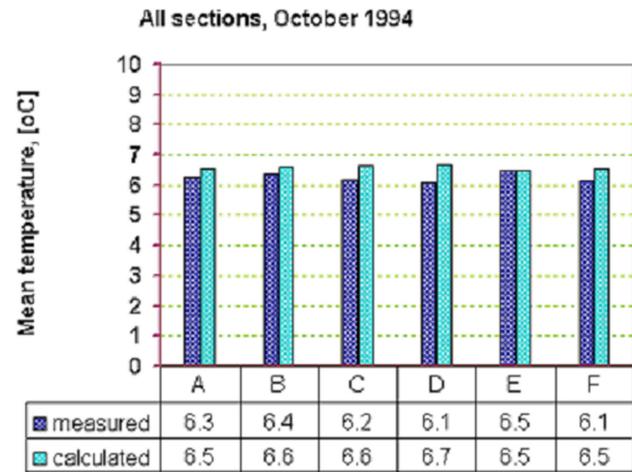


Figure 7 Measured and calculated mean values for the temperature in the attic. Results for all sections, from October 1994 to March 1995.

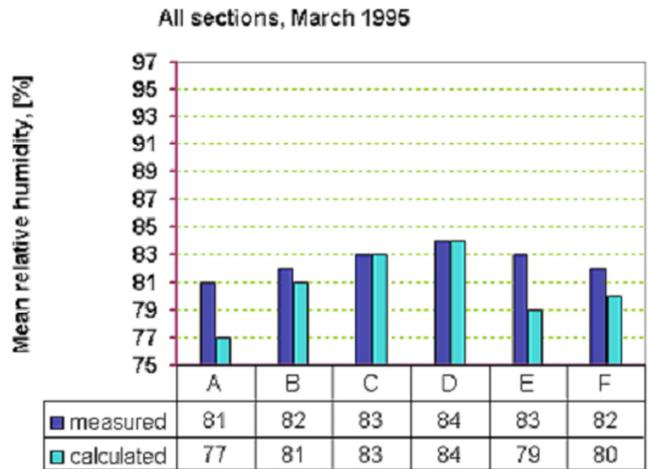
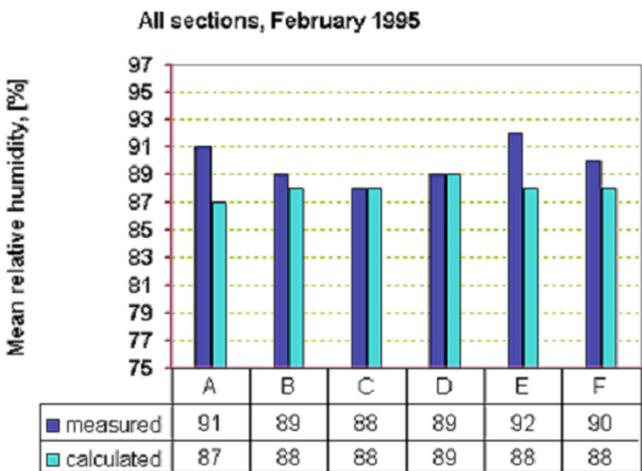
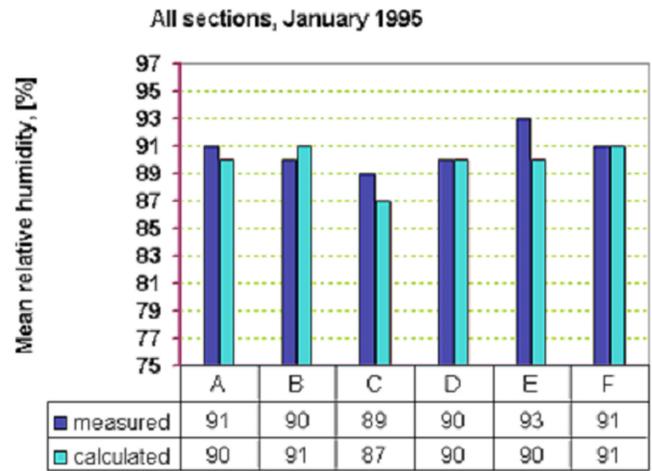
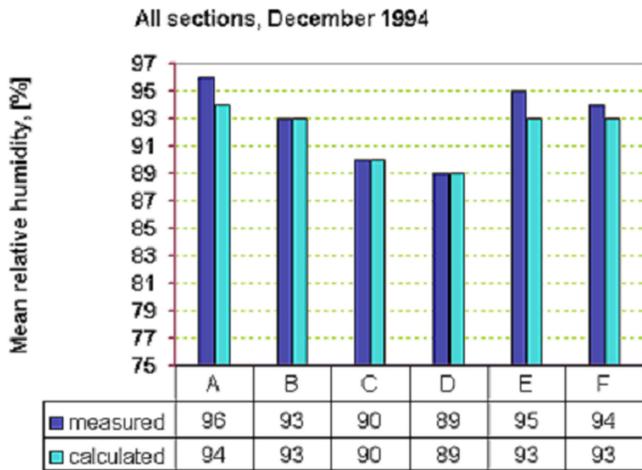
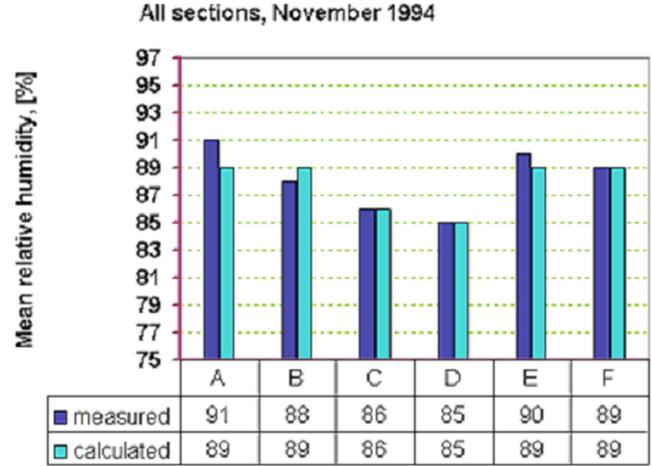
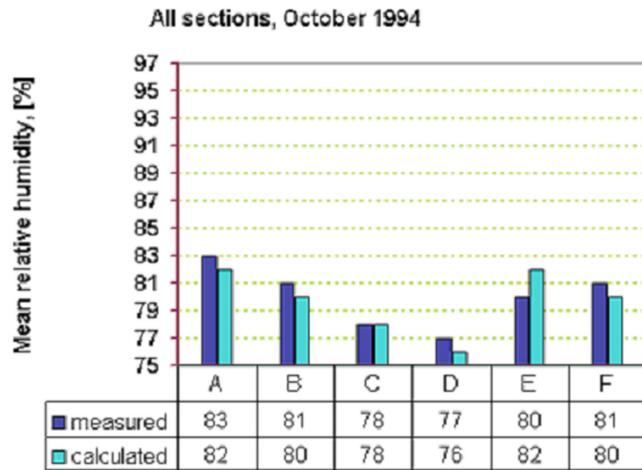
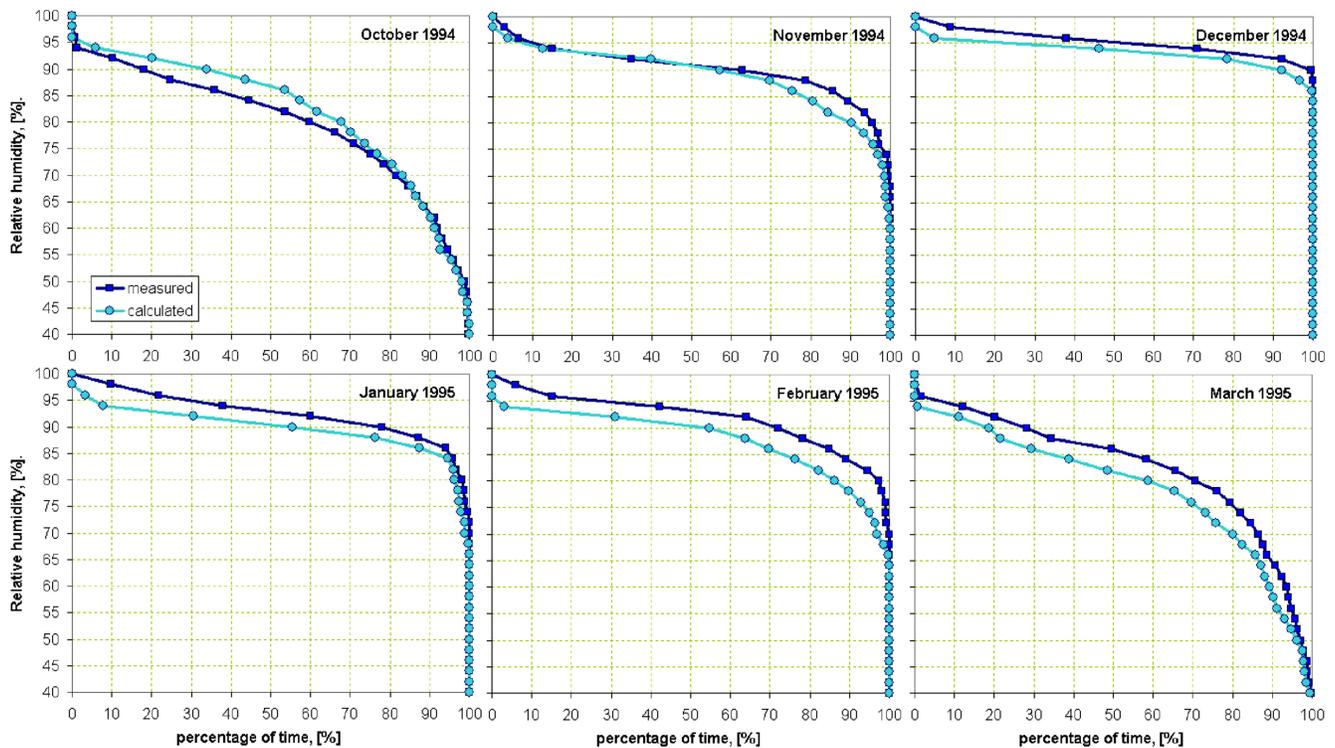


Figure 8 Measured and calculated mean values for the relative humidity in the attic. Results for all sections, from October 1994 to March 1995.



**Figure 9** Results for the air relative humidity in E section, sorted in descending order.

that, the climate is considered to be stable. On the other hand, the steeper the curve, the bigger are the variations in climate taking place. If the curves have the same slope but are on different levels, it implies that one section is a little colder or warmer than the other one. This method is also presented in Samuelson (1995).

Generally, as indicated before, the quality of the agreement between the calculated and the measured relative humidity varies with the ventilation rate and the construction type. The best agreement is in the case of nonventilated sections C and D, almost as good for mechanically ventilated section B with cellulose, and very good for section F. Results for section E exhibit a warmer and dryer climate starting from December to March. The same tendency is observed in section A.

## SENSITIVITY ANALYSIS

Sensitivity analysis aims to show the significance of input values to the results of calculations. Three parameters are investigated: initial relative humidity, ventilation airflow rate, and longwave radiation intensity. These parameters are not sufficiently defined from measurements but modeled for the simulations. Results previously presented appear here as the reference calculated results.

## Initial Conditions

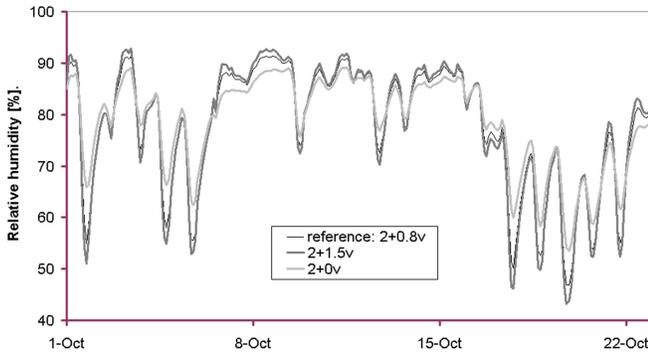
For the reference calculations, the initial relative humidity of the insulation is 20% less than in other construction elements (roof, walking path) (Table 1). In this analysis, it is set to be equal as in the rest of the construction. All other input parameters are the same as in the reference calculations. New results for the mean air relative humidity are given in Table 4, together with the measured and the reference calculations.

The higher moisture content in the insulation resulted in a more humid climate in sections B, D, F, and A than in the reference case. The change is seen throughout the first two months of operation. The climate in sections C and E is not changed, which can be explained by the low moisture capacity of mineral wool. The excessive amount of moisture that is released from mineral wool is in absolute value small and well absorbed by other (wooden) construction elements. Moisture mass of the A section is very small and even some small changes in moisture sources are noticeable. Cellulose, on the other hand, has a high moisture capacity and the increased initial relative humidity results in a significant release of moisture, which is not easily absorbed by other construction elements.

By changing the initial relative humidity of the insulation, other quality of agreement with measurements can be obtained. However, this parameter is modeled as it is described in the reference calculations in order to keep the same modeling procedure for all sections.

**Table 4. Sensitivity Analysis—Initial Conditions**

Mean Air Relative Humidity (%)												
Section	October						November					
	A	B	C	D	E	F	A	B	C	D	E	F
Measured	83	81	78	77	80	81	91	88	86	85	90	89
Reference calculated	82	80	78	76	82	80	89	89	86	85	89	89
New calculated	83	83	78	81	82	82	91	88	86	85	90	89



**Figure 10** Sensitivity analyses—ventilation rates. Air relative humidity in the E section.

**Ventilation Rates**

For these analyses, ventilation rates are varied by changing the wind contribution to the fixed airflow: from the zero wind contribution, i.e.,  $2 + 0 \cdot v$  ACH, to the doubled contribution,  $2 + 1.5 \cdot v$  ACH. With the mean wind speed of 2.2 m/s throughout the whole simulation period, the later flow gives 5 ACH on average, and, for the reference case (Equation 8), it is 3.6 ACH. Results for the relative humidity (as hourly variations) are given in Figure 10, and the mean values for four months in a row are given in Table 5.

The variations in wind contributions to the airflow rate do not have a significant influence on the final results—up to 1% on the mean level. The wind part contributes to the fluctuations

in the relative humidity, as can be seen in Figure 10, while the fixed part, set to 2 ACH, influences the mean value.

**Longwave Radiation Intensity**

This analysis is focused on the significance of the longwave radiation exchange with the surroundings, where the sky model is presented with Equations 5 to 7. In the first place, only the “clear sky” model is applied (Equation 5), whereas in the second one, only the “cloudy” model (Equation 6). Thus, the limits for the longwave heat exchange with the surroundings are set, having, in the first case, the maximum and in the second the minimum values, respectively. Results for the mean values of the temperature and the relative humidity are given in Table 6.

The “clear sky” gives the colder and the more humid climate, while the “cloudy” model does the opposite. Results vary up to 1°C for the temperature and 6% for the relative humidity on the mean level. Thus, the longwave radiation heat exchange is the parameter of great importance. Using a rather coarse model for this process, significant differences between measured and calculated values can be obtained.

**DISCUSSION**

**The appearance of rather large absolute differences** between the calculated and the measured temperature and the relative humidity (even if both profiles exhibit the same trend and the amplitudes as the measured values) (Figures 5 and 6) is to be discussed.

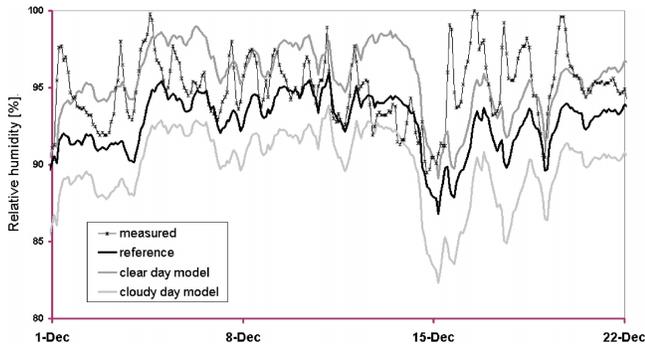
One can observe slightly faster response of the simulated attic compared to the measured one, which actually led to such differences. This could be attributed, in the first place, to the

**Table 5. Sensitivity Analysis—Ventilation Rates**

	October		November		December		January	
	$T_m$ (°C)	$RH_m$ (%)						
Measured	6.5	80	3.3	90	1.9	95	-2.3	93
Reference calculated $2+0.8 \cdot v$ ACH	6.5	82	3.8	89	2.2	93	-2.1	90
$2+1.5 \cdot v$ ACH	6.4	82	3.8	89	2.2	93	-2.1	90
$2+0 \cdot v$ ACH	6.5	82	3.8	88	2.2	92	-2.1	90

**Table 6. Sensitivity Analyses—Longwave Radiation Intensity**

	October		November		December		January	
	$T_m$ (°C)	$RH_m$ (%)						
Measured	6.5	80	3.3	90	1.9	95	-2.3	93
Reference calculated	6.5	82	3.8	89	2.2	93	-2.1	90
Clear day model	6.2	83	3.4	91	1.8	96	-2.5	92
Cloudy day model	7.2	79	4.4	86	2.7	90	-1.5	86



**Figure 11** Sensitivity analysis—longwave radiation intensity—discussion. Air relative humidity in the E section.

differences in thermal and moisture capacities of the simulated and the actual section. Another explanation is in the different time steps of the input data: solar radiation data were implemented (and recorded) as step changes on hourly basis, while temperature and relative humidity as step changes for every two hours. Thus, the change in solar radiation, in the case of a sudden increment for example, is not followed by the appropriate change in the outdoor temperature, and the latter one is coupled to the applied airflow governing the cooling or the heating of the section.

**Dryer and warmer calculated climate in the winter.**

Starting from December, the calculated relative humidity in the E section is 2% smaller than the measured one on the average level, reaching the value of 4% in March. The sensitivity analysis of the longwave radiation heat exchange with the surroundings has shown the significance of this process. However, it is not straightforward whether the problem is in the longwave radiation model (which is based on the solar radiation data and a lot of them are missing [see Table 2]) or it is the quality of the measured data (for example, in sections A and E, the measured relative humidity sometimes exceeds 100%) or it is the hygrothermal model of the air itself.

This is investigated by plotting the time variations of the relative humidity calculated by the one of the discussed longwave radiation models versus the measured ones (Figure 11). It is obvious that the sky model influences the mean level of the relative humidity—by increasing it, in the case of the clear sky,

or decreasing it for the cloudy sky—but it does not seem to influence the fluctuations—they remain dampened independently of the model used, while the measured ones are quite distinctive. Rather arbitrarily proposed ventilation rates (or the parts coming from the wind), in combination with different step changes in the input climatic data, and finally the model itself, which assumes well-mixed air in the attic, could be identified as the reasons for these discrepancies.

**CONCLUSION**

In order to assess the ability of the software to predict the building hygrothermal response to given climate and operating conditions, validation tests against measurements have been performed. As a case study, measurements of the air temperature and relative humidity of the cold ventilated attic space in real operating conditions were selected. Summarizing the measurements and the calculations, the following conclusions can be made for the investigated attic:

- There is some degree of moisture buffering in a hygroscopic insulation material (cellulose) compared to low-hygroscopic insulation (mineral wool). However, the difference is not particularly large.
- There are considerable differences in moisture and temperature variations in sections with high and low ventilation rates. The higher the amount of ventilation using outdoor air, the greater the variations.
- The climate in the attic is drier the less it is ventilated. Since the risk for mold growth increases with an increment of relative humidity, it suggests that attics should not be ventilated. However, this conclusion is valid only for the investigated attic, where no air leakages (i.e., no moisture sources) from the offices below were present. In practice, such a case is rather rare.

Validation results are presented as a comparison between measurements and calculations. Parametric sensitivity analyses have been performed and necessary adjustments for the missing input parameters have been fully documented. The code has shown a high degree of reliability, both in a qualitative and in a quantitative way.

This paper has also shown the entire complexity of performing the validation tests for the overall HAM building simulations. The selected validation results are the ones with

the “lowest” degree of agreement with measurements. This has been done on purpose to illustrate the limits originating from the abstraction level of the code itself (such as only one-dimensional HAM calculations applied to the three-dimensional case or an assumption of well-mixed air in the compartment even under high fluctuations of the airflow) and also to emphasize the uncertainties coming from the measurements (which are numerous): the airflow data specifications for naturally ventilated sections, solar radiation data, longwave radiation, precipitation, relative humidity that exceeds 100%, etc.

The selected case—the hygrothermal conditions in a cold attic under different ventilation regimes—was the only available data set at the time these simulations were performed. The author would like to express the necessity for the field measurements, with carefully defined data (and also publicly available), that could be used in the future for validation tests of this kind.

## NOMENCLATURE

$T$	= temperature, °C
RH	= relative humidity, %
$v$	= wind speed, m/s
$h_c$	= heat transfer coefficient, W/m <sup>2</sup> K
$G_{lob\_S\_45}$	= Global radiation intensity_on South oriented_and 45° inclined surface, W/m <sup>2</sup>
$G_{lob\_E\_30}$	= Global radiation intensity_on East oriented_and 30° inclined surface, W/m <sup>2</sup>
$G_{lob\_W\_30}$	= Global radiation intensity_on West oriented_and 30° inclined surface, W/m <sup>2</sup>

## Subscripts

$calc$	= calculated value
$ext$	= external
$m$	= mean value
$meas$	= measured value
$sky$	= sky

## Superscripts

$h$	= horizontal
$v$	= vertical

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