Estimating Values for the Moisture Sources and Buffering Capacities from Indoor Climate Measurements

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Abstract

The objective of the paper is to investigate the potentials of estimating values for the total human induced moisture source and the total buffering capacity of the interior objects with the use of relatively simple measurements and the use of HAM models. The paper presents the related modeling approaches, the implementation in the MatLab/SimuLink environment, a verification study and evaluation of the models using indoor climate measurements of a Dutch museum. It is concluded that the modeling approach may be useful for estimating the human induced heat & moisture sources. The case study was not usable for estimating the buffering capacity of the interior objects due to the minor dependency on the amount of moisture storage material. More case studies are required to evaluate our approach for the determination of such moisture capacities. However, our approach has the side effect that it might be usable to indicate the effect of wet clothing. Our study showed that the moisture source of wet clothing per person could be of the same order as the breath induced moisture source. Further research is needed if we want to quantify the effect of wet clothing more accurately.

1. Introduction

The impact of human induced moisture on monumental interiors and building envelopes is important. Visiting people, acting as moisture sources, may create large peaks in relative humidity (Rh) and this may cause damages to the interior objects such as monumental paintings, papers and wooden objects. In common practice computational modeling and simulation tools are used for the investigation of such moisture related problems and for the evaluation of suggested solutions. In most cases, the simulated Rh peaks are very dependent of important parameters that influence the Rh, such as the human induced moisture source and the moisture buffering capacity of internal objects. Directly measuring these parameters is problematic.

The objective of the paper is to investigate the potentials of estimating these parameters with the use of relatively simple measurements and the use of HAM models.

The methodology was: First, a model was developed to calculate human induced CO_2 production out of the CO_2 concentration during the presence of people. Second, the heat and moisture sources related to the CO_2 production were implemented into a whole building model. Third, three model parameters related with the heat & moisture source and buffering capacity were fine-tuned using the first half of measured time series of an indoor climate in a museum. Fourth, the model was evaluated using the second half of the time series.

The structure of the paper is as follows: Section 2 provides the modeling approaches. Section 3 provides the application and evaluation of the models using real-life indoor climate measurements in a single room of a famous Dutch museum with a high occupancy level. The objective of the paper is revisited and discussed in the conclusion section.

2. The modeling approach

2.1 Calculating CO_2 production from CO_2 concentration

We start with a CO_2 mass balance model for a room with a uniform CO_2 concentration, constant ventilation with fresh air and the presence of a human related CO_2 production source:

$$V\frac{dC_i}{dt} = \Phi \cdot (C_e - C_i) + G_{CO2} \qquad => \qquad G_{CO2} = V\frac{dC_i}{dt} + \Phi \cdot (C_i - C_e) \qquad (1+2)$$

in which V is volume of the room [m^3], Φ is ventilation flow rate [m^3/s], t is time [s], C_i and C_e are respectively the indoor and external CO_2 concentrations [kg/m^3 or PPM*] and G_{CO2} is CO_2 production source [kg/s].

Equation 2 provides a mathematical model to calculate the CO_2 production. We implemented both models based on Equation 1+2 into SimuLink. Furthermore we included a more or less realistic moisture source in order to verify the applicability of Equation 2. The models are shown in Figure 1.

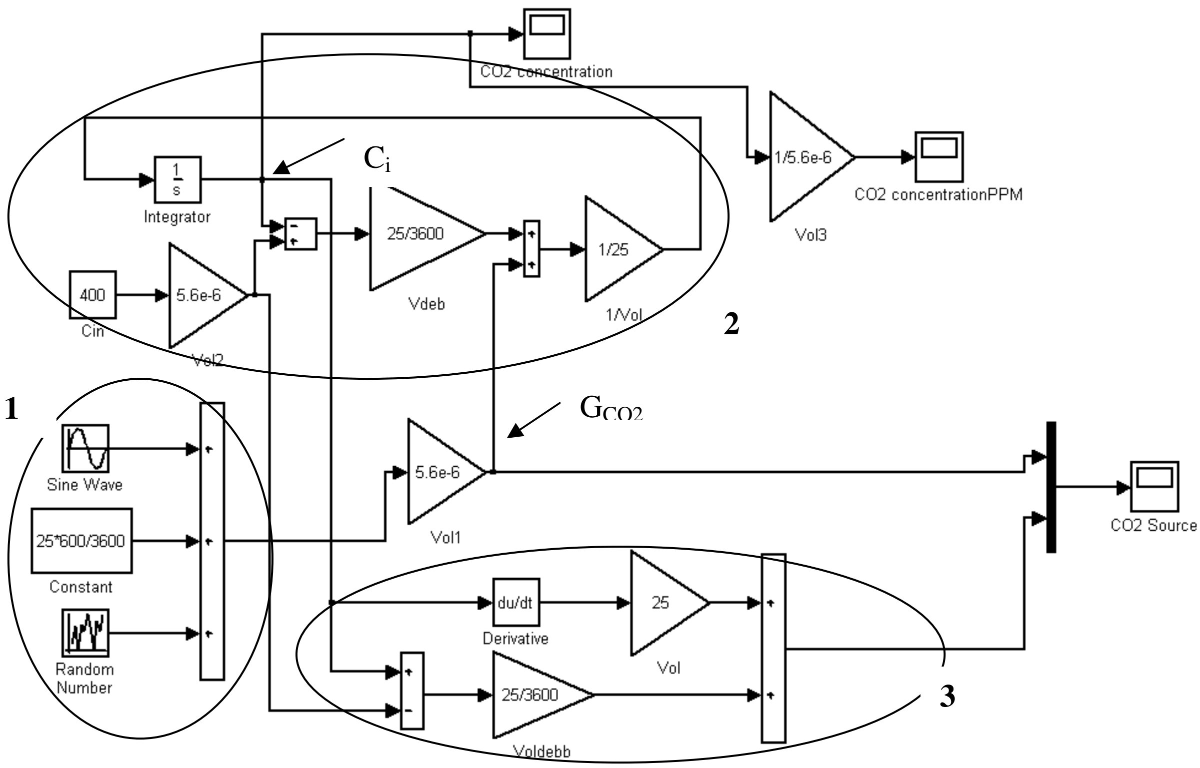


Figure 1: Implementation of both models (Equation 1+ 2) into SimuLink

Explanation of the areas: (1) The moisture source production G_{CO2} is an addition of a constant value, a daily fluctuation (slow) and a random fluctuation (fast). This 'signal' is plotted in figure 2 (top). (2) The representation of Equation 1 with V = 25;Φ = 25/3600; C_e=400, using SimuLink blocks. The input is G_{CO2} and the output is the simulated CO_2 concentration. The

* 1 PPM = $0.56 \; 10^{-6}$ kg/m^3

latter is also plotted in figure 2 (bottom). (3) The representation of Equation 2 (also with $V = 25; \Phi = 25/3600; C_e=400$), the inverse model of the previous presented one. The input is CO_2 concentration (C_i) and the output is the simulated human moisture source G_{CO2}. The latter is also plotted in the figure 2 (bottom).

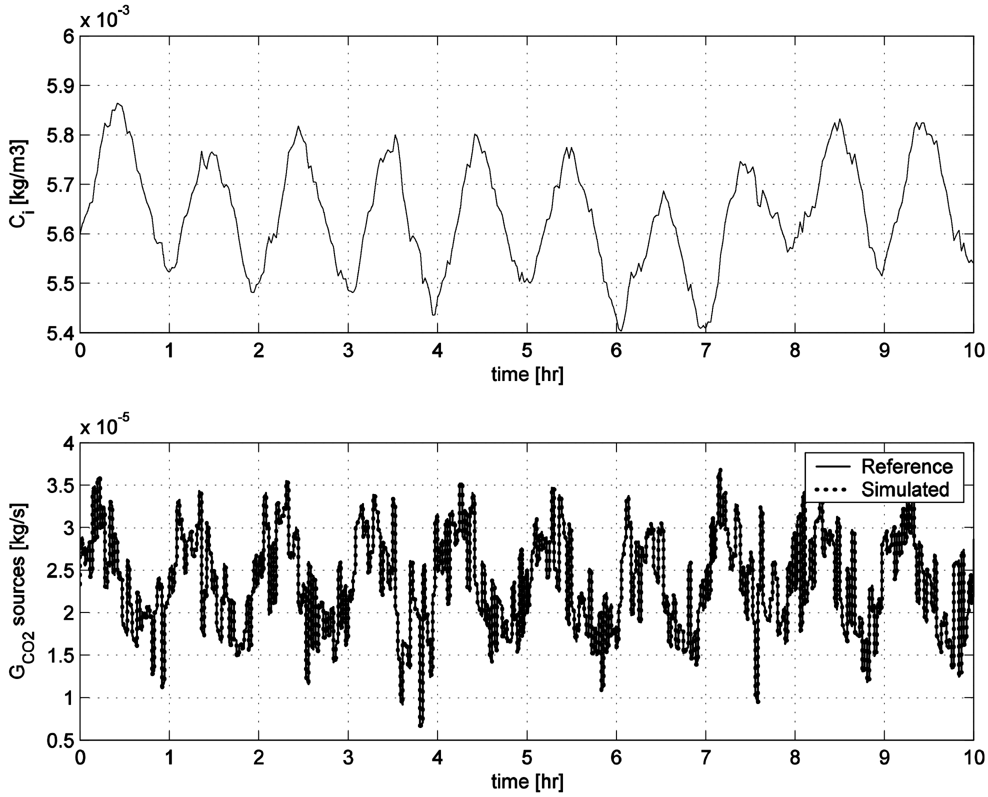


Figure 2: Top: The simulated CO_2 concentration. Bottom: The reference moisture source (-), the simulated moisture source from the CO_2 concentration (:).

This numerical exercise provides a verification of the model to calculate the CO_2 production out of the concentration. Moreover, Richieri et al (2006) provide experimental results that confirm the validity of the modeling approach with an error of 10% in the number of occupants. Unfortunately for this work, they used artificial CO_2 sources instead of real persons in their experiments so their results cannot be used for estimating the required human induced heat & moisture sources.

2.2 Calculating heat and moisture sources

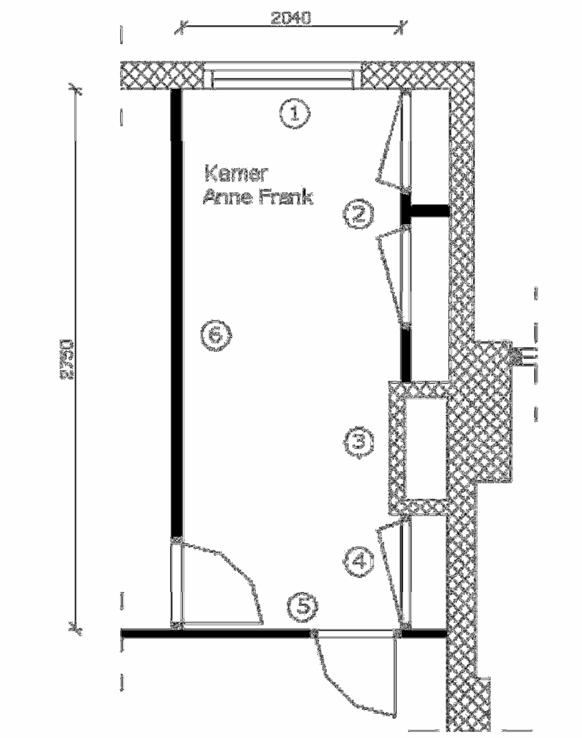
As first approximations both the human related heat source Q [W] and moisture source g [kg/s] are assumed to be proportional to the CO2 production source G_{CO2} i.e.:

$$Q = P_Q \bullet G_{CO2} \quad \text{and} \quad g = P_g \bullet G_{CO2}. \qquad (3)$$

Theoretical values for P_Q and P_g can be estimated using the human emissions at certain activities. For example, Recknagel provides for a human in rest:
$Q = 80$ W; $G_{CO2} = 10 - 20$ l/h $= (0.5\text{-}1) \cdot 10^{-5}$ kg/s ; $g = 20 - 80$ g/h $= (0.5\text{-} 2) \cdot 10^{-5}$ kg/s.
This means that P_Q ranges from $(8 - 16) \cdot 10^6$ and P_g ranges from $1 - 4$.

3 Case study: Anne Frank Room

We start with a short description of the case. Figure 3 shows the geometry and constructions.



1. external wall, ($2x2.7m^2$), plaster - 0.2m brick & window, ($1.1x1.7m^2$), solar transmittance coefficient = 0.25
2. external wall, ($2.4x2.7m^2$), wood - air gap - 0.2m brick
3. internal wall, ($1.6x2.7m^2$), 0.1m brick- air gap - 0.2m brick
4. internal wall, ($1x2.7m^2$), wood - air gap - 0.2m brick
5. internall wall, ($2x2.7m^2$), wooden panels
6. internal wall ($5x2.7m^2$), wooden panels

ceiling, ($5x2m^2$), wood

floor, ($5x2m^2$), linoleum - wood

Figure 3. The room of Anne Frank

The famous paper fragments are fixed to several walls in the room. The room window is oriented northeast. It is estimated by the museum employees that during opening times, the room is almost permanently occupied with about 8-10 persons. The measurements were carried out from June 2003 through February 2004. They include: (1) The air temperature, relative humidity, solar irradiance and rainfall of the external climate; (2) the air temperature and relative humidity at several places in the room and surrounding rooms, (3) the CO_2 concentration in the room and (4) the air temperature, relative humidity and mass flow of the air inflow to the room. The room (27.8 m^3) is constantly ventilated (11 ACH) with outside air. We refer to van Schijndel & Schellen (2006) for a more detailed description.

3.1 The modeling

In figure 4 the modeling in SimuLink is presented. Explanation of the areas: (1) We used the whole building model HAMBase_S (de Wit 2006) to simulate the indoor climate. The inverse model (2) is coupled with the measured CO_2 concentration (3). The output of the inverse model, i.e. the CO_2 source, is multiplied by respectively values for $P_Q = 8 \cdot 10^6$ (4) and $P_g = 1$ (5) and coupled to the input of the indoor climate model, providing the heat and moisture sources.

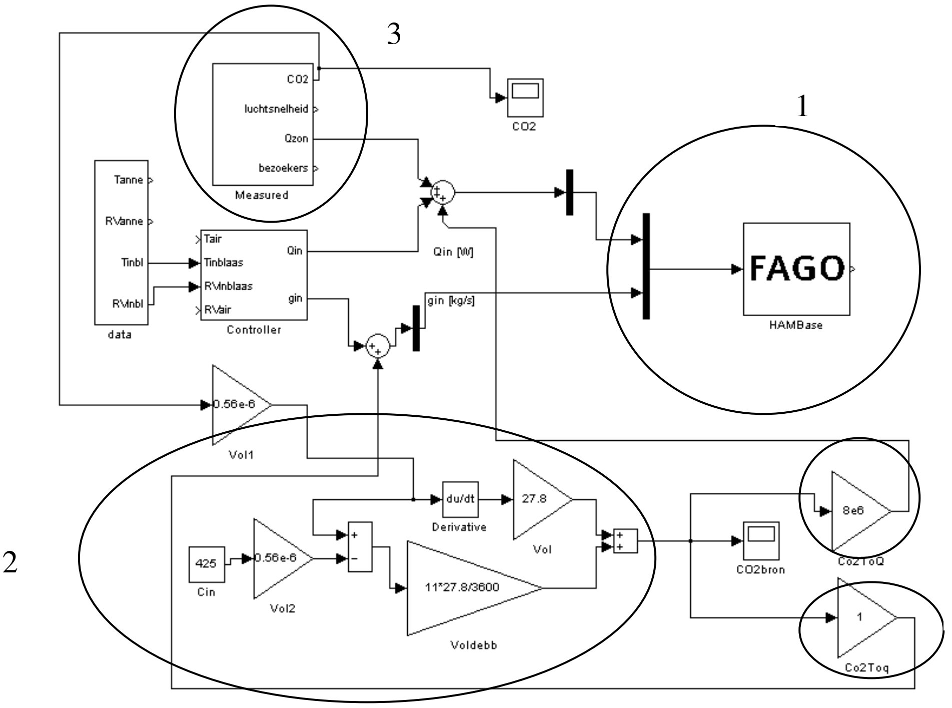


Figure 4. The whole building model including heat & moisture sources

3.2 Calculating CO_2 production from the measured CO_2 concentration

Figure 5 provides the results. The calculated number of people (bottom) agrees well with the estimated number of people provided by the museum employees.

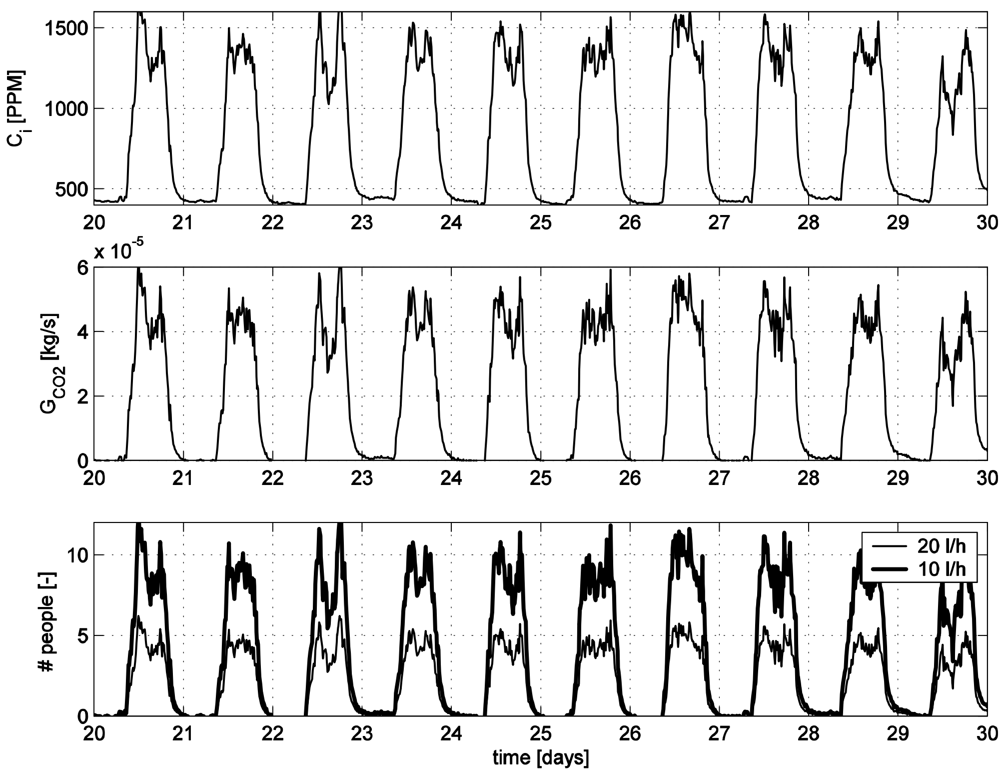


Figure 5. Top: The measured CO_2 concentration. Middle: The calculated source. Bottom: The number of people present based on 10 and 20 l/h CO_2 production person.

3.3 Calculating heat and moisture sources

We tested the sensitivity of the simulated indoor climate for several values for P_Q and P_g. In figure 6 the results are presented.

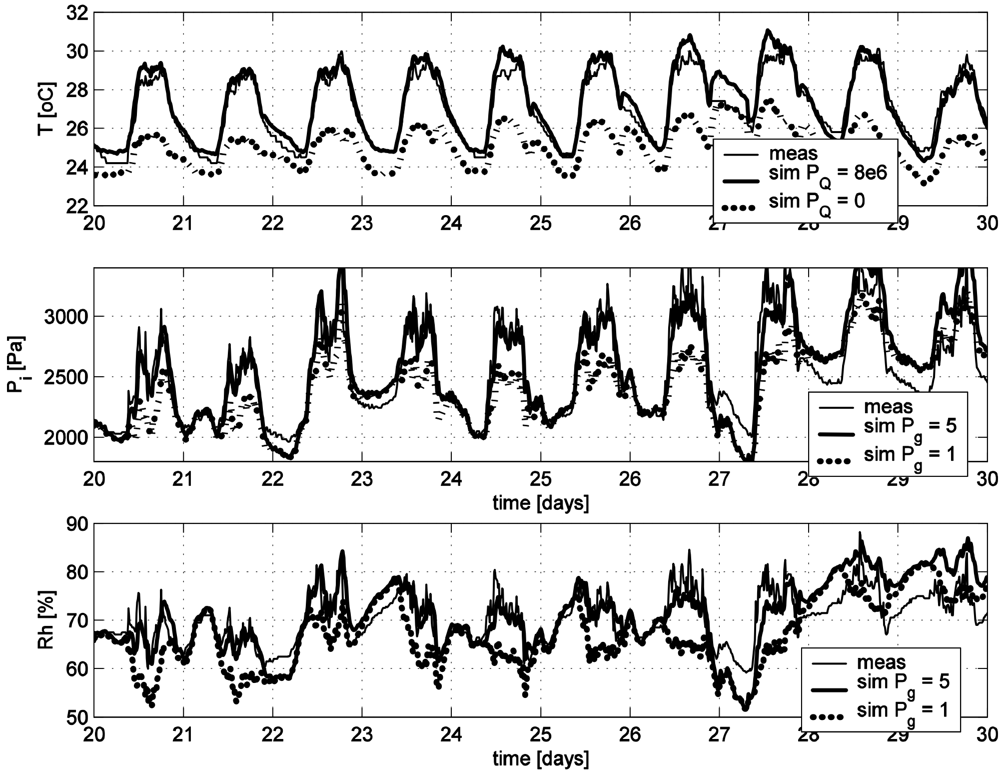


Figure 6. Top: The air temperature (measured and simulated with and without heat sources, $P_Q = 8\ 10^6$ resp. $P_Q = 0$). Middle: Vapour pressure. Bottom: Relative humidity for both (measured, simulated with respectively $P_Q = 8\ 10^6$ & $P_g = 5$ and $P_Q = 8\ 10^6$ & $P_g = 1$.

From figure 6 (top) we can see that the heat source can be reasonably calculated from the CO_2 production using $P_Q = 8 \cdot 10^6$. Other values for P_Q were also tested, but gave lesser results. We proceed using $P_Q = 8 \cdot 10^6$ and study the sensitivity for P_g values. The middle part of figure 6 shows that best results are obtained for $P_g = 5$. However the peaks are underestimated by the simulations. This is also shown in the bottom part of the figure.

3.4 Moisture buffering capacity

In this section the sensitivity for the amount of buffering material inside the room is investigated. Figure 6 showed that peaks are underestimated by the simulation results. A possibility to fix this is to lower the moisture capacity in the model, for example by significantly decreasing the air volume and indoor buffering material. We tried this in our model, but it had almost no effect on the results. This could be explained by the relatively high ventilation rate (11 ACH) of the room. To see the influence of the moisture storage of indoor objects, we must simulate large amounts of buffering material inside the room. In figure 7 the results are shown. We may conclude that in this particular case, the vapour pressure is only to a small extent depend on the moisture buffering capacity and therefore it seems not possible to estimate the moisture buffering capacity of indoor objects.

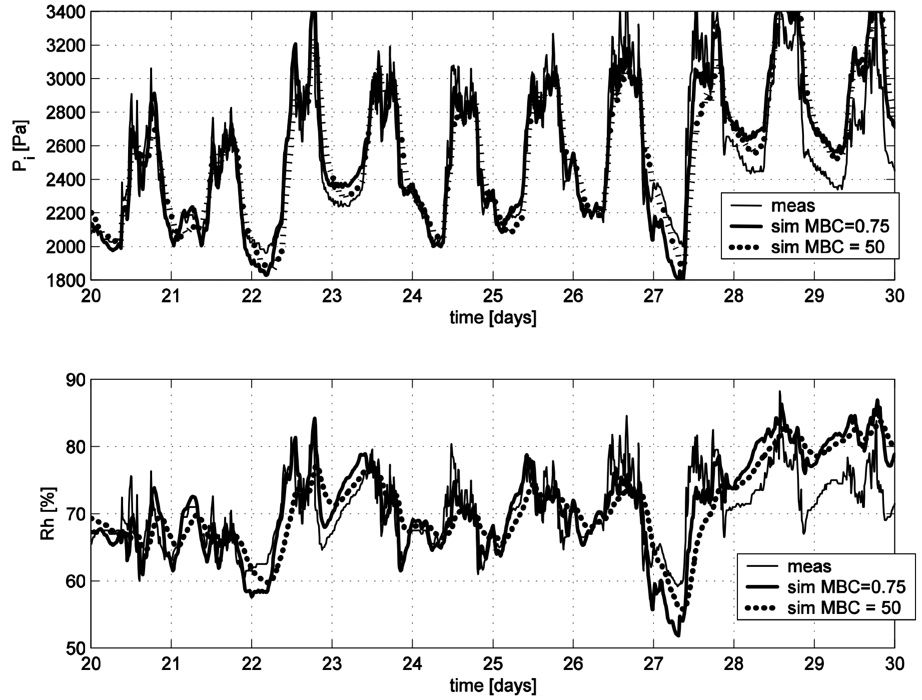


Figure 7. Top: Vapour pressure: measured, simulated with default moisture storage and extra moisture storage (equivalent of 50 air volumes). Bottom: Similar for the relative humidity.

3.5 Wet clothing

Beside people, another way for the moisture entering the room could be due to wet clothing. In figure 8 we have plotted results together with the measured time of rain nearby.

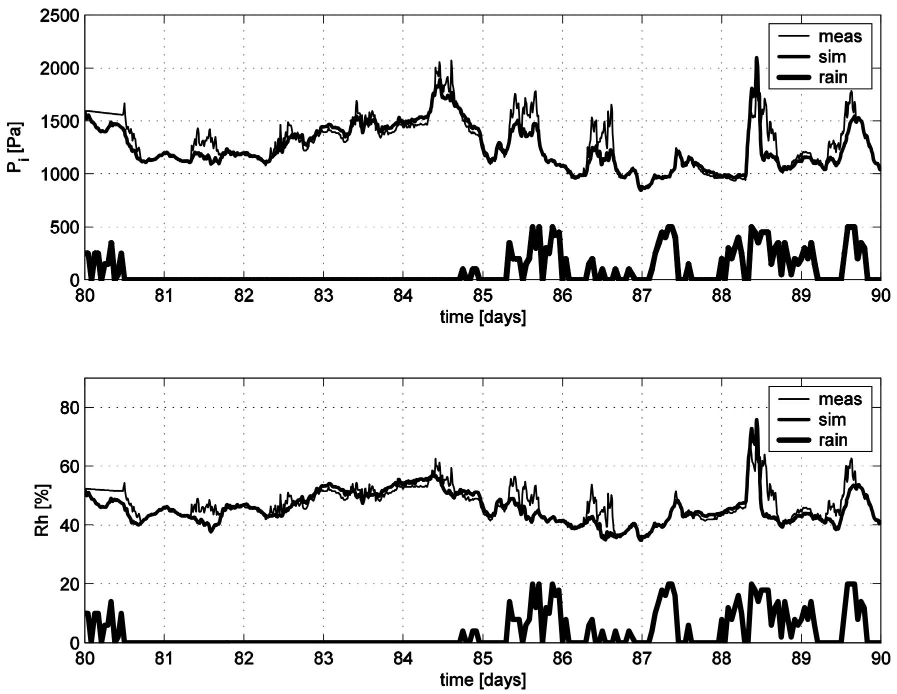


Figure 8. Top: Vapour pressure: measured & simulated together with the indicated time of rain (scaled) . Bottom: Similar for the relative humidity.

It is quite difficult to draw some conclusions because we may expect that the amount of wet clothing entering the room depends on the time of day and also on how long people had to stand in line outside (in the rain) before entering the building. However, there seems to be a correlation between the mismatch of the simulation results and measurements related with the time of rain. If we assume that for example on day 86, a peak vapour pressure difference of 300 Pa (2.2 10^{-3} kg/m^3) between simulation and measurements is exclusively caused by wet clothing, we are able to estimate (using $\Phi = 27.8*11/3600$ m^3/s) the moisture source of wet clothing at about 2 10^{-4} kg/s (for 10 people present). This might indicate that moisture source of wet clothing per person is of the same order as breath induced moisture source per person.

4. Conclusions

It is concluded that the modeling approach may be useful for estimating the human induced heat & moisture sources. The case study was not usable for estimating the buffering capacity of the interior objects due to the minor dependency on the amount of moisture storage material. More case studies are required to evaluate our approach for the determination of such moisture capacities. However, our approach has the side effect that it might be usable to indicate the effect of wet clothing. Our study showed that the moisture source of wet clothing per person could be of the same order as the breath induced moisture source per person. Further research is needed if we want to quantify the effect of wet clothing more accurately.

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References

Jansen, D.W.L. 2005. Simulation of the human influence on the indoor climate. Technische Universiteit Eindhoven, *pre Master thesis* (in Dutch), 47p.

Recknagel, Sprenger & Schramek. 1998. Taschen buch fur HEIZUNG und KLIMATECHNIK 97/98. *ISBN 3-486-26214-9*.

Richieri, F., Michel, P. & El Mankibi, M. 2006. Occupancy calculation for the control of mechanical ventilation. *Proceeding of EPIC 2006 AIVC Conference 20-22 November 2006 Lyon*. pp459-466

Schellen, L. 2006. Calculation of the human heat and moisture sources out of the CO_2 concentration as a function of time. Technische Universiteit Eindhoven, *pre Master thesis* (in Dutch), 43p.

Schellen, H.L., Schijndel, A.W.M. van & Aarle M.A.P. van. 2003. Simulation of the indoor climate of Anne Frank's room. Technische Universiteit Eindhoven, *FAGO report 03.20W*. (in Dutch) 37p.

Schijndel, A.W.M. van & Schellen, H.L. 2006. Application of a combined indoor climate and hvac model for the indoor climate performance of a museum. *Restoration of Buildings and Monuments*, Vol. 12 No.3 pp 219-228.