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Moisture Control in Indoor Environments: When Hygric Inertia May Contribute to Deliver Better Comfort Conditions

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ABSTRACT HEADING

The importance of moisture control in indoor environments is increasingly recognized. Air humidity affects human health and comfort, and it is also connected to the durability of several building components and to energy efficiency. In many cases, it is possible to control the level of humidity with passive solutions, taking advantage of the moisture buffering capacity of hygroscopic materials. Nevertheless, current standards do not give any prescriptions on this matter. In this paper we investigate how the hygric inertia of a room may contribute to improve the indoor comfort conditions. In particular, the aim is to fix a desired value of hygric inertia of a room in relation to its size, use and air change rate in order to maintain the amount of relative humidity under a given threshold. The study has been conducted through simulations, using the Effective Capacitance model with the software TRNSYS 18. The indoor conditions are typical of the winter period in a cold climate, with a constant air temperature of 20°C and a very low humidity of the inlet air (30 %RH). Two moisture production patterns have been used to simulate the conditions of a bedroom and of a living room, and the maximum value of relative humidity has been registered after 10 days of simulation. This study demonstrates the importance of the hygric inertia to mitigate the peaks of humidity, especially in the case of small rooms. A good ventilation remains the most important condition (also considering indoor air quality), but high values of hygric inertia, which can be obtained through the use of finishing materials with a good moisture buffer value, allow to avoid over-ventilation also with great benefits in terms of energy consumption.

INTRODUCTION

Humidity is the measure of the content of moisture in the air and it is usually expressed as a percentage of the saturation vapour pressure as relative humidity (RH). This parameter should not be overlooked in the design of buildings in order to guarantee durability, healthiness and comfort [1]. In fact, the trend of humidity in the close environments has an influence both on the inhabitants, affecting thermal comfort and indoor air quality perception [2], and on the building envelope, given the risk of reducing its durability. If intermediate levels of humidity have little influence on comfort, several problems arise when RH reaches extreme values. A high rate of humidity can lead to condensation and mould growth, with consequential respiratory problems and allergies for the inhabitants [3]. On the contrary, low levels of humidity can cause dryness and irritarion of eyes and air ways [4].

A possibility to control the level of air relative humidity is the use of humifier and dehumifier, but their installation and use come with a cost both in terms of money and energy consumption [1]. An alternative method consists in the use of materials with a high hygric capacity, both for the finishes and for the furnishing. These materials act as a

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buffer, absorbing humidity during the wet periods and realizing it when the air is dry. Several studies demonstrate how interior moisture buffering positively affects indoor comfort and energy consumption [1], [5]. Various protocols to characterize the moisture buffer potential of single elements have been proposed [6]–[8] and also studies on furniture and indoor objects have been conducted [9]. Ramos and de Freitas [10] have gone beyond proposing the superposition of the capacity of the single elements, hypothesis corroborated by Janssen and Roels [1]. Abadie and Mendonça [3] try to bridge the gap between material characterization and indoor environment simulation. The study of mould combined with heat and air transport is an issue that has been investigated for almost a century [11]; however, in the last years, it has been fostered by the addition of pollutants as further measured data. These models take the name of CHAMPS [12] and aim to give an holistic description of the indoor environment quality (IEQ) of the building.

All these studies demonstrate that the topic is gaining research interest; nevertheless, a full forecast of the behaviour of an environment (with moisture storage and transport) is still unrealistic, because of the complexity of the phenomenon. The aim of this paper is to propose an easy and useful tool that can be used for estimating the right amount of hygric inertia of a room for guarantying comfort during the winter period. This season is usually characterized by large variations of RH because the inlet air is dry and the air change rate is kept to a minimum. It is believed that a certain level of hygric inertia can contribute to improve indoor comfort and to avoid overventilation, therefore decreasing the energy consumption. In particular, we want to establish the required value of hygric inertia in relation to the room size and the air change rate in order to prevent an excess of humidity. This aim is reached trough a series of simulations and polynomial interpolations of the results, giving as final output two very simple graphs useful in the pre-design phase of a building project.

STATE OF THE ART

The variations of humidity in a room may be described using the moisture balance equation. Assuming that the air is well mixed (conditions are the same all over the room) and there is no surface condensation, neglecting the temperature dependency of air density and the vapour flux through the envelope, and considering only air exchange with the outdoor environment, the moisture balance equation may be written as follows:

$$\frac{dc_i}{dt} = \frac{n(c_i - c_o)}{3600} + \frac{G_{vp}}{V} - \frac{G_{buf}}{V} \quad ; \qquad (1)$$

- c_i vapour concentration of the indoor air (kg/m^3);
- c_o vapour concentration of the outdoor air (kg/m^3);
- n air change rate per hour (h^{-1});
- G_{vp} interior vapour production (kg/s);
- G_{buf} moisture buffering (kg/s);
- V volume of the room (m^3).

From this equation it is possible to infer that the value of moisture buffer is not enough to fully describe the behavior of a room in relation to the trend of humidity. Even considering all the simplification that were taken as hypothesis, it is necessary to know the internal moisture production, the volume of the room, the air change rate and the outside conditions. The amout of humidity that is stored in the buffer depends on the hygric inertia (HIR) of the room. This quantity is defined as the superposition of the moisture buffer potentials (MBP) of the interior finishes and objects in the room [10], according to equation (2):

$$HIR = \frac{\sum A_k \cdot MBP_k + \sum MBP'_j}{V} \quad . \qquad (2)$$

The estimation of the MBP of a material is still a challange and no agreement has been found on this topic yet. For sure the MBP depends both on the vapour permeability and the moisture capacity, but also on external factors like the extent and the speed of the air humidity variation and the air temperature. Some protocols on this issue have been developed [7], [8], being the most complete and widespread the Nordtest [6]. It describes a laboratory procedure that leads to the definition of the moisture buffer value (MBV) which is a value that expresses the amount of buffer potential of a material under typical residential moisture loads.

The moisture exchange between the air and the buffer is commonly simplified using two main models: effective capacitance (EC) and effective moisture penetration depth (EMPD). The first model considers that the humidity in the storage is constantly in equilibrium with the room air. This simplification allows to sum the hygric inertia and the moisture capacity of the air of the room, following equation (3):

$$M \cdot \frac{dc_i}{dt} = \frac{n(c_i - c_o)}{3600} + \frac{G_{vp}}{V} \quad , \tag{3}$$

where M (-) is a multiplication factor for the room air moisture capacity. The coefficient M is equal to 1 when no extra moisture buffer is available except the room air capacity, while high values of M denote a high potential of moisture buffering. This method is straightforward and widely used but it has some down sides. First of all, it is not clear how to estimate the M value. Moreover the precision of the model has been questioned: Janssen and Roels [1] refer that the EC model is able to give a fair prediction of maxima and minima but doesn't precisely foresee the trend of relative humidity. On the other hand, the coefficient M may be considered a way of measuring the HIR of the room and even a correlation has been proposed [1]:

$$M = 1 + \frac{100 \cdot HIR}{\rho_{V,sat}(T_i)} \quad ; \tag{4}$$

- $\rho_{V,sat}$ saturated interior vapour density (kg/m^3).

The EMPD model is more suitable for scenarios in which the moisture buffer is made by the surface layer of the room envelope. In this case, the description of the moisture buffer is more complex and depends on the moisture penetration depth and the characteristics of the finishing material, according to equation (5):

$$G_{buf} = \mathrm{A} \cdot \xi \cdot d_b \cdot \frac{\partial}{\partial \mathrm{t}} \left(\frac{p_{vb}}{p_{v,sat}(T_b)} \right) \quad ; \tag{5}$$

- A area of the buffer material (m^2);
- ξ moisture capacity (kg/m^3);
- d_b moisture penetration depth (m);
- p_{vb} vapour pressure of the buffer layer (Pa);
- T_b temperature of the buffer layer (K).

This method allows a better prevision of the indoor RH variations but it has some limitations. It is hardly applicable to indoor multidimensional objects, it requires a large computational effort and it relies on the calculation of the moisture penetration depth [1]. The latter property can be calculated in an analytical way from the moisture capacity and the vapour permeability, which require long and difficult tests. Moreover the moisture penetration depth is not well defined for multi-layer materials.

METHOD

Given the complexity of the problem, this paper is focused on one single room during the winter season. This period of the year has been chosen because it is the most susceptible to humidity discomfort: the indoor environment is isolated from the outside and the humidity variation are wider because of the dry inlet air and the internal humidity production. From the moisture balance equation we have inferred that the RH trend depends on the volume of the room, the hygric inertia, the air change rate and the internal humidity gains. Working on these relations, the intent of this paper is to find the amount of hygric inertia that is required for keeping the RH under a given threshold, when all the other variables change.

Parametric simulations

A series of simulations has been done using the software TRNSYS 18 [13]. This program simulates the environmental conditions of a space as a function of the building's characteristics, the weather condition and the internal gains. Concerning the buffer effect of humidity within a zone, two different models are available: effective capacitance and buffer storage. The latter is an empowered EMPD model, where the buffer is separated in two different storages: shallow and deep. Doing so, both short and long term effects of the buffer can be considered, but 6 parameters are needed for completely describe the storage system.
Aware of its limits, we have decided to use the EC model for the following reasons:

- as it will become clear in the following paragraphs, the main focus of this study is on the peaks of humidity, we are not interested in describing the trend with extreme precision;
- we want to keep this study as wide as possible: using the EMPD model would force us to speculate the extension and characteristics of the material used for the finishes;
- this study is focused on the daily variation of humidity, so splitting the moisture buffer in two parts is excessive and time consuming.

The simulations are run for a period of two weeks with a timestamp of 15 minutes: at the end of the simulation, a steady periodic cycle is achieved in all cases. From a simulation to the next, the following variables have been parametrically changed in a way that all the combinations have been tested:

- volume of the room – V (m^3) Levels: 25 - 30 – 35 – 40 – 50 – 60 – 80
  Considering the tipical ceiling high of 2.7 m, the levels cover roomsizes that go from 9 m^2 (single bedroom) to 30 m^2 (wide living room);

- air change rate – n (h^{-1}) Levels: 0.1 – 0.2 – 0.3 - 0.4 - 0.5
  The ventilation is simulated as constant so these values can be considered averages over the day. These levels go from poor ventilated all the way to well ventilated buildings. Note that the simulation period is winter, so a higher level of air change rate is unlikely;

- hygric inertia – M (-) Levels: 1 – 2 – 4 – 8 – 16 – 24;
  As previously explained, the coefficient M of the EC model can be considered a measure of the hygric inertia of the room. The value of M=1 means that no moisure buffer is present. Hygric inertia may be obtained in different ways: selecting specific materials for the finishings or taking advantage of furniture and curtains. Calculating the exact value of M is beyond the aims of this paper, but some examples may be found in literature. Janssen and Roels [1] propose an interesting table showing how a 90 m^2 room can be assigned a value of M that goes from 1 to 21,61 depending on the type of finishes and furniture.

- Humidity production - G_{vp} (kg/s) Levels: bedroom – living room
  Two patterns of humidity production have been considered, representative of different uses of the space:
  1. Bedroom: typical production of two people sleeping (0,120 kg/s from 0.00 to 8.00);
  2. Living room: a more intense and short production (0,300 kg/s from 6.00 to 8.00 and from 17.00 to 21.00).

A routine in R [14] was created to automatically lauch the simulations and collect the results; the total amount of simulations was 420.

Boundary conditions

The simulations are set to emulate the conditions of a typical winter period. The indoor temperature is fixed to the value of 20 °C, guaranteed thanks to an ideal heating system. It is assumed that the inner heat gains are compensated by a lower functioning of the heating system, so the temperature remains constant. The vapour concentration of the incoming air is taken constant at 5.32 g/m³ which corresponds to outdoor conditions of 8 °C and 65 %RH. After the heating process the relative humidity of the inlet air is equal to 30 %. It was decided to use a constant value for the RH of the inlet air instead of a variable one taken from a weather file in order to keep the study as wide as possible, without fixing it to a specific location. This set up covers both the case where the ventilation is reached through the windows' opening and the case where a mechanical ventilation system is installed, as long as it has no moisture recovery unit. All the constant parameters are summarized in Table 1. The vapour transfer trough the building envelope is neglected.

Table 1. Boundary conditions of the simulations

Parameter	Abbreviation	Value
Indoor temperature	T	20 °C
Saturated vapour pressure	$p_{v,sat}$	2340 Pa
Saturated vapour density	$\rho_{v,sat}$	17.56 g/m³
Inlet air vapour concentration	x_{VENT}	5.32 g/m³
Inlet air relative humidity	RH_{VENT}	30 %
Initial value of relative humidity	RH_0	50 %

Threshold value

The whole process of this study is aimed at keeping relative humidity under a given threshold, but which could be the maximum desirable value of RH in order to guarantee comfort and health to the inhabintants? On this matter we reffered to UNI EN 16798-1:2019 [15], that recommends the design values reported in Table 2 for occupied spaces where humidifcation or dehumidification is needed.

Table 2. Recommended design criteria for RH – UNI EN 16798-1:2019

Category	**Design RH for dehumidification** (%)	**Design RH for humidification** (%)
I	50	30
II	60	25
III	70	20

Category II is considered the boundary between comfort and discomfort and it is the design category when there are no inhabitants with specific needs. Anyway, considering that we are not fixing the set point of a machine and the peaks of high humididty are very brief, we left some tolerance and fixed the threshold at 65 %RH.

RESULTS AND DISCUSSION

The outputs of this analysis are multiple, because of the wide amount of simulations conducted. In order to better understand the process of the study, we first begin by showing the results of one single case: a room with volume of 40 m³ and with a bedroom-type moisture gain.

The chart in Figure 1 reports the 30 simulations run for the mentioned room. The columns represents the amount of hygric inertia while the rows stay for the value of air change rate. The red dotted line is the threshold that was established as the upper limit for relative humidity. Let's have a look at the first case (M=1 and n=0.1): the relative humidity increases during the night and the saturation concentration is reached. During the day the RH lowers thanks to the ventilation and the absence of internal humidity production, but the lower spikes barely reach 50 %RH. Increasing the amount of ventilation shifts the line downward but it has little effect on the daily excursion of humidity. On the contrary, increasing the value of hygric inertia has the effect of smoothing the trend and lowering the daily variation, but it doesn't affect the mean value of the relative humidity. The most effective method for guaranteeing an adequate humidity inside the room seems the use of a high ventilation, because it works in all the cases, no matter which is the amount of hygric inertia. This is true, but it is important to remember that ventilation comes with a cost: the air that is introduced has to be heated up and, if the room is equipped with a CMV system, it also has a running cost. Moreover, overventilation may threaten the opposite situation, where the room air is too dry. On the other hand, a high value of M helps but in some cases it is not enough: with a ventilation rate of 0.1 h^{-1}, for instance, the level of relative humidity rises over the threshold of 65 %RH no matter how much we increase the hygric inertia. This is due to the fact that the humidity produced during the night is more than the quantity that can be removed with this limited amount of ventilation. The best solution is probably a combination of ventilation and hygric inertia. A decent amount of ventilation is essential also for other purposes (first of all air quality), but in many cases it is not possible to guarantee a constant level of air change rate, like in historic and existing buldings in general.

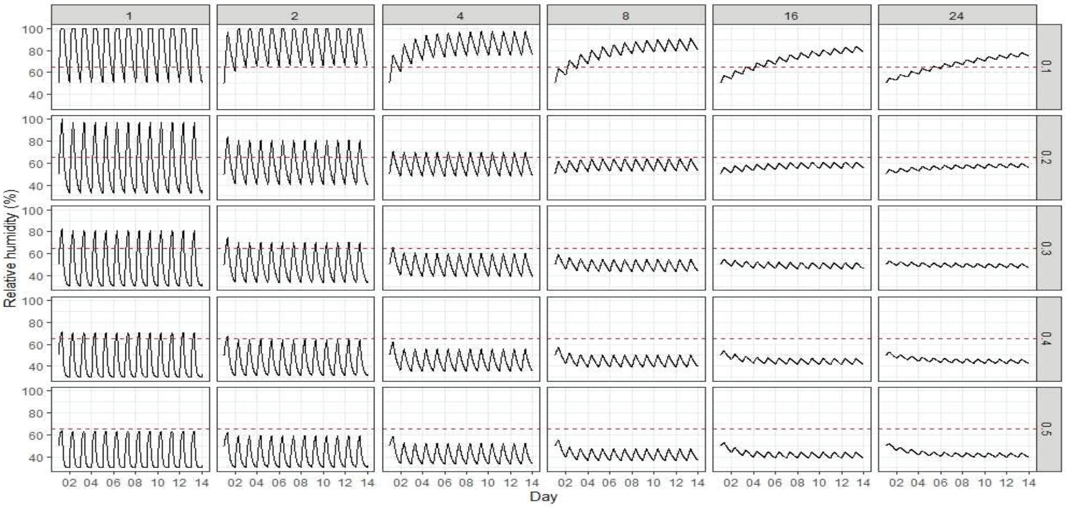


Figure 1 All the simulations for the case with volume of 40 m^3 and bedroom-type moisture gain. The columns are the different amounts of hygric inertia (parameter M) while the rows are the different values of air change rate.

Since we are interested in the maximum value of RH, it is possible to display the results in a more synthetic way, as shown in Figure 2.

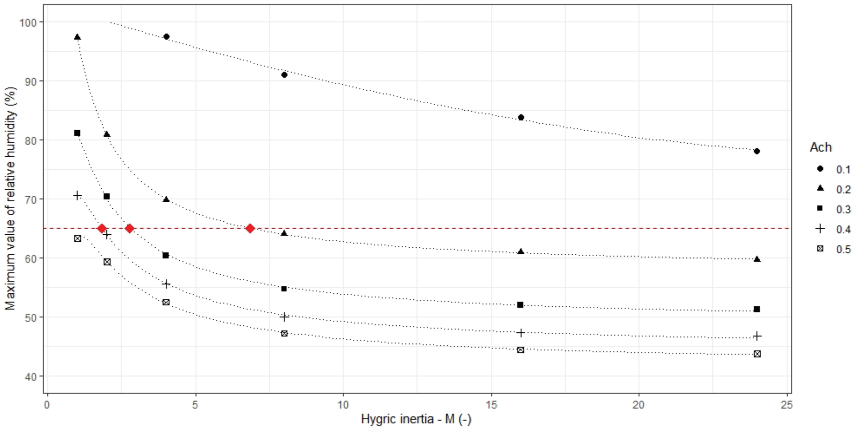
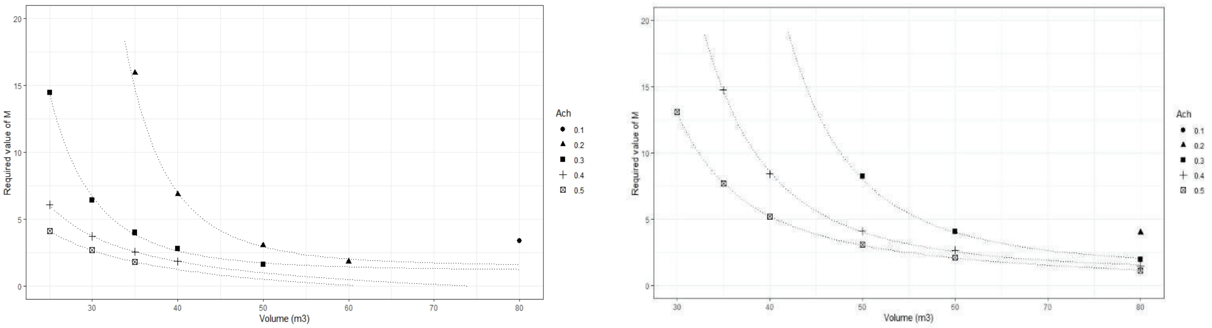


Figure 2 Summary of all the simulations conducted for the room of 40 m^3 with bedroom-type humidity gains where only the maximum values of RH are reported. Interpolating the results, for every air change rate, it is possible to find the required amount of hygric inertia that is needed to keep the RH in the comfort range (red dots).

The points of the chart in Figure 2 represent the maximum values of relative humidity that are reached in every simulation for the 40 m³ room with bedroom-type humidity gains. Note that the maxima are calculated on the last day of simulation, because we are interested in the situation were an equilibrium is reached and the first part of simulation is biased by the starting value of humidity. These values are displayed as a function of the parameter M and subdivided for the different levels of ventilation. A polynomial interpolation between the points has been made with the aim of calculating the minimum value of hygric inertia that is necessary to guarantee that relative humidity doesn't overpass the threshold. These values are visually represented by the intersection between the curves and the threshold line and they have been highlighted with red dots. Of course this operation may be done only for the curves that cross the horizontal line: in this case we can see that with an air change rate of 0.1 h^{-1} the peaks of humidity are constanty over 65% for any value of M. On the contrary with $n=0.5$ h^{-1} the comfort zone is always reached.
The final step of the study has been to report these critic points in a chart. In this case, only with Figure 3, it is possible to report the results of all the room sizes.



(1) (2)

Figure 3
Required values of hygric inertia (M) for keeping the RH under the threshold for every value of air change rate in the case of the bedroom-type humidity gain (1) and for the living room-type humidity gain (2).

The chart in Figure 3.1 shows the minimum value of M that is required in order to maintain the humidity below the threshold value as a function of the room volume and the air change rate, in the case of the bedroom-type humidity gain. This is the final and more interesting output of the study and it is meant as a tool for the design phase of a building: knowing the size and the level of ventilation of the room, the designer can decide the material for the finishings or the type of furnishing on the basis of the hygric inertia required. In fact, the hygric inertia of the room can be estimated by the superposition of the MBV of the finishing materials [6] and the furniture [9]. Here is what we can infer from the chart:

- with a normal amount of ventilation (0.3 h^{-1}) hygric inertia plays an important role in order to avoid an excess of humidity: the required level of M varies from 1.59 to 14.46 according to the room size;
- with a level of ventilation of 0.2 h^{-1}, hygric inertia is equally important, but for very little rooms the required value of M is probably difficult to achieve in a real case;
- with very low ventilation (0.1 h^{-1}) hygric inertia doesn't allow to reach humidity comfort conditions simply because the moisture produced is more than what it is possible to remove;
- with higher levels of ventilation (0.4 and 0.5 h^{-1}) a certain level of M is essential but mostly for rooms under 40 m³.

All the described process has been conducted also for the living room-type humidity production pattern. The final output is reported in Figure 3.2. The results are similar to the other case but the need of ventilation and hygric inertia is even more pronounced due to the heavy moisture loads. These graphs may be used to guarantee that the humidity level of the room does not exceed the comfort value during a typical use.

The following is a set of instruction on how to use the charts represented in Figure 3:

- select the use of the room: bedroom (1) or living room (2); consider the proper graph;
- select the volume of the room on the abscissa axis (from 25 to 80 m^3);
- select the daily average air change rate (from 0.1 to 0.5 h^{-1}) and consider the proper curve on the graph;
- read on the ordinate axis the amount of hygric inertia (M).

The required value of M is the final output of the proposed method, a further step could be to propose a specific material for the finishings of the room in order to reach the required hygric inertia. However, this final step need a preventive investigation of the MBV of a large set of materials.

CONCLUSIONS

This paper is built around the following research question: is it possible to find the minimum level of hygric inertia required for guaranteeing indoor comfort avoiding unnecessary levels of ventilation? An answer to this question would be very helpful for designers during the very first phase of the project of a new building or renovation. In this study the answer has been seeked through a series of simulations and polynomial regressions for the case of a single room during the winter season. 420 simulation were conducted testing 7 room sizes, 5 air change rates, 6 levels of hygric inertia and 2 humidity production patterns. The final output consists of two graphs that correlate the required value of hygric inertia with the room size and the level of ventilation. Hygric inertia proved to be essential for preventing excess of humidity expecially for small rooms and it may be used for avoiding the need of overventilation that causes great energy consumption. On the other hand, there are conditions where any tested level of hygric inertia is not enough for reaching comfort conditions, like the case with very low ventilation (0.1 h^{-1}).
Relative humidity is a key parameter in the design of healthy, comfortable and durable buildings and neglecting it during the design phase could lead to inadequate buildings. This study is a first step in the direction of indoor environmental quality design according to the moisture aspect. Future work will be a study on how it is possible to reach the required hygric inertia in the indoor environment and which are the most suitable materials for the finishes.

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NOMENCLATURE

RH = relative humidity (%);
c_i = vapour concentration of the indoor air (kg/m^3);
c_o = vapour concentration of the outdoor air (kg/m^3);
n = air change rate of the outdoor air (kg/m^3); interior vapour production (kg/s);
G_{vp} = moisture buffering (kg/s);
G_{buf} = volume of the room (m^3); hygric inertia per cubic meter ($kg/(m^3 \cdot \%RH)$);
V = moisture buffer potential per square meter ($kg/(m^2 \cdot \%RH)$);
HIR = area of the moisture buffer surface (m^2);
MBP = equivalent moisture buffer potential (kg/%RH);
A = moisture buffer value ($g/(m^2 \cdot \%RH)$);
MBP' = coefficient that quantifies the hygric inertia according to the EC model (-);
MBV = saturated interior vapour density (kg/m^3);
M = moisture capacity (kg/m3);
$\varrho_{V,sat}$ = moisture penetration depth (m);
ξ =
d_b =

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