COMPARISON OF MEASURED AND CALCULATED VALUES FOR THE INDOOR ENVIRONMENT IN ONE OF THE FIRST DANISH PASSIVE HOUSES

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ABSTRACT

Energy savings in the residential area are essential in order to achieve the overall goal for energy savings outlined in the recast of the Energy Performance of Buildings Directive. This was adopted by the European Parliament in 2010. Unfortunately, the large focus on energy performance has reduced the focus on indoor environment. This has, among other problems, resulted in problems with overheated buildings. Therefore, a need for a simple and cheap method for evaluation of possible problems with overheating has arisen among the designers. A method which can be used early in the design process.

The paper compares the measured indoor temperatures of a Danish passive house with results of both a simple prediction of the 24-hour average and maximum indoor temperature during summer and a dynamic simulation of the indoor conditions in the building in order to find a useable method for prediction of problems with overheating.

INTRODUCTION

During 2008 ten passive houses were built in Skibet near Vejle in Denmark. The houses were some of the first of their kind in Denmark, which all were built and certified after the German passive house standard. The ten houses were a result of the development project "the Comfort Houses" which aimed for dissemination of knowledge, and the necessary expertise, of building a passive house in a Danish context. In Denmark the sun is lower and the climate is slightly colder than the context in Germany, where thousands of passive houses are built since the 1990's. Examples of the houses are seen in Figure 1.

The characteristic of a passive house is very low energy consumption for heating (15 kWh/(net m^2) pr year). This is achieved by a well-insulated and airtight building with an efficient heat recovery unit for the ventilation air (only for mechanical ventilation, not for mechanical cooling, which is rarely used in Danish dwellings). Unfortunately, large deviations between calculated and measured values of indoor environment and energy consumption are afterwards often seen. Typical deviations can be 300-400% on the energy consumption (Gram-Hanssen, 2005). These deviations are partly caused by the calculation methods, which of course approximate the true values. In addition, the performance of the constructions and technical installations during operation may deviate from the predicted values during the design process caused by different behavioural patterns of the users.

Figure 1 Eight of the ten passive houses in the "Comfort House" project.

In order to document the function of the 10 passive houses, a large program was carried out including detailed measurements of the obtained indoor environment and energy consumption from the houses. Data were logged from the houses every 5th minute during a period of 3 years starting in October 2008. Detailed measurements have been made of the indoor temperatures, relative humidities and CO_2-levels in kitchens, living rooms, bathrooms and nurseries. In addition, the energy consumption for heating, production of hot water and electricity consumption for ventilation were measured. All measurements are held up against weather data from the area, to be able to compare different seasons and different years.

The first results from the houses have shown severe problems with overheating during summer and insufficient heating during the winter period even

though the calculations made in PHPP (Passive House Planning Package) did not indicate any kind of problems during the design phase. The same problems are known from Sweden, which has similar outdoor conditions (Isaksson, 2006 and Janson, 2010).

Today, it is not a demand in the Danish building regulations to simulate or document the expected indoor environment, and the aim with this analysis is to find a simple, but still reliable, method for evaluation and documentation of the indoor environment in future low energy buildings. A documentation which hopefully will become mandatory.

CASE STUDY

To illustrate the problems regarding overheating, one of the ten houses are selected. Figure 2 shows the plan of the house together with positions for inlets (blue dots) and exhausts (red dots) used by the mechanical ventilation and two point with sensors for temperature, relative humidity (RH) and CO_2-levels (green dots).

Figure 2 Plan of the building used for the case study

The house has an area of 141/169 (net/gross) m^2 and is heated by a ground source heat pump (underfloor heating in bathrooms) combined with air/water heat pump for air heating and production of hot water. The ventilation is demand controlled based on temperatures and relative humidity. It has balanced mechanical supply and exhaust with efficient heat recovery. U-values of external walls are 0.085 W/m^2K and windows 0.66 W/m^2K. The house has fixed solar shading on southern (seen in figure 1) and partly eastern and western windows.

Measurements from two summer periods

During the summers 2009 and 2010 the house became overheated a large part of the time resulting in thermal discomfort for the occupants. Figure 3 shows measurements from July 2009 and 2010.

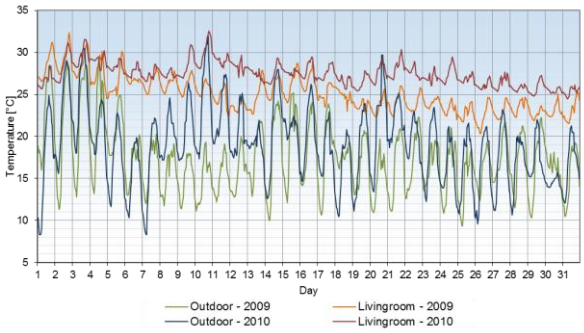

Figure 3 Measurements from the living room and outdoors July 2009 and 2010.

In order to analyse the results, the categories from the European standard "Ventilation for buildings – Design criteria for the indoor environment" was used (CR1752, 2001). It was chosen to aim for category B. Figure 4 shows the results for the thermal indoor conditions from July and August 2009 and 2010 respectively. Here it is seen, that category B is only achieved 60% of the time in 2009 and 40% of the time in 2010.

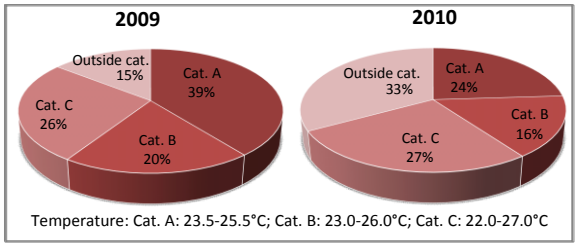

Figure 4 Analysis of measured temperatures in the living room during July 2009 and 2010. Levels are based on CR1752, 2001.

During these periods the house was occupied by two different families of four but with different venting patterns. In 2009 windows were open most of the occupied hours, which is seen at both the lower indoor temperature in 2009 (see Figure 3 and Figure 4) but also at the measured CO_2-levels (see Figure 5).

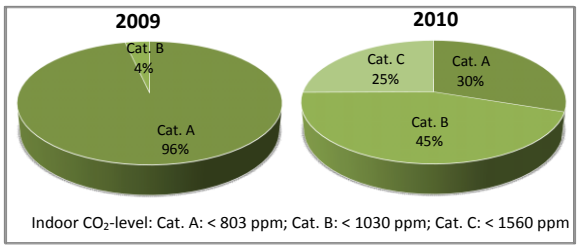

Figure 5 Analysis of measured CO_2-levels in the living room during July 2009 and 2010. Levels are based on CR1752, 2001.

Since the internal loads were the same in 2009 and 2010, Figure 5 shows how the occupant behaviour regarding the venting patterns in 2009 influences the air quality. But also the thermal environment is affected in a positive direction by the 2009 venting pattern even though the temperature level still is way above the level for thermal comfort (max. temperature should be below 26°C).

Prediction of the problems with overheating

Unfortunately, the possible problems with high indoor temperatures were not analysed during the design process and therefore, were not found before the building was standing finished at the site. It has in Danish building tradition not earlier been a problem with overheating in dwellings since natural ventilation could handle the heat gains and ensure thermal comfort even during summer. With new low energy buildings, the problem becomes more severe. The low energy buildings are very air tight and well insulated, and even small heat gains can very fast heat up the building. It is therefore important, that focus on the thermal indoor environment is increased during the design process, for instance by use of simple predictions or simulations of the expected thermal environment for critical rooms with high internal loads and/or high solar heat gains.

SIMULATION OF INDOOR TEMPERATURE

When a simulation of the indoor temperature is made, it is important to focus on the needed results and their accuracy before the simulation is defined. In this case, also the time spend on the simulation is important, since a lot of the simulations of indoor temperature in critical southern rooms are made during the very first phase of the design process. A lot of simulations can be needed in order to obtain the best design solutions and time will therefore be an important parameter here in order to also make an economical sustainable solution.

Two different methods are described in the following. A detailed dynamic simulation with calculations on an hourly basis (time consumption app. 10 hours) and calculation of a 24-hour average and maximum temperature on a warm summer day based on monthly data (time consumption app. 1-2 hours)

Method 1: Dynamic simulation

In this method, a model of the house used in the case study is made in a dynamic hygrothermal building simulation program called BSim. The model is shown in Figure 6.

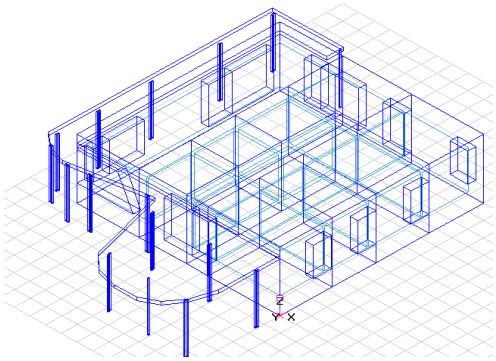

Figure 6 Model of the house built in BSim.

The advantage of carrying out a dynamic simulation of the house is that more realistic profiles of user behavior (presence or not, window opening etc.) can be included. Thereby, the temperature will become much more realistic with variations (and especially peak values) almost similar to reality.

The zones of the model

The house is in the current model divided into four thermal zones and follows the same structure regarding U-values, infiltration, ventilation etc., as it is the case for the real building. The house is simulated as inhabited by a family of five people. The layout of the dwelling can be seen at Figure 7 as well the four ventilation zones. Zone 1 consists of three bedrooms and an office. Zone 2 consists of a hall and a corridor. Zone 3a consists of a living room and a kitchen combined. Zone 3b consists of a bathroom, a toilet and a utility room (only divided into two rooms on the figure).

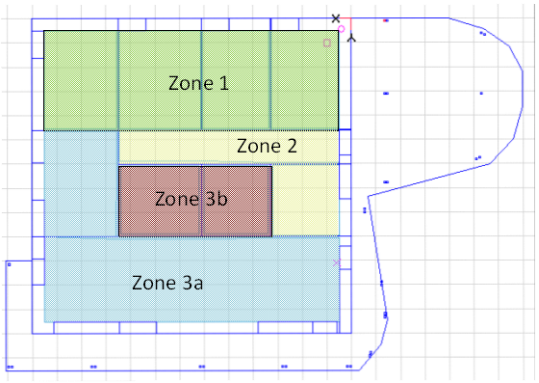

Figure 7 Thermal zones used in the dynamic building simulation

The air enters into Zone 1. From there it passes through Zone 2 and is finally extracted from Zone 3a and 3b. The amount of air extracted per square meter from Zone 3a and 3b are the same.

Occupants

Since occupants and their behavior will affect the indoor environment, special care has been devoted to the distribution and numbers of hour's people spend in their home. According to (Keiding et al., 2003) Danish people between the age of 16 and 74 spend in average 16.3 hours in their home. The dwelling is according to (Bergsøe, 1994) empty 5.4 hours a day on weekdays. Based on this, a distribution of the five people is shown in Table 1 for a week. This week is used throughout the simulated year knowing that there are times where there are more and less people. It is assumed that the people are a sleep from 23 to 7 (hour 1-7 and 24). For these hours they are placed in Zone 1 and in the rest of the hours they are placed in Zone 3.

Table 1
Number of people present during a week. Hour 1 is from 0:00 - 1:00 etc.

Hour	M	T	W	T	F	S	S
1	5	5	5	5	5	5	5
2	5	5	5	5	5	5	5
3	5	5	5	5	5	5	5
4	5	5	5	5	5	5	5
5	5	5	5	5	5	5	5
6	5	5	5	5	5	5	5
7	5	5	5	5	5	5	5
8	5	5	5	5	5	5	5
9						5	5
10						5	5
11						5	5
12						3	3
13						3	3
14						3	3
15					3	3	3
16					3	3	3
17	3	3	3	3	3	3	3
18	3	3	3	3	3	3	3
19	3	3	3	3	3	3	3
20	3	3	3	3	3	3	3
21	5	5	5	5	5	5	5
22	5	5	5	5	5	5	5
23	5	5	5	5	5	5	5
24	5	5	5	5	5	5	5

Natural ventilation (venting)

I order to make the description of natural ventilation caused by window openings as realistic as possible, it is chosen to activate window openings only during the occupied hours. The rest of the time (weekdays between 8 am and 4 pm), the windows remain closed as it is assumed to be in reality. The windows are opened when the indoor temperature exceeds 23°C (and the house is occupied). When windows are opened, the achieved air change rate is 1.57 h^{-1}. This value is based on the original documentation from the building. Further description of the schedules used in the model can be found in (Jensen at al., 2008).

Results for method 1

The results from the simulation are seen in Figure 8, where the amount of hours during one year above 26°C can be evaluated.

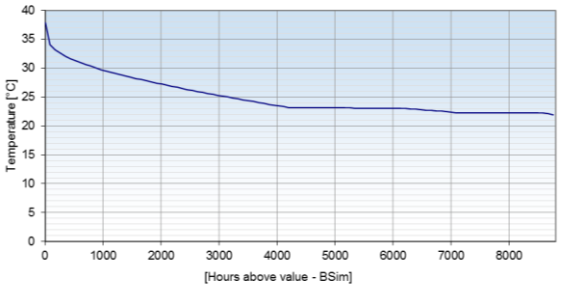

Figure 8 Results from dynamic simulation of temperatures in zone 3a during one year

The curve in Figure 8 shows that according to the dynamic simulation, there will be temperatures above 26°C for approximately 30% of the time corresponding to approximately 2600 hours. This is a very high amount of hours outside category B, which was the aim for the temperature levels in the house. Therefore, a dynamic simulation would, for this case study, be a very suitable, though time consuming, way to predict the problems with overheating. Thereby changes in the building design (solar shading, number of windows or increased use of natural ventilation) could be implemented before the problem occurred in the finished house. Measurements during the summer period (May-September) showed that only 44% of the period fulfilled Category B.

If the results from the simulation are compared to the results from the measurements in the house, a very good correspondence is found. In the measurements, the temperature is above 26°C for 27% of the time in the living room (corresponding to zone 3a) when all hours during one year are included. The results are seen in Figure 9. If weekdays between 8 am and 4 pm are excluded, since it can be argued that the temperature in this period is unimportant if the house in unoccupied, this percentage changes to 26%. Thereby the period included in the counting, in this case, seems only to have a very small effect on the results.

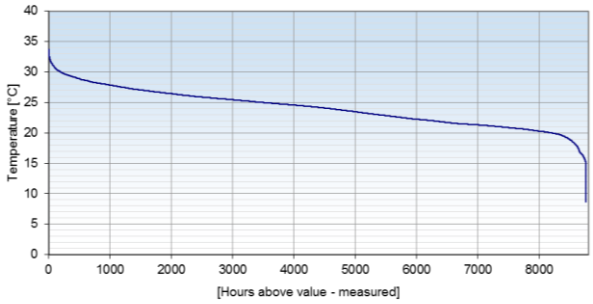

Figure 9 Results from measurements of temperatures in the living room during one year (April 2010 – March 2011)

Method 2: Calculation of 24-hour average and maximum temperature

The 24-hour average temperature is determined from a simple calculation based on a heat balance for the volume included in the calculation (eg. room or building). The calculation is based on monthly values for the weather data and the results from the method are an estimation of the mean temperature for a day in a summer month together with the variation of temperature during 24 hours in order to also assess the maximum temperature.

Description of the calculation

The main input parameters are the mean temperature of the outdoor air in a given month and the corresponding outdoor variation during 24 hours, thermal mass in the construction materials, constructions (in terms of U-values), internal loads, solar radiation and ventilation rates. The calculation is typically carried out in a few hours. The method is described in (SBI instruction 202, 2002). A short description is given in formula (1) to (5).

The 24-hour average indoor air temperature ($t_{i,a}$) is found by (1)

$$t_{i,a} = t_{o,a} + \frac{\varphi_{int,24-hour} + \varphi_{sun,24-hour}}{24(H_T + H_V)} \quad (1)$$

After calculation of the average temperature, the variation between minimum and maximum temperature is found in order to predict the temperature on the warmest day during the period. For this calculation, the accumulation capacity (thermal mass) of the room must be taken into consideration since the amount of thermal mass will influence on the variation of temperature. The variation (Δt_i) is found from (2)

$$\Delta t_i = t_{i,max} - t_{i,min} + \frac{\Delta\varphi_k}{H_T + H_V + H_{acc}} \quad (2)$$

where

$$\Delta\varphi_k = \frac{\Delta\varphi_{k,int+sun} + \Delta\varphi_{k,to}}{H_T + H_V + H_{acc}} \quad (3)$$

and

$$\Delta\varphi_{k,int+sun} = \frac{2}{3}\left[(\varphi_{int} + \varphi_{sun})_{max} - \varphi_{int,min}\right] \quad (4)$$

$$\Delta\varphi_{k,to} = \Delta t_o\left(H_{T,win} + H_V\right) \quad (5)$$

Before starting the calculation of the 24-hour average and maximum temperature it should be decided, which room(s) in the house that has/have the highest solar radiation and/or internal loads, and thus will have a potential risk to obtain problems with over-temperature, which is the only parameter evaluated with this method.

Determination of the critical room

The following calculation again uses the house from the case study (see Figure 2). It is assumed in the calculation, that the critical room is the living room and kitchen / dining area to the south. It is this space and the corresponding area, which is used to determine the 24-hour average and maximum temperature. Figure 10 shows which parts of the house that are used in the calculation.

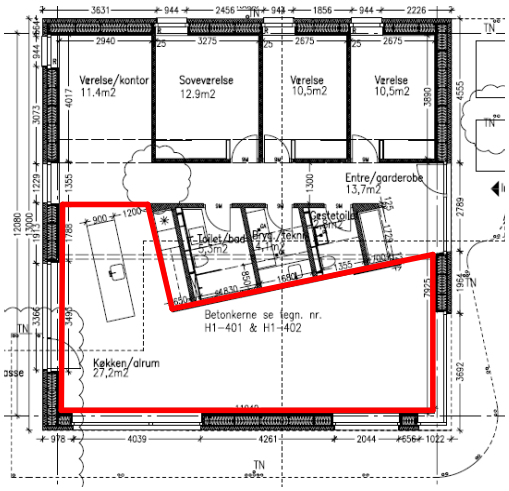

Figure 10 Area used for the calculation of 24-hour average and maximum temperature

Results for method 2

The calculations are made both for a house in use (L1) and an empty house (L2). The amount of natural ventilation is defined as both a standard ventilation quantity ($1.3h^{-1}$) (V1) and an increased use of natural ventilation ($2.5h^{-1}$) (V2). All calculations are done for the weather data for June. The results of the calculation are shown in Table 2.

Table 2
The four cases used for prediction of the 24-hour average and maximum temperature together with the results

Case	**A**	**B**	**C**	**D**
Person load + lighting	L1	L1	L2	L2
Natural ventilation	V1	V2	V1	V2
24-hour avr. temperature	35.4°C	30.4°C	34.5°C	29.8°C
24-hour max. temperature	38.6°C	33.8°C	37.6°C	33.1°C

From Table 2 it is seen that for all the cases, temperatures reached well above the comfort temperature. This prediction indicates thus that the house will have problems with overheating during the summer. It is therefore, also with this very simple method, possible to predict the problems with overheating in the house, which should have been fixed during the design phase.

COMPARISON OF THE METHODS

As mentioned earlier, the time consumption between method 1 and method 2 is a factor of at least five. Therefore, method 2 will be preferable in the beginning of the design process, if it shows reasonable results. In the following, the methods are compared by doing simulations/calculations with the loads and ventilation rates assumed to be present in the house. Figure 11 shows the results for the average values found from April until September. For these values, a very good coherence is found and both methods can thereby very well predict the average values – and thereby also the problems with overheating during summer. The dynamic model is more accurate than the "24-hour average" method during spring and autumn, but for the highest and most critical temperatures, both methods give good results.

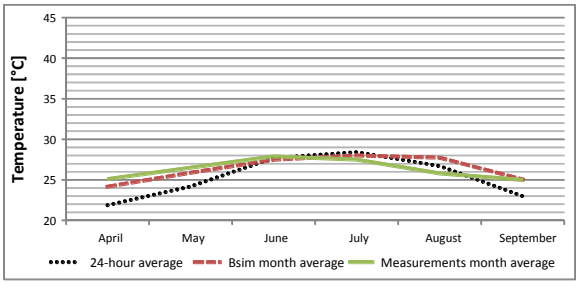

Figure 11 Comparison of the 24-hour average temperature during the summer season based on the "24-hour average method", calculations in BSim and measurements (Madsen et al., 2011)

Figure 12 shows values from the day with the maximum 24-hour average temperature. In this case, there is a large deviation between the "24-hour average"-method and the measurements. The deviation is probably caused by a different occupant behavior on very warm days (eg. opening more windows and more active use of solar shading) – a difference which is not included in this method. A part of this behavior can be included in the BSim model, which also predicts the measured temperatures better.

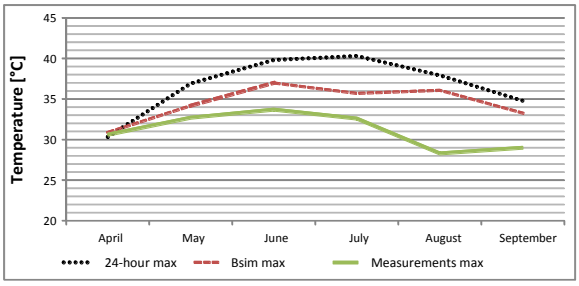

Figure 12 Comparison of the 24-hour maximum temperature during the summer season based on the "24-hour average method", calculations in BSim and measurements (Madsen et al., 2011)

DISCUSSION

The comparisons between the very simple "24-hour average" method, the dynamic simulations carried out in BSim and the measurements show that as long as only the average temperature is considered, the results are good for both models. With the common knowledge, that the maximum temperature is above the average temperature, and results showing an average temperature above or equal to the level for thermal comfort, it should be enough for prediction of problems with overheating. Therefore, in this case, the simple method is sufficient.

When it comes to prediction of the maximum temperature, both methods becomes more inaccurate, but especially the "24-hour average" method deviates from the measurements. It is assumed, that the changed occupant behavior is the main cause for this deviation, since the behavior regarding eg. window opening will change between an average day and a very warm day (in Denmark it is not normal to have mechanical cooling in dwellings. Overheating needs to be removed by natural ventilation only). This change in behavior is not taken into consideration in the simple method but is currently the aim for further research, since the existence of a simple model is essential to increase focus on the indoor environment in future low energy buildings and thereby avoid the problems we have today.

The main force of the "24-hour average" method compared to the dynamic simulation is the time consumption, which is a very important parameter in a design process which, for most cases, is on a very

tight budget. Therefore, this very simple method could be useable in the first part of the design phase where the design is often changed, and a lot of important parameters, when the indoor environment is considered, is fixed during this phase. Later on, when the design is more fixed, the more time consuming dynamic calculations can be made in order to make a more accurate control of the indoor environment.

CONCLUSION

As the focus on energy savings increases, the designers optimize their buildings in order to save energy but unfortunately, this optimization is often causing a poor indoor environment. The main focus during the design process is left at saving energy – not at assuring a comfortable indoor environment. This misbalance in focus has, among difference problems, caused problems with overheating, which has left several house owners from the first generations of Danish passive and low energy houses with overheated houses during several months during the summer period.

We know from the EU's Energy Performance of Buildings Directive from 2010 that energy savings in the residential area are essential. It is therefore important to come up with simple methods for test and documentation of the indoor environment and bring the focus back on this parameter.

The paper suggests two methods for documentation of the indoor thermal environment. The methods are compared to detailed measurements taken every 5th minute in a case study described in the paper. The most simple method is the "24-hour average" method. This method shows good results for prediction of the average temperature, but the deviation between measured and calculated values becomes large when the maximum temperatures are compared. It is therefore necessary to improve the prediction of the maximum temperature before this method is released for documentation of the indoor temperatures. However, it can at this stage still be used as a simple guiding tool for designers, since a high average temperature close to the comfort levels for the project will indicate that revisions to the design are needed.

The other method described is the use of dynamic simulations of the indoor thermal environment. This method predicts very well the average temperatures but is also better at predicting the maximum temperatures since this method is able to include changed behavioural patterns on the warmer days, which is not possible to include in the simple "24-hour average" method. Thereby, the dynamic method shows the best results, but is also much more time consuming than the simple method.

The great advantage in the simple model is the large savings on hours for calculation, which can mean a lot in a tight budget. Therefore, simple, but still reliable, methods are necessary in order to ensure that the indoor environment is taken into consideration during the early stages of the design process before the design is fixed and the indoor environment becomes a bad result of some saved hours for control and documentation.

ACKNOWLEDGEMENTS

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NOMENCLATURE

$\Delta\varphi_k$ Difference between largest and smallest convective heat load (hourly values) [W]

$\Delta\varphi_{k,int+sun}$ Difference between largest and smallest convective heat load from internal sources and sun (hourly values) [W]

$\Delta\varphi_{k,to}$ Variation in convective heat load due to variation in the outdoor temperature (hourly values) [W]

$\varphi_{int,24-hour}$ Total internal heat gain during 24 hours [Wh/(24-hours)]

$\varphi_{sun,24-hour}$ Total solar gains during 24 hours [Wh/(24-hours)]

H_{acc} Accumulation capacity of the room [W/°C]

H_T Specific heat loss for transmission [W/°C]

$H_{T,win}$ Specific heat loss through windows [W/°C]

H_V Specific heat loss for ventilation [W/°C]

$t_{i,a}$ 24-hour average indoor air temperature [°C]

$t_{o,a}$ 24-hour average temperature outdoors [°C]

Δt_o Difference between largest and smallest outdoor temperature [°C]

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