# Integrated Hygrothermal Analysis of Ecological Buildings

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ABSTRACT: Ecological buildings typically are made with a lot of organic materials, e.g. for insulation of the building envelope, and even in cold climates they are often built without the use of a vapour barrier. The paper describes such a house and field measurements of the indoor humidity conditions. A new model makes it possible to analyse the overall moisture conditions in a building by considering both the indoor environment and the building materials in constructions and furnishing. The model gives new analytical capabilities as it combines the analysis of the moisture conditions in the indoor environment with the analysis of the exterior building envelope. The paper demonstrates a comparison of the experimental results from the ecological house with predictions with the integrated model. It is then illustrated how simulations can be used to optimise the hygrothermal quality of building constructions by analysing the effect of: (1) Moisture buffering of materials, (2) Effect on perceived indoor air quality, and (3) Simulation of moisture conditions in building envelopes when the indoor climatic conditions is part of the simulation.

## 1 INTRODUCTION

Humidity in indoor spaces is one of the most important factors influencing indoor air quality. Many health-related problems in the indoor environment, e.g. the Sick Building Syndrome (SBS), can be associated with high indoor humidity and "damp buildings" (Clausen et al., 1999). The humidity level in a building depends on a combination of factors such as moisture sources, ventilation and air movement, reservoirs and sinks, heating, insulation, external conditions, as well as building materials and occupants. Among these, the moisture buffering effect of the materials in a building could be an important factor. There is a general interest in exploiting the moisture buffering effect of building materials to dampen the cyclic variations of indoor humidity. However, this effect is often disregarded by building designers and engineers.

Several attempts have been made to model the indoor humidity condition. Such modelling may cover the simultaneous prediction of moisture conditions in whole buildings – their indoor climate and all constructions of the building envelope. Some references to previous attempts of modelling moisture conditions of rooms or whole buildings are given in (Matsumoto, 1991), (Wang, 2000), (Virtanen et al., 2000) and (Rode et al., 2001).

Moisture conditions cannot be predicted without knowing the thermal conditions. It is quite obvious therefore to develop a model for prediction of whole building moisture conditions as an extension to an existing model for detailed thermal analysis of buildings. Such a model already predicts the thermal condition of the indoor environment and all the adjacent building components as well as air flow between zones. Normally, the thermal calculation models are rather elaborate themselves, and their thermal predictions have already been validated. One such model is , which is included in the integrated building simulation tool (Wittchen et al., 2002). will be applied in this paper.

Furthermore there is a need to experimentally verify the predictions of whole building hygrothermal models. Some relevant experimental investigations are reviewed in (Mitamura et al., 2001) and (Virtanen et al., 2000). In this paper a field test of a so-called ecological building is described where the moisture buffering effect of building materials has been investigated under practical circumstances. The measured hygrothermal indoor climatic parameters are compared with predictions of a numerical model for whole building hygrothermal analysis (). The term “moisture buffering effect” will be used to indicate the ability of building materials to moderate humidity variations in indoor spaces.

## 2.1

is a computational design tool for analysis of indoor climate, energy consumption and daylight performance of buildings. integrates different computer models that make it possible to carry out a complete thermal and daylight analysis of a building. The core of the system is a common building data model shared by the design tools, and a common database with typical building materials, constructions, windows and doors. Figure 1 illustrates the user interface of

The following computational analyses can be made on most buildings using :

- Heat gains from solar radiation, people, lighting, and equipment
- Solar radiation through windows
- Heating, cooling and ventilation
- Power and energy balance
- Steady state moisture balance
- Temperature, moisture and $CO_2$ conditions
- Perceived indoor air quality (PAQ)
- Heat and air exchange between zones
- Shading conditions
- Variable infiltration and venting
- Several different ventilation systems simultaneously
- Surface temperatures and condensation risks
- Air exchange in connection with infiltration and opening of windows
- Air exchange between rooms
- Air-to-air energy recovery in ventilation systems
- Supply and exhaust air temperature in ventilation systems
- Power from heating and cooling coils in ventilation systems
- Humidification in ventilation systems

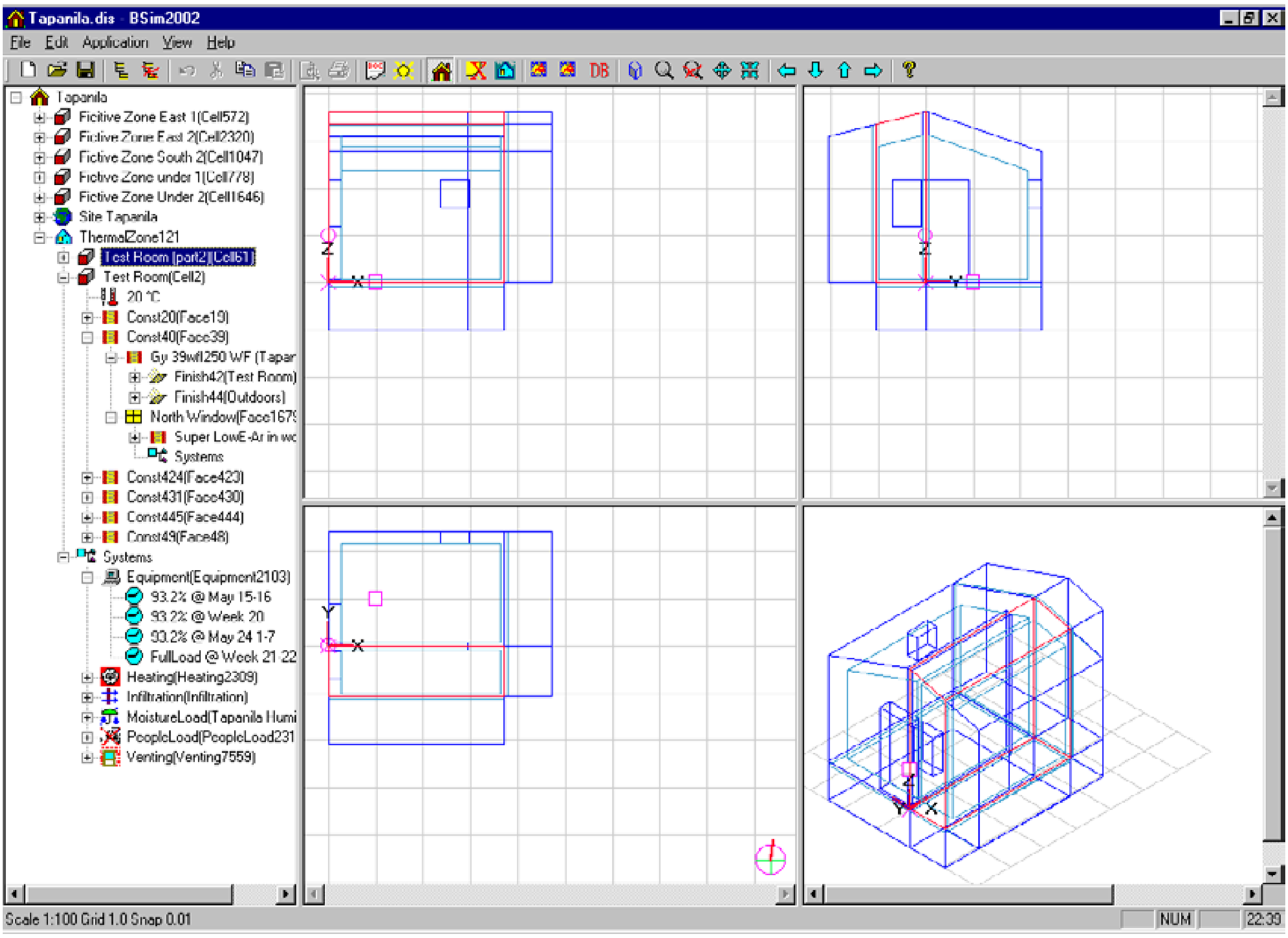

Figure 1. Graphical user interface of the program showing the model of the test room from which experimental data will be used to compare against model predictions.

### 2.2

A transient moisture model for the whole building - its indoor climate and its enclosure - has been developed as an extension to the thermal simulation model. sees a building as consisting of a number of zones, separated from each other and from the outside, by constructions of different kinds. A moisture balance is set up separately for each zone. The balance equation expresses that moisture is exchanged by infiltration, ventilation and air change with the outdoor air and with adjacent zones. Furthermore, moisture is exchanged by convection between air in the zone and the surfaces of adjacent constructions, and moisture is released to the zones as a result of activities in the zone. The balance equation is dynamic, so it takes into consideration the buffer capacity of the zone air itself.

The new moisture model makes simultaneous calculations of transient moisture conditions in all interior and exterior constructions of the building. The exterior environment constitutes the boundary conditions, while the indoor environment is calculated, which is different from many models that require the indoor environment as one of the boundary conditions.

The following influences on the air’s humidity condition are considered:

- Moisture transfer from adjoining constructions
- Contribution of moisture from various sources and activities, e.g. people, laundry and drying, bathing, cooking, industrial processes, humidification/drying, and other
- Entry of moisture from outdoor air (by infiltration and venting)
- Supply of humid air from ventilation systems
- Humid air transferred from other zones (mixing)

The model for moisture transport in the constructions considers moisture transport in the form of vapour diffusion. The moisture transport internally in the constructions is described in a transient way, i.e. by considering each layer’s moisture buffering capacity. For each time step and control volume in the construction vapour diffusion is balanced by the adsorption or desorption of moisture. The sum of these contributions causes a change of the moisture content from one time step to the next. Using the sorption curves of the materials, the new moisture contents can be recalculated into new relative humidities and vapour pressures. For the sake of numerical stability in all situations, an implicit calculation procedure is used in the model.

The moisture model is described in details in (Rode et al., 2001).

## 3 FIELD TEST

### 3.1

Organic building materials can function as moisture buffers that may absorb significant quantities of moisture without reaching a high equilibrium relative humidity. If the moisture buffering capacity is sufficient it may be possible, even without using tight moisture barriers (which are normally of synthetic material), to avoid such high humidity in the constructions that fungi can grow or other moisture related damage occur.

With highly hygroscopic building materials in open building structures it may even be possible that the whole building will benefit from the moisture buffering. The materials will release humidity in winter, and thus minimize indoor dryness, and they will absorb humidity in summer minimizing the dampness of indoor air. It may be possible to improve satisfaction of the inhabitants with the quality of indoor air if such effects can be utilized, and it may be possible to reach this satisfaction just by using this passive way of climatising a building.

Fang et al. (1998) developed an expression to predict the voting of occupants with the acceptability of indoor air quality on a scale from -1: to 1: . The predicted voting depends linearly on the enthalpy of the air. For clean air, the relationship is:

$$= -0.033 \quad +1.662 \tag{1}$$

where is the enthalpy of air (kJ/kg). Compared to other thermal comfort indices, the perceived indoor air quality (PAQ) is w. Therefore it does for instance not depend on the clothing of the subjects. Fang found a relationship between the voting of subjects and the enthalpy of air. As the enthalpy content of air depends not only on the temperature, but also strongly on the humidity, the indoor air will be assessed more acceptable if it can be kept dry. Warm and humid air, that may feel comfortable from a normal thermal comfort viewpoint if the activity or clothing levels are low, may be assessed as “stuffy”, and not particularly acceptable according to the PAQ index.

One of the purposes of the research on the Finnish, so-called (Simonson, 2000), was to develop a set of experimental data of moisture transfer between the indoor air and the building envelope when the constructions were made with extensive use of organic building materials and no plastic vapour retarders.

### 3.2

The test building is a two-story house in the outskirts of Helsinki, Finland. The floor area is 178 m$^2$, including a full basement. The house has been built with extensive use of wood and wood based materials and a limited use of plastic materials, e.g. with diffusion open coatings and without the use of plastic vapour retarders. The thermal insulation material is wood fibre insulation with a thickness of 250 mm in the walls, and 425 mm in the roof. The walls and roof are completed on the outside with 25 mm of wood fibre board behind a 50 mm ventilated cavity and exterior siding of wood for the walls, or sheet metal for the roof. On the inside, the walls and roof are clad with 13 mm of gypsum, and a layer of building paper as a convection break between the gypsum and the insulation. The gypsum was plastered and then primed with a single coat of diffusion open paint at the time the tests presented here were conducted. While the exterior walls and roof are wood frame constructions there are some interior walls of 140 mm brick with plaster and primer. The interior floors have 32 mm thick wooden floorboards, and are insulated with 125 mm of wood fibre insulation.

A bedroom on the second floor was used as test room for measurements of the hygrothermal conditions. The floor area of the room was 10.5 m$^2$ and the room volume was 29 m$^3$. The room had external wood based walls to the north and west, the partition wall against the room to the east was made of brick, and the partition wall against the room to the south was a lightweight wall insulated with 100 mm wood fibre insulation and clad with gypsum. In addition, a 62 cm wide and 14 cm thick load bearing brick wall with plaster extended into the room from the east wall. The room had two small windows, one on each facade, and a glazed door in the western facade opened to a second-floor balcony with an overhang. In Figures 2 and 3 are shown a photo of the building and a plan and section of the test room.

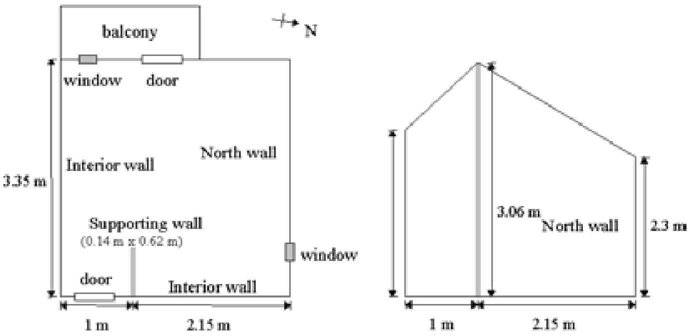

Figure 3. Plan and vertical section of the test room in the Tapanila ecological house.

Figure 2. Photo of the Tapanila ecological house as seen from northwest.

The experimental period was from May 14 to May 31, 1999. This period was divided into two parts: One in which the room was used with the constructions as described above, and one in which the interior surfaces of all constructions were covered with plastic vapour barrier (0.15 mm of polyethylene). In the following presentation of test conditions and results, the two parts of the test periods are referenced as  and , respectively. The room was not inhabited during the test period, but a humidifier produced vapour at a rate of about 800 g/day - predominantly in the night hours, and a PC, five fans and some measurement equipment released altogether about 300 W. The varying rate of moisture production during the test period is shown in Figure 4.

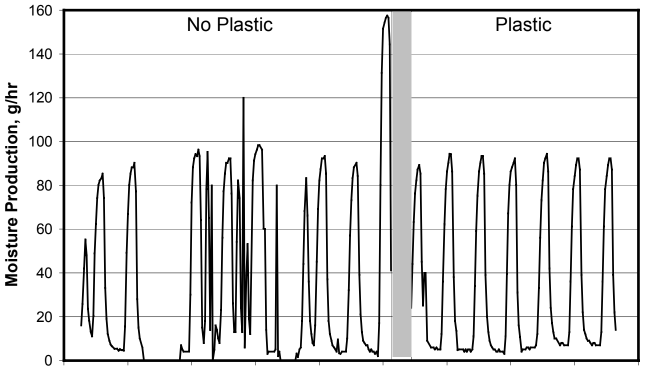

Figure 4. Moisture production rate during the test period. The shaded field, May 24, represents the period when the room was under refurbishment for installation of the internal plastic vapour barrier.

During the measurements all natural ventilation supply vents of the house were sealed with plastic and tape, and windows and doors were closed but not sealed. A variable speed fan caused air change at different levels, and the flow rate was measured with a calibrated orifice. The air change rate was held at the following levels: 0.08, 0.28, 0.55, and 1.10 ach in different parts of the test period as shown in Figure 5. It should be noted that when the fan was off, the air leakage was estimated to be 0.08 ach from tracer gas measurements.

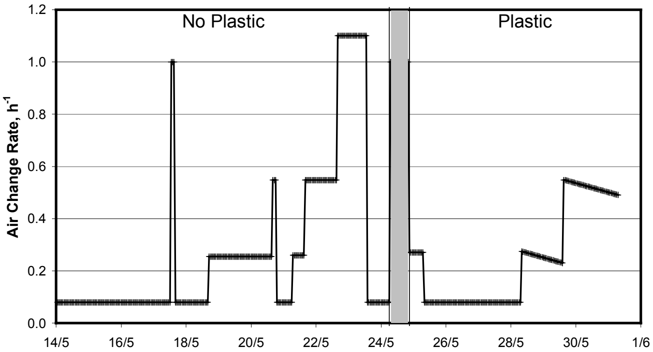

Figure 5. Air change rate during the test period.

Measured results of temperature and humidity from the test are presented in the next section in conjunction with simulation results.

## 4 WHOLE BUILDING HYGROTHERMAL SIMULATIONS

### 4.1

A calculation model of the test house for the actual measuring period was set up in . The hygrothermal properties of most of the building materials specifically used in the Tapanila building have not been determined, but some properties from literature are suggested in (Simonson, 2000) and they were used also for these calculations. The weather data was the outdoor temperature and humidity that were measured at the test house in conjunction with the field test, combined with data for solar radiation, wind speed and direction from another site in the Helsinki area during the month in which the measurements took place (May 1999). Weather data used for the rest of the year were ASHRAE data for Helsinki (Department of Energy, 2002).

The model in is illustrated in Figure 1. Only the actual test room was modelled. It faces the outdoor climate on the western and northern facades, and through the roof. The internal walls and the floor face so-called fictive zones which were not modelled as such, but set to be constant at 21°C and 32% RH corresponding to the average vapour pressure outdoors in the test period. This was chosen because the house was under construction during the field test. The air change rate was set in a time schedule to represent the actual conditions during the test, as shown in Figure 5.

The simulations in were carried out as a simultaneous calculation of thermal and moisture conditions in the indoor air and all envelope constructions. The calculations were made twice: Once for the normal walls, as they were in the first half of the test period, and a separate calculation for the same walls covered internally with plastic vapour barriers. Results from the second calculation will be labelled (PE) in subsequent graphs. The calculation period of both calculations started in January the year before the test period.

The interior surface conditions were calculated with prediction of the long-wave radiation between indoor surfaces and the surface coefficients for heat and moisture transfer by natural convection (Rode, 2000). The calculations were carried out with consideration of latent heat effects associated with evaporation and condensation of moisture in the materials.

### 4.2

The calculated indoor air temperatures during the test period are shown in Figure 6 together with the measured results.

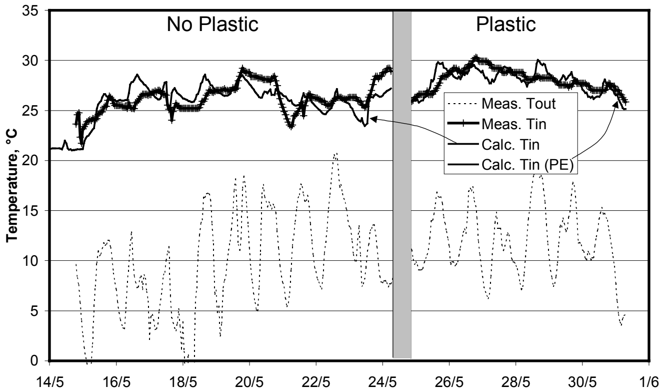

Figure 6. Measured and calculated temperatures in the test room.

The indoor humidity came out of the same calculations, and the results are shown in Figure 7 as relative humidity, and in Figure 8 as vapour pressure.

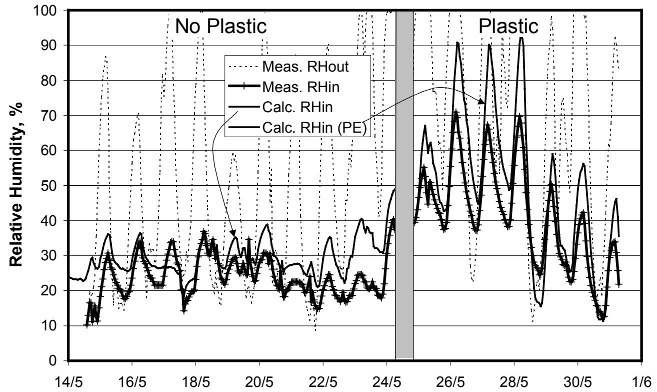

Figure 7. Measured and calculated relative humidity in the test room.

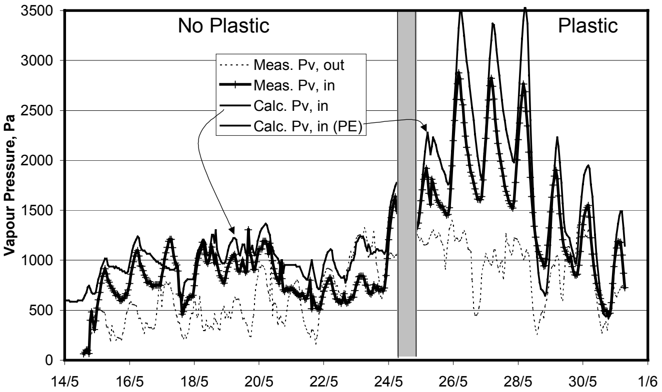

Figure 8. Measured and calculated vapour pressure in the test room.

Since both the indoor temperature and humidity are modelled, it is possible to get a prediction of the perceived indoor air quality according to Equation (1). The enthalpy can be calculated from the temperature and humidity. The resulting prediction of the acceptability is shown in Figure 9 for the two cases that have been calculated: With and without an internal plastic vapour barrier. To be able to compare them, the results of each calculation have been shown for both parts of the test period, both before and after the plastic vapour barrier was indeed installed in the field test.

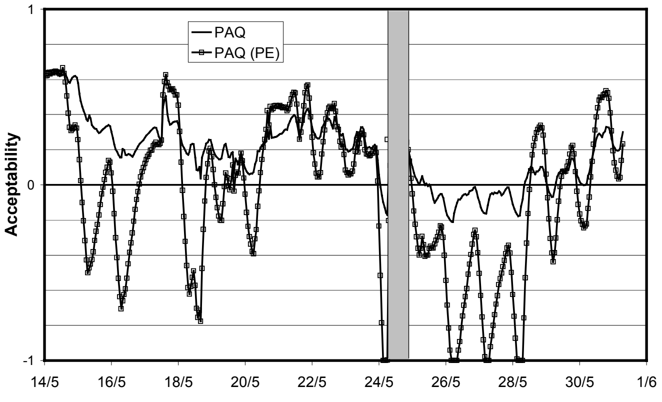

Figure 9. Predicted acceptability of the indoor air of the test room with (PE) and without the installed plastic vapour barrier.

### 4.3

The experimental results are described and discussed in depth in (Simonson, 2000 and Simonson et al., 2001). The presence of the plastic vapour barrier had a clear effect to cause higher variations of the humidity of the indoor air.

The calculations track the measured results reasonably well, but with the following noticeable deviations:

- The calculated indoor temperatures do not follow exactly the same daily variations as the measured temperatures. The maximum deviation is 2.9°C.
- The average level of the calculated temperatures is the same as for the measurements. However, this was expected as the heat gain from equipment was adjusted in the calculations just to achieve this result. After this adjustment, the heat supply from equipment was 215 W (as opposed to the 300 W given as an approximate expectation in (Simonson 2000)).
- The average level of the calculated vapour pressure is 200 Pa too high in the period without plastic vapour barrier, while it is 320 Pa too high in the period with plastic.
- In the period with plastic vapour barrier, the calculated vapour pressure seemed to exaggerate the daily variations in indoor vapour pressure. It could seem as if there were some buffer effect in the test room, which the calculations did not catch. There may also have been some moisture absorption and desorption by the plastic cover on the constructions that was not considered strongly enough by the simulations – although the polyethylene was calculated as a (rather vapour tight) hygroscopic material in the calculations.

These problems could be caused by not knowing the initial moisture level, and not having sufficiently precise information about the actual hygrothermal properties of the materials nor of the surface transmission coefficients for heat and moisture transfer. It is a well-known problem, also from thermal building simulation, that many parameters are needed for the calculation of a complete room or building, and the results depend on each other – therefore it may be not be realistic to obtain complete and exact correspondence between results of a field experiment and a simulation of the same results. Qualitatively, however, the results are regarded as being sufficiently accurate that similar simulations can be used to compare and analyse different design options, such as will be done in the next section.

## 5 OTHER ANALYSES WITH THE MODEL

### 5.1

The integrated calculation model is now used in full year simulations to investigate the possible difference in perceived indoor air quality for three different choices of insulation material and vapour retarder solutions. The analysis was carried out with a room model similar to the one used for the Tapanila ecological house, and two of the choices for the building constructions were the same as investigated previously:

1 With wood fibre insulation and building paper, but no vapour retarders.
2 The same, but with all internal surfaces covered with a plastic vapour barrier. The barrier could also be thought to represent a non-hygroscopic structure or a vapour tight paint.

Finally, as a third option, the following more traditional constructions were assumed for the analysis:

3 The roof, wall and floor constructions were insulated with mineral wool, and polyethylene vapour retarders were used between the gypsum board and insulation in the exterior constructions.

The calculations were carried out for the same test room and building located in Helsinki as in the analysis of the Tapanila case. The air change rate was set constant at 0.5 air changes per hour. A sufficient heating system was prescribed with a set-point of 21°C. All other internal rooms in the building that are adjacent to the test room were set to follow the same conditions as in the test room itself. The room was assumed occupied for 9 hours every night by two adults that release 66 W and 30 g/h of humidity each.

Figure 10 shows the monthly average results of outdoor temperature from weather data and the calculated indoor temperatures during the second year of calculation. As expected, the temperature profiles are practically identical.

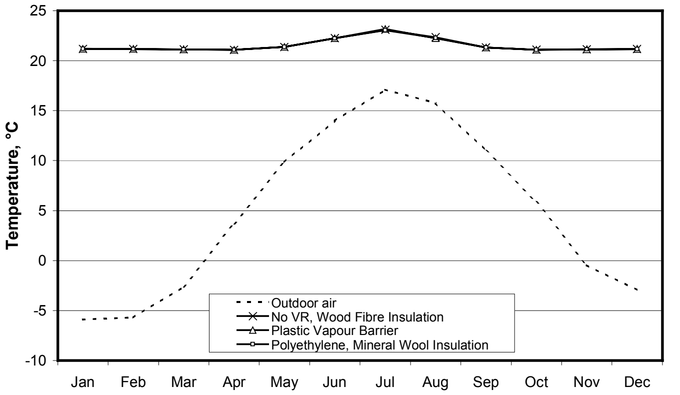

Figure 10. Annual distribution of the monthly means of the outdoor temperature and the calculated indoor temperatures for the different choices of construction type.

Figure 11 shows the monthly averages of calculated indoor relative humidity for each of the three calculations as well as the outdoor relative humidity.

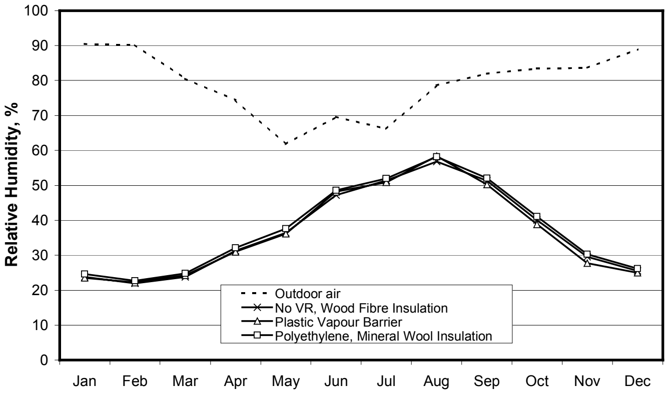

Figure 11. Annual distribution of the monthly average relative humidity of outdoor and indoor air for the three different construction types.

It may come unexpected that also the indoor relative humidity is practically the same for the different choices of construction types when the monthly averages are observed, i.e. no long term moisture buffering effect seems to stand out for some constructions compared to the others. But indeed there are some differences, which can be seen when the daily variations are observed. Figure 12 shows the hourly distribution of relative humidity during the first two weeks of June.

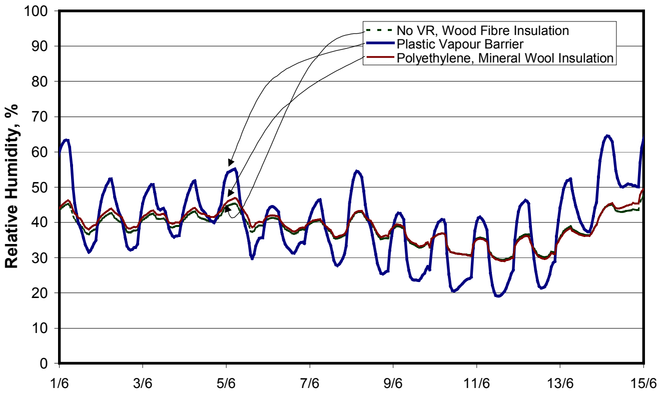

Figure 12. Hourly development of the indoor relative humidity during the first two weeks of June for each of the three different construction types.

Figure 12 reveals that, although the average relative humidity is more or less the same for all three constructions types, the humidity has both higher peaks and lower valleys when the constructions are clad with a plastic vapour barrier. The highest relative humidity occurs in the early morning (by the end of occupation for the night), and has its minimum in the middle of the afternoon.

Figure 12 also reveals that there is only a negligible difference in indoor relative humidity variations between the case when wood fibre insulation was used without a vapour retarder, and the situation with mineral wool and polyethylene vapour retarder.

The acceptability of the indoor air for the building with each of the three construction types is shown in Figure 13 as monthly averages. It is clear that generally the acceptability is highest in winter. This is because the indoor humidity is lower in winter, and the temperature more or less constant at 21°C. In summer both the indoor temperature and humidity are higher. This means that the enthalpy content of the air is higher, and therefore the acceptability is lower.

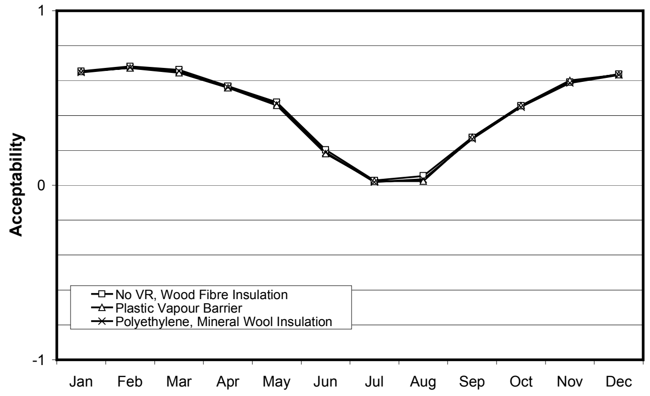

Figure 13. Annual distribution of the monthly averages of the acceptability of the indoor air for the different construction types.

Judged on the monthly results, the analysis reveals only small differences between the acceptability of the indoor air quality when different solutions were chosen for the insulation material and choice of vapour retarder. However, Figure 14 shows hourly predictions of the acceptability in the first two weeks of June for each of the three choices of construction types. Again, it becomes clear that the daily variations are larger for the construction with a vapour tight plastic barrier than for the other two constructions. It can also be seen that the lower acceptability coincides with the occupancy of the room (at night), which is of course unfortunate.

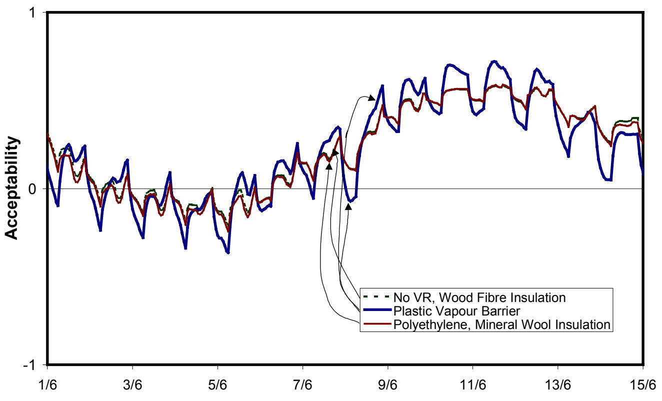

Figure 14. Hourly distribution of the acceptability of the indoor air during the first two weeks of June for the three different choices of construction types.

Like for the humidity, also the acceptability appears to be practically the same for the room with wood fibre insulated, open constructions as when the constructions are insulated with mineral wool and have a vapour retarder. That the differences are so small can be attributed to the fact that most of the exchange of moisture between the indoor air and the building constructions takes place with the inner surface material, which in both cases was gypsum boards. The moisture penetration depth in gypsum board for daily humidity variations is in the order of half a cm (Olsson, 1996), and therefore it does not appear to be very important which material comes behind the gypsum.

The use of a plastic barrier as a cover on the very interior surfaces of the constructions seems to have a somewhat more pronounced effect. The plastic barrier cause the indoor humidity to rise to uncomfortable levels too rapidly during occupied conditions, and likewise, it falls more quickly to lower levels when the occupancy ceases. The evaluation used here with Fang et al.'s equation for acceptability does not consider the question of whether very dry indoor air, like in the Finish winter, could be perceived as an uncomfortable condition.

For all three choices of construction types, Table 1 gathers the average results of indoor air temperature, relative humidity, and acceptability over the whole year when it is split up in occupied and unoccupied hours.

Table 1. Average indoor air temperature, relative humidity and acceptability of the indoor air during the whole year for the different construction types. For each variation, the first line contains the average during the occupied hours (night), and the second line the result during unoccupied hours (daytime).

| Construction type<br>↓ | Room occupied | T<br>°C | RH<br>% | Acceptability<br>- |
|---|---|---|---|---|
| Wood Fibre, | y | 22.2 | 35.9 | 0.41 |
| open construction | n | 22.2 | 32.3 | 0.46 |
| Plastic barrier | y | 22.2 | 42.6 | 0.31 |
|  | n | 22.2 | 29.4 | 0.50 |
| Mineral Wool, | y | 22.2 | 36.4 | 0.40 |
| vapour retarder | n | 22.2 | 33.0 | 0.45 |

Other building uses, materials and operation strategies may be relevant to investigate before drawing decisive conclusions on the performance of different types of building technologies. The objective of the example in this paper has been to demonstrate the potential for analysis, which seems to be good.

## 5.2

An advantage of the integrated hygrothermal simulation is that also the moisture conditions within the building constructions come out of the same simulations. This is particularly important since it is well known that, when making predictions of the hygroscopic conditions in constructions, the internal boundary conditions can be very determinative. Traditional heat and moisture calculations of constructions used to be limited by the assumptions one had to make about the indoor boundary conditions for the calculations. The new model should circumvent this problem - or at least it moves the question of reasonable assumptions to a matter of which heat and moisture loads and air change rates are assumed for the building.

Figure 15 and 16 show calculations of the moisture conditions in the roof over the test room in Helsinki for a complete year (the last of two years of calculations with the reference year for Helsinki). The results are shown for the case with wood fibre insulation without vapour retarder, and for the case with mineral wool insulation with vapour retarder between the gypsum and insulation, respectively.

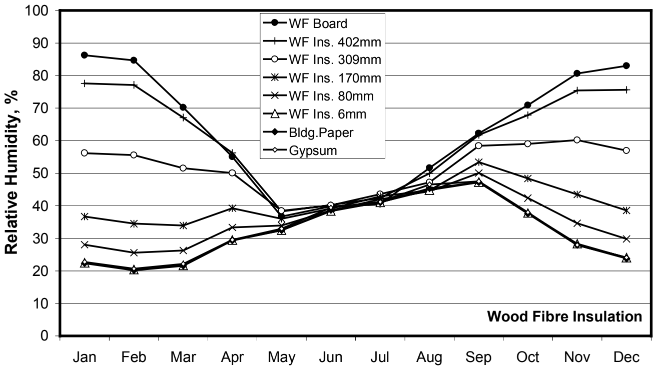

Figure 15. Relative humidity in the roof with wood fibre insulation and no vapour retarder. The legends for the different insulation layers show their distance from the internal cladding.

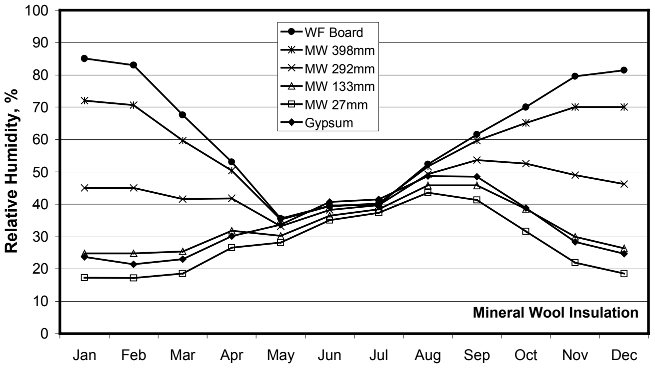

Figure 16. Relative humidity in the roof with mineral wool insulation and polyethylene vapour retarder.

The two graphs in Figure 15 and 16 show the development of the relative humidity of the material layers in the roof. From the outside: The wood fibre board, the insulation at several depths, building paper (if present), and finally the gypsum board. At a quick glance the calculations look identical which is not so strange since both constructions are open to the outside through the porous wood fibre board, and the wood fibre board itself predominantly follows the outdoor climate. The main difference is for the internal layer of the insulation. When there is a vapour retarder of polyethylene, as in the mineral wool insulated roof, the inside of the insulation gets very dry (<20% RH) in winter. In the roof with building paper instead of a vapour retarder, the relative humidity of the gypsum, the building paper and the inside of the wood fibre insulation are practically the same. In summer all layers of both roofs are more or less at the same level: 40% RH. From the calculations it can also be stated that neither of the two roofs should have problems with too high humidity in any period of the year.

## 6 DISCUSSION

The model is tested against measurements of hygrothermal conditions in a test room of a so-called ecological building in Finland. Qualitatively, the calculation results show some reasonable correspondence with the measured results – although the results are not always in perfect quantitative agreement. The lack of perfect quantitative agreement can mainly be attributed to the large number of degrees of freedom in the comparison, e.g.: Many parameters influence the thermal conditions of the test room, and not all of them were known from the test; the hygrothermal parameters were most often not determined for the same materials as were used in the experiment; and the local coefficients for surface heat and mass transfer were influential, but had to be estimated for the calculations.

Assuming that the model yields qualitatively adequate results it can be applied to analyse the indoor hygrothermal conditions and perceived indoor air quality, and to compare different solutions. When comparing ecological building technical solutions (organic insulation materials without polyethylene vapour retarder) to conventional building technology with mineral based materials and vapour retarders, it seems like only small differences in the indoor air quality are to be expected. A reason seems to be the presence of internal cladding materials, which are the most influential.

It is anticipated that improved calculations of the hygrothermal conditions in building envelope components can be achieved when the calculations for the indoor environment and the building components are integrated.

## 7 CONCLUSION

An existing computer tool BSim2002 for dynamic thermal simulation of buildings has been extended with a transient model for moisture release and uptake in building materials. With the new model it may be possible to make more accurate predictions of indoor humidity variations. Simultaneously, complete transient calculations are carried out of the moisture conditions within all the envelope constructions of the building. Since the moisture conditions in building constructions depend very much on the indoor humidity and since the building constructions also influence the indoor humidity, it is anticipated that the new development will result in improved simulations of moisture conditions both for the indoor air and for the building constructions.

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