TOPIC
Low Energy Buildings

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Case study – Performances of a masonry house – Energy consumption and air-tightness

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KEYWORDS
Masonry house, air-tightness, energy consumption, case study, measured values

SUMMARY
Air-tightness and energy consumption was measured in a one-family house built in 2009 and 2010. The air-tightness fulfilled the goals, which was set to 0,3 l/s, m². The energy consumption was measured from the start in May 2010. The figures in this report refer to measurements between May 2010 and October 2013 and are well below the authority demand of 55 kWh/m², year.

1 Introduction
In the last decade or so the energy performance for buildings have kept increasing. Focus has shifted from U-values to energy consumption. Houses with thick insulation, taped foils and many layers were in media focus. In the light of this a new sandwich block made of lightweight aggregate concrete has been developed and tested, with focus on how to build air-tight with few layers. The air-tightness goal was <0,3 l/s, m² which is comparable with the demands for a passive house. Together with a consultant and close discussions with the building company, the air-tightness was measured three times during construction. Minor changes in the construction such as the thickness layer of the rendering and the direction of the plastic foil were made. When the house was finalized the final measurement showed 0,16 l/s, m². The energy consumption is approximately half of the authority demands.

2 Back ground
In the beginning of 2009 we had developed a new model of a well-tested masonry block. The next step was to put it on the market and build a house with as good performances as possible.

The back ground discussions were that we knew we had a very good masonry block, with a low U-value. Increasing the thickness would not necessarily give better energy performance compared to the cost increase for the product. We needed to work with other parts of the building process and the air-tightness was the obvious next big part, more or less directly connected to our products in order to decrease the energy demand for houses.

A family who was in the process of building a house for themselves was contacted. We agreed that we could follow the building process and do some follow ups. Their aim suited our aims. They wanted to build a low energy house with performances close to the demands for passive houses. The main criteria were air-tightness and we agreed to have an air-tightness consultant involved in the project from the start.

3 Aim of the project
The goal for the company in this project, was to verify that with good communication between involved parties and only minor changes in erecting the building, it is possible to build a low energy and air-tight house with existing technology and modern architecture.
4 Technical aspects for the chosen materials

The building is a one-family house and is situated just outside Malmö in the south part of Sweden. It is a two story building with 192 m² living space (Atemp).

The outer walls of the lower floor consists of a masonry sandwich block with 150 mm of polyurethane foam and with 100 mm of lightweight aggregate concrete on both sides. On both sides of the wall there is a layer of 10-15 mm of rendering.
The outer wall of the upper part is a wooden frame with mineral wool.
To reduce the cold bridge in the roof beams they look like I-beams made of two wooden load bearing part connected with a wooden fiber board, with a thickness of 500 mm.
The foundation is a massive low density light weight aggregate concrete connected to a concrete slab.

<table>
<thead>
<tr>
<th>Building part</th>
<th>Thickness (mm)</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer wall, 1st story, LECA® Isoblock</td>
<td>370</td>
<td>0.15</td>
</tr>
<tr>
<td>Outer wall 2nd story, wooden frame</td>
<td>340</td>
<td>0.14</td>
</tr>
<tr>
<td>Roof</td>
<td>500</td>
<td>0.08</td>
</tr>
<tr>
<td>Windows</td>
<td></td>
<td>0.9</td>
</tr>
</tbody>
</table>

The installations consist of a heat pump, solar panels and a storage pump (in a separate building).
5 The building process

Together with the construction company and the consultant we held a few meetings regarding important and critical points in the building process in order to achieve as good air-tightness as possible. Therefore everybody was “on their toes” already from the start. The first layer of rendering is critical. Not only the façade part of the masonry needs to be rendered. But it is also very important to render the top of the masonry and door- and window-openings before doors and windows are installed. This is to ensure the air-tightness of the masonry structure. Of equal importance was the way to connect the plastic foil from the roof to the masonry, which was pinched with expanding rubber tape between the top of the masonry and the roof construction. The joints of the plastic foil were as far as possible taped and connected lengthwise to the roof beams in order to minimize air leakage.

![FIG 3. Pinching of the plastic foil between top of the masonry wall and wooden beam.](image)

Before closing the building with the finalizing layers we did an air-tightness measurement. This was to be able to do some enhancements if there might be some obvious errors. But after connecting the blower door we could not even achieve the proper pressure difference to get a value. It was however very easy to locate where the air leakages were and in this part of the process very easy to fix them. It was a few misses in the taped plastic foil joints and misses with the rendering in window openings. These were easily corrected in this phase of the building process.

We did a second blower door test with a fairly good result and some minor adjustments where done and then the building was finalized.

The air-tightness of the house was measured according to EN 13829 “Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method (ISO 9972:1996, modified)”, commonly referred to as the “Blower Door Test”. And a Blower Door Modell 4 was used to receive an overpressure of 50-100 Pa.
6 Results

The third and final blower door test was carried out in 2010 and gave us at the time a very good result. The few leakages were typically between frames and walls in both the masonry part and the upper wooden frame part.

The air leakage measured to 0.16 l/m²s, compared to the goal of <0.30 l/m²s. This goal was taken from the Swedish passive house regulations, FEBY.

The energy consumptions figures up to today are also very encouraging.
The separate storage pump building (heated) of 32 m$^2$ is not taken into account, which would have been beneficial for the calculations.

In this house it is possible to separate the energy consumption for hot water. And looking at the total monthly consumption for the summer months one can make a good estimate for the energy for lightning, TV, appliances etc.

Included in the figures for bought energy there is a huge computer server that uses 3000 kWh per year. I have pulled that out from the calculations. Below the table show a summary for the two complete years of 2011 and 2012, regarding energy and hot water.

**TABLE 2. Summary of energy, taken from the appendix.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Bought energy</th>
<th>Solar gain</th>
<th>Hot water</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>12072</td>
<td>3204</td>
<td>2963</td>
</tr>
<tr>
<td>2012</td>
<td>11957</td>
<td>1344</td>
<td>2412</td>
</tr>
<tr>
<td>Mean</td>
<td><strong>12014</strong></td>
<td></td>
<td><strong>2687</strong></td>
</tr>
</tbody>
</table>

To make an estimate of the energy for lightening, washing machines etc I looked at the summer months for 2012 and 2013, where there are measured values.

**TABLE 3. Summary of summer months, taken from the appendix.**

<table>
<thead>
<tr>
<th>Year</th>
<th>June</th>
<th>July</th>
<th>August</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>710</td>
<td>703</td>
<td>710</td>
</tr>
<tr>
<td>2013</td>
<td>757</td>
<td>773</td>
<td>812</td>
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<tr>
<td>Mean</td>
<td><strong>744</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The mean bought energy for 2011 and 2012 was approximately 12 000 kWh per year. This is for heating, hot water, light and appliances and the server. Looking at the summer months for 2012 and 2013 the bought energy is 744 kWh per month, that is 8 928 kWh per year. This is then energy for the kitchen appliances, TV, light, hot water etc and the server. Hot water is a little more than 200 kWh per month, which gives 2 687 kWh per year.

The total energy demand for heating and hot water is then $12 000 - 8 928 + 2 687 = 5 759$ kWh per year. The heated area is 192 m$^2$. The energy demand per square meter and year is 30 kWh. This is a little more than the level for electrical heated passive houses according to FEBY. But on the other hand, this was not meant to be a passive house, since the installed heat exchanger had too high effect according to the FEBY-regulations at the time.

### 7 Conclusions and discussion

The goals that were set up where fulfilled. The level of the air-tightness was reached by far (0,16 l/m$^2$s). The energy consumption for heating and hot water is well below the regulations for normal houses (30 kWh/m$^2$, year). And it is a modern architecture.

There are some obvious energy loss points:

- First you have the storage tank that is situated in a separate building, which means that it is impossible to utilize the heat loss inside the house.
- Then there are losses from the pipes leading from that building into the house.
- The house has fairly normal windows with a U-value of 0,9 W/m$^2$K.
- And from an energy point of view, the architecture is not optimal.
- Another big source for the energy demand is that the indoor temperature in the house varies between 22 and 23 °C, according to the inhabitants. This is more than the 21 °C that is normally calculated.
8 Acknowledgements

The author gratefully acknowledges the owners of the house, for sharing their energy data, for letting me interview them and for fruitful discussions.

9 References

LTH rapport EBD-R-12/36; IVL rapport nr B 2027; ATON rapport 1201 (2012). FEBY12
“Kravspecifikation för nollenergihu (passivhus och minienergihu – Bostäder
Boverkets regelsamling, BBR
AK-konsult, Tätning och termografering, ordernummer 18556

Appendix

Monthly energy figures.

<table>
<thead>
<tr>
<th>Month</th>
<th>Bought energy kWh</th>
<th>Solar gain kWh</th>
<th>Hot Water kWh</th>
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<tbody>
<tr>
<td>2010-05</td>
<td>1053</td>
<td></td>
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<tr>
<td>2010-06</td>
<td>1053</td>
<td>492</td>
<td>230</td>
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<tr>
<td>2010-07</td>
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<tr>
<td>2010-08</td>
<td>1053</td>
<td>474</td>
<td>194</td>
</tr>
<tr>
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Sum 8 months: 8424 2354 1534

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<th>Month</th>
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<td>21</td>
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<td>2011-12</td>
<td>1006</td>
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Sum 12 months: 12072 3204 2963
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<td>10 months:</td>
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</tbody>
</table>

**Bold figures are calculated mean.**
Statistical study on the link between real energy use, official energy performance and inhabitants of low energy houses

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KEYWORDS: low-energy houses, EPBD, survey, user behaviour

SUMMARY:
Energy performance regulations are becoming increasingly strict and governments supply simplified calculation tools to assess whether new buildings fulfil the requirements. However, one can wonder what the accuracy of those tools is for assessing the next generation of houses, that will have to fulfil the upcoming energy requirements. In order to investigate the discrepancy between predicted and real energy use in low energy houses, 537 dwellings were analysed. Data on building characteristics and theoretical energy use from the Flemish EPBD-database was complemented with data from the energy utilities and a survey of the inhabiting households, providing information about the households, their user behaviour and real energy use. While an undeniable correlation was found between theoretical and real energy use, the EPBD-method overestimated the heating energy use for most of the cases. Two building related parameters and two user related parameters proved to have a significant impact on that gap: the use of default values for the air tightness of the envelop and for the efficiency of the gas boiler, the heating profiles of the master bedrooms and the amount of baths and showers taken by the inhabitants. However, two comments must be made. First, the dataset consists of early adopters who could afford such energy performance years before it would be imposed and are therefore not representative of the average household. In addition, the analysis showed significant correlations between household characteristics on the one hand and building characteristics and performance on the other. These last two points question the possibility to extrapolate findings from samples of existing forerunners towards prognoses on future, entire building stock level.

1. Introduction

It is often questioned whether theoretical improvements in the energy performance of buildings, imposed by European and national regulations, will be fully obtained in practice. This question is important not only to estimate the real reductions in CO2-emissions, but also to calculate the financial returns on investments and cost-optimal performance targets, as asked by the European Union to each member state. However, when defining the future energy standards that will be imposed, the question on prediction accuracy becomes even more difficult to answer as there are few houses already fulfilling those performance targets, resulting in less relevant data being available. Building simulation software allow researchers to calculate the energy performance of building more in detail and to compare those results with results from the simplified assessment tools. However, this approach might overlook unpredicted user behaviour as well as the varying thoroughness of the energy assessors when performing the calculations. One solution is to use large datasets, analysing
together both the officially reported building characteristics and performance on the one hand and real energy use and data on user behaviour on the other hand, as was done by Guerra Santin (2010). For this study, the approach was similar, though it focused solely on recent houses with good energy performances and therefore it is based on a much smaller dataset.

2. Material & methods

2.1 Data collection

Every new house in Flanders, built from 2006 onwards, must meet the energy performance requirements from the Energy Performance of Buildings Directive (EPBD). Technical building data and administrative data (e.g. address) of all these houses is kept in one centralized database by the Flemish Energy Agency (VEA). For this study, VEA selected 1850 projects, based on the four following criteria. (1) The energy performance had to meet at least the current energy standards. (2) The housing units had to have their own, individual heating system. (3) They had to be inhabited for at least two years. (4) Their EPBD-file had to be free of any major error or shortcoming with regards to data (e.g. missing data) or with respect to the energy performance requirements.

Three complementary data-sources provided the needed information for this study. (1) The EPBD-database itself provided technical data on the buildings and on their theoretical energy performance. The database does not contain the full inputs for the EPBD-calculation (e.g. data on each individual wall). However, it does contain some of the most important variables (e.g. the size and type of the building, the type of services, the average insulation levels etc.) as well as the intermediate and final results of the energy calculation. Those are expressed in monthly primary-energy use for sanitary hot water, heating, cooling and auxiliary energy for services, calculated with a primary energy conversion factor for electricity of 2.5. The database also contains the estimated monthly electricity production of the photovoltaic-panels (PV-panels). (2) Surveys of the households supplied additional data on the buildings as well as on the households, their behaviour and their real energy use. (3) Meter readings from the energy utilities further completed this dataset. The surveys obtained a response rate of 29%, resulting in a total dataset of 537 housing units. However, the response rate was not homogeneous over all energy performance levels: significantly higher response rates were obtained for the better performing houses, as will be further discussed in paragraph 3.2.

2.2 Data filtering & subsampling

A thorough analysis of the dataset revealed hidden shortcomings as well as contradictions, e.g. between the survey and the EPBD-database. As it was often impossible to elucidate the contradictions, several cases had to be removed from the dataset for further analysis. In order to keep the dataset as large as possible, those cases were only excluded from subsets for analyses depending on their specific erroneous or dubious data points. Thus, for example, faulty data on the PV-panels were not taken into account for the analysis on heating energy use based on gas combustion.

Three subsamples were identified within the full dataset, in order to analyse the total energy (subsample S1), the heating energy use for space heating and sanitary hot water (subsample S2) and the domestic electricity use (subsample S3) separately. Due to the relevant shortcomings in the dataset, these subsamples were reduced respectively from their original size of 350, 135 and 260 to 100, 75 and 150 cases. However, the analyses that didn’t require real energy use, could be performed on much larger subsamples, with small variations depending on the specific analysis.

2.3 Normalization method

The statistical study of the data and further analysis were performed in SPSS, using multivariate regression analysis. However, prior to comparative, statistical analysis of the predicted, calculated
energy use and the real energy use, both have to be normalized to comparable boundary conditions such as similar climatic data. The most common way to do this, is to normalize the real energy use of all houses to one single, average climatic year, coinciding with the one used in the theoretical calculation method. However, this was impossible for this dataset due to several reasons. Normalization of the energy use requires to perform some regression, based on the real energy figures. However, data on real energy was provided for only one time period per dwelling and different types of energy demands were often aggregated into one single figure (e.g. sanitary hot water and heating on one single, yearly gas consumption bill). Therefore, individual normalisation regression could not be performed for the separate energy use types of the individual houses. Applying one common (e.g. degree-day based) formula on all the houses would neglect both the technical differences between the houses (e.g. thermal time constants) as well as the behavioural differences between households (e.g. heating profiles). Applying, on the real energy use data, a normalisation based on the theoretical EPBDcalculation of each separate house, would also ignore the impact of user behaviour of the individual household and it would assume an approximately correct, relative weight of the different energy demands of the house. However, these are two of the investigation topics of the study.

To tackle these issues, the procedure of normalisation was turned around: the theoretical calculation of each individual energy demand, according to the EPBD-method, was ‘(a)normalised’ to coincide with the period of the real energy figures available. Redoing the full EPBD-calculation for the real climatic conditions was impossible, due to missing calculation input data in the EPBD-database. However, based on the formulas of the EPBD-method and on the main characteristics of the buildings and their services, accurate normalisation of the energy use was possible, using the monthly calculated values available for space heating, sanitary hot water, cooling, auxiliary energy and electricity-production for the PV-panels for each house separately. The limited variations in climatic conditions and time periods between the separate cases, were taken into account in the statistical, multivariate analysis, in order to ensure that these variations would not bias further analysis. However, their impact proved to be negligible, due to the relative homogeneity of the duration and average climatic conditions of the real periods.

3. Buildings & inhabitants

3.1 The buildings

The sample mainly consists of detached houses, with only a very low percentage of terraced houses, as shown in TABLE 1. Due to the very low number of apartments within the dataset, these were left out of the further analysis. With an average gross floor area of 257m² (median: 248m²), these relatively large houses are also not representative of the average size of new built houses in Flanders, though these numbers lie close to those of all detached houses within the EPBD-database (Defruyt et al. 2013).

<table>
<thead>
<tr>
<th></th>
<th>Detached</th>
<th>Semi-detached</th>
<th>Terraced</th>
<th>Apartments</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPB-database:</td>
<td>26%</td>
<td>20%</td>
<td>8%</td>
<td>45%</td>
</tr>
<tr>
<td>Single family houses</td>
<td>48%</td>
<td>37%</td>
<td>15%</td>
<td>-</td>
</tr>
<tr>
<td>Data sample</td>
<td>68%</td>
<td>28%</td>
<td>4%</td>
<td>-</td>
</tr>
</tbody>
</table>

In Flanders, each new building gets an ‘E-level’ as a label to indicate the primary-energy performance of the house with regard to space heating, sanitary hot water, cooling and auxiliary energy use for services, after deducting the electricity production of PV-panels if present. This level indicates the relative primary-energy use of a building, in comparison to a reference building of the same type dating from 2006. Reaching the same level as the reference building would deliver a level ‘E100’ (100%), but in the meantime, the requirements have been tightened towards E70. All of the selected
houses fulfil this current requirement, even though their building permits date from between 2006 and 2010. In addition to the total primary-energy use requirements, the insulation level of the houses is also subject to legal requirements. While all selected houses fulfilled the insulation requirements valid at the time of their building permit, only approximately 60% of the houses would fulfil the current, updated insulation requirement. This discrepancy within the sample is explained by the high performance of the building services and the very high presence of PV-panels, compensating the lower insulation levels within the calculation of the primary-energy demand. 83% of the houses have a mechanical, balanced ventilation system with heat recovery, 33% use heat pumps and 46% have PV-panels. While these numbers are not representative at all of current standard built houses, let alone standard practice three years ago, these numbers are representative for houses with similar E-levels, as illustrated by De Baets and Jonckheere 2013.

3.2 The inhabitants and their houses

Almost all of the households (co)owned their respective houses (99%) and were the original builders (99%). They are mainly young households (FIG.1), from the upper middle class (with high level of education, a good job and a good income). While this is to be expected for the average builder of a new house, this is not representative of the total population. These households having built their own houses, we can also assume they had their saying during the building process and were thus at the basis of the choice for an energy-performant house (considering the requirements and standard practice of that time). This assumption of looking at a sample of deliberate low-energy builders is strengthened by the response-rates to the survey: the response rate proved to be significantly larger for the higher performing houses within the sample, as shown in TABLE 2. The income of the households also proved to be significantly, positively correlated with the primary-energy performance of their houses. This could be directly linked to the correlation that was found between the income of the households on the one hand and, on the other hand, the possession of PV-panels or, even stronger, the area of PV-panels installed on the roofs. Looking further at the link between the households and their houses, one could expect to find a correlation between the size of the house and the size of the household. However, this was not found and the lack of correlation can be explained by the young age of the households, building for the future and, possibly, considering future family extension.

These tight links between household characteristics and building characteristics oblige us to be cautious with the further analysis as well as with possible extrapolation of further findings. These cross-correlations complicate the task of disentangling the relationships between the building characteristics, household characteristics and resulting energy use, let alone the goal to assess causality. Furthermore, due to the specificity of this sample, the applicability of findings on this dataset, onto the larger Flemish, Belgian or other population has to be questioned.

FIG 1. (a) Amount of inhabitants and (b) age distribution (date of birth): mainly young families

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TABLE 2. Response rate to the survey, suggesting a sample of motivated low-energy builders

<table>
<thead>
<tr>
<th></th>
<th>≤ E40</th>
<th>E40-E50</th>
<th>E50-E60</th>
<th>E60-E70</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contacted</td>
<td>167</td>
<td>241</td>
<td>611</td>
<td>833</td>
<td>1850</td>
</tr>
<tr>
<td>Participated</td>
<td>70</td>
<td>86</td>
<td>183</td>
<td>199</td>
<td>537</td>
</tr>
<tr>
<td>Response-rate</td>
<td>42%</td>
<td>36%</td>
<td>30%</td>
<td>24%</td>
<td>29%</td>
</tr>
</tbody>
</table>

4. Real energy performance

4.1 Total energy use

Within the EPBD-calculation method, not all of the types of domestic energy demands are included. Foremost missing, are the energy demands for cooking, for lighting and for domestic electrical appliances (from refrigerators onto televisions). Further analysis in this paper will focus on the heating demand for space heating and for domestic hot water. As a reference, FIG. 2(a) compares the total primary energy demand of the households with the heating demand and the electricity demands (not for heating) according to data from the surveys and energy suppliers. The auxiliary electricity demand for building services, included in the EPBD-method, can be considered low in comparison to the other electricity demands. Furthermore, houses with active cooling were removed from the sample. Therefore, the total energy demand from subsample S1 in FIG. 2(a), can be (approximately) considered as the sum of the heating demand from subsample S2 and the electricity demand from subsample S3. Comparing real energy use with predicted energy use, FIG. 2(b) shows that the underestimation of the total, primary energy use is caused mainly by the higher domestic electricity use, as the heating-energy use is overestimated in most of the cases.

4.2 Heating & sanitary hot water

While an undeniable, positive correlation was found between the real and the predicted heating-energy use, there was no close fit between both. On average, heating energy use appeared overestimated by the EPBD-method. Furthermore, this gap between predicted and real values showed large variations, depending on the specific house and household. Four parameters were identified as a significant cause for these variations. Two of them are building related and two are user related.
4.2.1 Air tightness

The air tightness of the houses, or rather the way the air tightness is implemented within the calculation, proved to greatly influence the gap between real and predicted energy use. Within the EPBD-calculation, one can chose to perform the energy calculation with a default value for the air tightness, or with a measured value, based on an air tightness test performed after completion of the building. The overestimation of the heating energy use proved to be the largest for calculations using the default value. This seems to indicate that the real air tightness levels of the houses that were not measured, are better than that default value. This would also be in agreement with the most recent studies on air tightness of Belgian houses (Laverge et al.). However, statistical regression analysis on this or similar datasets cannot prove this, nor can they prove that the heat losses due to air infiltration are correctly modelled in the EPBD-method. The statistical analysis only proves the strong relative influence of choosing to use the default rather than a measured value.

The magnitude of this influence can be explained by the size and typology of the house and the unit used for the default air tightness. The default air tightness is expressed in v50-value, in cubic meter air infiltration rate at 50Pa pressure difference per square meter of envelope area \([\text{m}^3/(\text{h.m}^2)]\). Therefore, any difference with the real air tightness value is magnified within the EPBD-calculation by the large envelope area of the large, detached houses in this sample. The influence of the assumed air tightness rate was such that the calculations had to be corrected towards a more realistic default value, before performing further analyses.

FIG 3. (a) Air tightness rates taken into account in the calculation (v50 in \([\text{m}^3/(\text{h.m}^2)]\)) and (b) its effect on the gap between real and predicted heating-energy use

4.2.2 Gas boiler efficiency

The efficiency of the gas boilers, according to the EPBD-files, proved to be significantly, negatively correlated with both the absolute and the relative overestimation of the heating energy demand. The negative correlation with the absolute overestimation can be explained by the fact that a lower heat production efficiency would amplify any overestimation of the net heating demand. However, this would not explain the correlation with the relative overestimation. Three possible explanations were formulated, though none can be proven by statistical analysis on this type of data. (1) The formula used in the EPBD-method to correct the partial load efficiency from the manufacturer’s data, based on the real return temperature of the system, might be flawed. (2) When a high performing boiler is chosen, one might be more inclined to use a lower return temperature to take full benefit of the investment and, consequently, to use that lower temperature in the EPBD-calculation, instead of keeping the fixed default value of 70°C. (3) Many houses had a combi-boiler, used both for space heating and for sanitary hot water. Due to the relatively low space heating demand of these houses,
the boilers would have to be sized based on the hot water demand. This could result in a lower, effective efficiency when the boilers are used for space heating only and have a larger, relative effect on the boilers with the highest theoretical efficiency. Further analysis on this problem is needed to identify whether its cause is related to the physical EPBD-model, to the varying scrupulousness of the EPB-assessor, to incorrect or imprecise installation on site or to any combination of these or other possible factors.

4.2.3 Heating profiles

The importance of user behaviour on energy use is generally acknowledged, as discussed e.g. by Guerra Santin (2010). However, the influence of the different heating profiles on the real energy use could not be proved directly from the answers to the surveys. Many different combination of heating profiles occurred within the sample, due to variations in daily heating times and heating set points over the different rooms of each different house, having also its own thermal time constants. Considering the size of the dataset, the amount of parameters for the regression analysis had to be reduced. This was achieved by clustering the daily heating times, set points and time constants of the buildings, using the simplified corrections formulas from EN 7120, resulting in one instead of three parameters per room. This allowed to identify the heating profiles of the master bedrooms as having the most significant effect on the real energy use. The statistical importance of the master bedroom can be explained by the fact this room is present in all houses (e.g. in comparison to a study or play room) and that its heating profiles showed larger variations than e.g. the living rooms, which almost all households heated to a similar set point.

**FIG 4.** Heating profiles in the master bedrooms: (a) large spread in daily heating times [h] and (b) set points [°C]

4.2.4 Showers & baths

Neither the weekly amount of baths, nor the weekly amount of showers were proven to have a significant effect on the gap between real and predicted heating-energy use. This contra-intuitive finding was explained by the strong, negative correlation that was found between both ways of having a wash. Therefore, similar to the problem of multiple parameters for heating profiles, the parameters for baths and showers were merged. As the average heating-energy use for showers is not equal to that for baths, the weighted sum of weekly baths and showers, per household, was calculated. Based on EN 13203-2, the average energy use was estimated to be 3.6kWh for a bath and 1.4kWh for a shower. Using this aggregated parameter, the weekly amount of baths and showers taken by each household revealed itself as the second most influencing user behavioural factor explaining the divergent gaps between real and predicted heating-energy use.
5. Conclusions & discussion

This study aimed both at investigating the gap between real and predicted energy use in low-energy houses as well as at identifying the most significant parameters influencing this gap. This study proves the influence of both technical as well as user behavioural parameters on the gap between real and predicted energy use. The implementation (default values and formulas) of air tightness and combustion efficiency within the calculation method proved to be significantly correlated with the size of the gap. These issues could partly be tackled by choosing more realistic default values, improving the predictions’ accuracy. However, this would oppose itself to the role of conservative default values, namely to admonish building teams to perform better and to prove it, by rewarding these efforts through better energy labels based on measured values. The realistic estimation of user behaviour is an even more complex task within energy performance regulations. The contradiction there lies between choosing a default user behaviour to enable comparison of energy labels on the one hand and delivering accurate predictions on energy use to the future, specific inhabitants and investors on the other hand. Therefore, one might question if it is realistic or even recommendable to aim both at labelling and at an accurate, case-specific prediction based on one single, simplified calculation.

The presented study pointed out some significant parameters. However, the limited representativeness of the sample, as well as the strong, direct correlations between building parameters and household parameters hinder further extrapolation towards building stock levels. These findings question the possibility of accurately predicting the effect of future, tightened building requirements, using data collected from past forerunners. Larger datasets would be needed for further thorough statistical analysis, due to the complexity of the problem, the large amount of influencing variables and the important possible amount of unknowns and contradictions within different datasets. However, collecting such size of datasets appears be in contradiction to the target of such study: the few forerunners.

6. Acknowledgements

The authors want to thank all inhabitants who participated to the data-collection.

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NBN EN 13203-2, Gas-fired domestic appliances producing hot water - Appliances not exceeding 70 kW heat input and 300 l water storage capacity - Part 2: Assessment of energy consumption

Optimized energy concept for an office building with waste heat from IT cooling using building energy simulation

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KEYWORDS: building energy simulation, EnergyPlus, waste heat, radiation heating

SUMMARY: (Style: Summary Heading)
For the prognosis of the energy demand and the summer comfort as well as for the energy optimisation of a new office building in Potsdam, Germany, a building energy simulation was carried out with EnergyPlus. Summer conditions must be considered carefully in regard of on the occupancy and the inner thermal loads. The paper describes the tool chain used to model the complex geometry and the HVAC components as well as some inherent problems of the simulation software.

1. Introduction

The Potsdam Institute for Climate Impact Research (PIK) was founded in 1992 and currently has a staff of about 300 people. The historic buildings of the institute and its high-performance computer are located on Potsdam’s Telegrafenberg campus, along with a number of other major research institutions. The most famous building at this location is the Einstein Tower (Einsteinturn).

Until 2015 a new building for ca. 200 employees will be erected, containing mostly office space and a computation centre in the basement. The design of the new building has the intention of being unobtrusive in respect of the historical buildings on the campus and being mindful of the green surroundings.

The waste heat from the cooling of the computation centre significantly exceeds the heat demand. The German Federal Ministry of Economics and Technology is funding a research project for exploring the options of using this waste energy for heating this building as well as other ones nearby, at the same time reducing the energy necessary for cooling. New technologies like vacuum glazing in parts of the facade, hot water cooling in the data centre and LED lighting will be applied. A main part of this project is the energy optimization of the new building with the help of simulations.

For the building energy simulations the software EnergyPlus is used. The aim is mainly to predict the energy demand, the room temperatures for a later comparison to measurements, and the optimization of the comfort in the offices and meeting rooms. The paper also describes some problems and weaknesses encountered during the simulations.

2. Building Description

The building is designed similar to a cloverleaf. The outer areas contain the offices and meeting rooms. Inside are the sanitary, copy, and tea rooms and the staircases (Fig. 1). The public areas which also contain small areas for informal meetings are in between. In the centre an atrium stretches from the ground floor to the roof. The basement contains the computation centre, a conference room for 200 people and storage areas.

The heat source will be the waste heat from the computation centre. If necessary, the temperature level will be raised by a heat pump. The rooms are then heated by a panel heating system in the ceiling which can work with relatively low temperatures. It is planned to use "hot water cooling" for a part of...
the racks - water cooling directly at the processors with a temperature of approx. 50°C which increases efficiency and provides waste heat with a higher exergy.

A ventilation system with heat recovery provides supply air. Heating and ventilation are operated via a building automation system, including individual room thermostats, presence detectors and window contacts for turning off ventilation and heating when the user opens a window.

Supply air is provided from the cavity floor near the outside wall. The inner walls between office space and corridor contain an integrated overflow opening. Exhaust air openings are in the corridor and sanitary rooms central in the building. The office rooms (i.e. ground and upper floors) contain no active cooling systems. The lighting is daylight dependent.

3. Simulation Model and Input Parameters

Since the cardinal direction of each room in a floor is different, a simulation should provide individual room temperatures to ensure summer comfort. Additionally many of the rooms will be monitored. Therefore the simulation model was set up with more than 280 zones, which is a challenge for the simulation tool. For the same reason the individual control of room temperature, ventilation, lighting and shading are taken into account. To create the model and reproduce the complex building geometry as close to reality as possible, the software DesignBuilder was used.

DesignBuilder is a graphical user interface for the simulation program EnergyPlus, which enables the user to enter three-dimensional data for geometry, materials and constructions and schedules for all kinds of time dependent values. The user profiles (room use, lighting, shading, inner heat sources etc.) were created in agreement with the building owner to represent a realistic simulation environment.

Fig 2. Three-dimensional representation of the building model at building, floor, and room level. The screenshots are taken from the DesignBuilder GUI.
It then creates an input file (IDF) for the simulation kernel EnergyPlus which can be edited if necessary. The HVAC system was implemented directly in the EnergyPlus IDF description including code written using the included programming language EMS. The postprocessing of the simulation results is mainly done with the help of self developed code in C++ generating key figures from the numerous outputs.

3.1 Schedules and user profiles

The simulation requires schedules for the energetically relevant values in each zone. The input can be very detailed, which on one hand enables an exact representation of the building in use. On the other hand, most of the values are unknown in the planning stage, and even in the practical case it will be impossible to measure them.

This concerns mainly the objects

- people - for inner thermal loads due to user presence,
- lights - for lighting,
- electric equipment,
- infiltration,
- and shading.

Since these schedules are interconnected in practice, emphasis was put on a logical set of values (this topic is connected to the EU research project ISES, http://ises.eu-project.info/). The flexible work time, with people coming in the morning and leaving in the evening, as well as lunch break can be taken into account. The default for the daily sums of the values was taken from the German code DIN V 18599 and adjusted with information from the building user. A sample representation of the user presence is given in Fig. 3 for some zone types.

![Fig 3. Occupancy schedules of several room categories. The daily sums for the zones correspond to the German code DIN V 18599.](image)

The artificial light calculation represents the daylight dependance of the building automation system.

3.2 Modeling of the HVAC systems

3.2.1 Heating

The following modules in EnergyPlus were tested to model heating:

- Ideal Loads Air System (ILAS)
• Baseboard heater
• Low Temperature Radiant System (LTRS) with variable flow

As the name implies, the ILAS is an idealized system where all heating/cooling is provided by the supply air and no other HVAC components are regarded. This is useful for approximations or for the case of an unknown HVAC configuration. This model has been thoroughly tested and validated.

The baseboard heater model contains parameters for a radiative part of the supplied heat. However, the simulation with radiation shows errors of partly neglecting the radiation part in the energy balance. Hence only a simulation with completely convective heat transfer delivers useful results.

The low temperature radiant system is provided as a module by EnergyPlus. In the current case the system works with a water loop. The water is heated to the required temperature by a heat source representing the waste energy.

Internally the simulation kernel calculates the thermal energy necessary for each zone for each timestep. For the low temperature panel heating this calculations are not working satisfyingly.

The reason for this can be seen in the EnergyPlus iteration strategy. First, the solver performs the wall calculations. These are carried out primarily without the heat source of the panel heating, independent of the zone balance. After finishing this calculation the zone balance is started, resulting in heat fluxes. Since the wall calculation is at this time already finished, the solver for the wall temperatures is not started again (Fig. 4).

Fig 4. Iteration order in the EnergyPlus solver.

This leads to errors described below in more detail. It seems that the LTRS module was implemented without sufficient testing of its results.

3.2.2 Ventilation and air mixing

All zones with boundary to the outside air receive an infiltration corresponding to wind speed and temperature difference taken from the climate file. A ventilation rate per area and per person is provided by the ventilation system. The HVAC system contains a heat recovery system with an efficiency of approximately 60%.

The ventilation and the heat recovery unit is modeled with the "SingleDuct:Uncontrolled" module, regulated by code written in the internal EMS language. This enables a better control of the system for the individual zones including the detailed schedules.

The integrated overflow openings are modeled with an air mixing module of EnergyPlus. This module only considers the energy fluxes, which is sufficient for the current case of a pure energetic simulation. Moisture or contaminant fluxes are not regarded.
4. Problems during HVAC modeling with EnergyPlus

Several problems have been encountered in the application of heating and ventilation models of EnergyPlus. Though most modules of EnergyPlus work as expected when used alone, combinations can lead to unexpected and undocumented behavior. Therefore the following systems were tested to find a way to integrate the actual HVAC into a working EnergyPlus simulation model:

1. Panel heating with ventilation system - regulation of the ventilation with "Controller:MechanicalVentilation" element: Though the controller was implemented in the controller list, the connection with the system was not functional.

2. Panel heating with ventilation - regulation of the ventilation with EMS code and "SingleDuct:Uncontrolled" element: The ventilation system could be modeled in line with the demand. The air volume fluxes are then calculated from air change related to area and persons. A cooling by extended ventilation (if the inside temperature exceeds the comfort limits and outside temperature is lower, and extended night ventilation) could be realized.

The panel heating was not working physically correct. An example is given in Fig.5.

![Fig 5. Physically incorrect results for a low temperature radiant element. When energy transfer from the surface to the room is required, the temperature in the water outlet decreases far below room temperature, and the temperature of the room surfaces take values of 100°C and more](image)

It seems that these kinds of radiation heating are inherently not truly functional due to the reasons described above. Therefore the heating representation had to be changed to a simpler system with convection heat transfer only.

3. Ideal system with ventilation - regulation of ventilation with EMS code and "SingleDuct:Uncontrolled" element: The panel heating was simplified by an "IdealLoadsAirSystem". Both system parts are working correctly if applied individually. In combination, however, the volume fluxes show errors.

4. Baseboard heating with ventilation system - ventilation energy balance is modeled by EMS code via "OtherEquipment" elements: Because of the shortcomings described above the heating was described by a relatively simple water heating with baseboards as heat transfer elements. The ventilation was completely programmed in EMS code, including the heat recovery unit. With this approach it was possible to reproduce both the heating and the air volume flow combined in a consistent way.

Additionally, the following other errors were encountered:

The control of some desired values is not always described correctly. Thus, target values for feed and return flow can only be used with reservations. In this case the documentation states: "... the
component models and system solvers may or may not be able to use them." Therefore it is highly recommended to test implemented components before relying on the results.

Some serious problems occurred within the EMS programming language when comparing negative numbers. In if-statements or allocations the expressions "if (a == -1)" or "Set var1 = -var2" are not evaluated correctly. This leads to errors which are hard to find, especially since debugging is somewhat tedious within EMS.

5. Tool chain

As mentioned above, the software DesignBuilder was used for the input of the geometry. Despite the complex geometry, the graphical input in a 3D-CAD-like environment could be done relatively quickly.

For energy simulations, the software then writes an input file for EnergyPlus (a text file, so called input data file or IDF), calls the EnergyPlus solver internally and displays a limited set of results. Due to inefficient automatic writing of the IDF with lots of redundancies, the solver could not handle the input file for this large simulation model. Due to this fact and to provide for the detailed input of HVAC components the IDF had to be handled manually. Unfortunately the many redundancies and automatically generated quasi-random names make the file very impractical to use.

For this purpose a software tool was written which removes redundancies in construction definitions and schedules, creates zone lists, renames constructions and zones to human readable names while keeping all logical connections between all objects. In the case of the simulated buildings for instance the number of objects for the internal heat production related to people was reduced from over 250 to 10, more than 1000 schedules for time dependant input values were reduced to less than 40, and the output variable definitions from nearly 10000 to 50 output variables and variable groups, respectively.

The HVAC system as described above was partly added with usual IDF descriptions and in case of the ventilation system programmed in the EMS language.

6. Parametric study

To estimate energy demand and comfort for different scenarios, a number of variations have been analyzed with the simulation. The varied parameters are occupancy density, heat loads by electric devices, setpoint and setback temperature, and the ventilation control.

According to the code DIN V 18599, 12 m² are assigned to one office worker. The value of 10 m² is somewhat more realistic for the current building due to the size of the single offices. Since the number of employees might increase in the future, a case for increased occupancy was included with 6 m² per person, which represents roughly two employees in one office.

The values for electric devices, mainly be produced by computers and monitors, originates from own measurements. The used numbers represent cases of normal and high energy use of the devices. These two variations represent the inner thermal loads which in combinations result in a factor four between the lowest and highest inner loads.

The setpoint/setback temperatures of 21°C/17°C are taken from the DIN V 18599-10. A possible saving option is assessed by using 20°C/16°C.

The ventilation control is mainly planned for supplying fresh air for the offices. An additional amount of outside air for night cooling could increase the comfort level during warm periods, but will at the same time need energy for ventilation.

The energy gains and losses are shown in Fig. 6. Since the thermal standard of the building is high, the losses over the facade are comparatively small. The inner loads due to the internal sources are in the same order of magnitude as the heating energy provided by the HVAC system. The total energy
consumption should therefore consider both. In the current case, the pure heating energy consumption lies between 6 and 10 kWh/m²a, and the total consumption between approximately 20 and 40 kWh/m²a.

**Fig. 6. Energy consumption for the parametric cases.**

In well insulated buildings the winter comfort is usually not a problem, since all room surfaces temperatures are close to the room air temperature. The summer case can be much more critical, especially for office buildings with a higher occupancy density. Therefore the summer comfort was evaluated for all the above variations in terms of Kelvin-hours \((\Theta_{\text{room}} - 26^\circ C) \cdot n\) with \(n\): number of hours) over the limit of the EN 15251 category II under realistic conditions.

**Fig. 7. Frequency distribution of the Kelvin-hours over the temperature limit of EN 15251 for all 137 office rooms with normal occupancy (10 m² per person, in blue) and high occupancy (6 m² per person, in red) and appropriate inner thermal and electric loads.**
The German code DIN 4108 accepts a limit of 500 Kh over 26°C (under slightly different conditions). In the case of high occupancy density this limit is not reached but a number of rooms come near that value.

These parameter variations are only a limited approach. Naturally, there are many other values that will deviate in the practical case and should therefore be considered as variation parameters. This applies particularly for the user related values and will be part of further research.

7. Conclusions

For the satisfying modelling of the relatively complex building geometry a tool chain of different tools was used in the preprocessing to create the input for the EnergyPlus simulation kernel. The low temperature radiant elements of the heating system could not be modelled with the internal structure of the simulation solver. However, these elements become more and more important if energy from renewable sources is used in the building sector with a low temperature range. Despite these limitations, EnergyPlus remains a powerful and flexible simulation tool. A simulation software which will be able to describe such systems in detail and include them in thermal building simulation is currently in development under the EnTool research initiative (Tools and Data for Energy-optimized Buildings, Neighborhoods and Cities), see Nicolai (2012).

Two variations in input parameters reflect an influence in user behaviour (occupancy and inner loads mostly due to computational devices), while two others reflect some range of the HVAC control. As can be expected, the user influence in a building with good thermal quality is significant and exceeds most other input parameters. Summer comfort without active cooling can be achieved for most cases but will not be completely satisfying in all rooms if high inner loads are present.

8. Acknowledgements

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Zhen Tian & James A. Love, August 2006, Radiant slab cooling: a case study of building energy performance
The performance of subsoil frost protection system of mechanical heat recovery ventilation unit in a cold climate in the context of net zero energy building

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KEYWORDS: net zero energy building, frost-protection, ground-source brine heat exchanger.

SUMMARY:
Mechanical heat recovery ventilation (MHRV) units with very high heat recovery efficiency are mandatory for achieving good indoor climate without excessive heat loss in cold climates. Higher heat recovery efficiencies, however, mean that more preheating energy is needed to avoid the frost formation in the heat exchanger. Typical methods for frost protection (electrical preheating coil or disbalancing the airflows) are not favourable solutions in cold climates with excessive period of low outside air temperatures. Several alternative systems with subsoil heat exchangers are possible for lowering the energy need for frost protection of net zero energy buildings (nZEB).

A subsoil-brine frost protection system in first certified passive house in Estonia and its performance during the first heating period has been further analysed in this paper. The measured performance data was compared to the modelled values in order to enable the subsequent retrospective analysis, but existing specific calculation routines could not be fully validated within this study. The variability of net energy demand for preheating was simulated using retrospective real climate dataset for time period between 1970 and 2000. The calculations show that the energy demand for the frost protection of MHRV can play significant role in overall energy use of the nZEB and the subsoil-brine heat exchanger is a viable solution for frost protection with additional cooling effect during the summer period.

1. Introduction

In the context of European directive on the Energy Performance of Buildings (EBPD) [2002/91/EC, 2002; 2010/31/EU, 2010] the energy demand of the buildings in the next decade is drastically reduced compared to previous practices. The transmission losses are significantly reduced by thick insulation layers, thermally optimized glazing and more compact architecture, which enable the reduction of cooling surfaces and thermal bridging. The infiltration and ventilation losses are minimized by careful realization of different air-tightness techniques and utilization of balanced mechanical heat recovery ventilation (MHRV) units with very high heat recovery efficiencies.

As the overall energy demand of the building decrease the auxiliary energy demand for powering the technical systems (ventilators, pumps, electronic controllers etc.) increases. In the case of ventilation units, higher heat recovery efficiencies, however, mean that additionally to ventilators and electronic controllers more preheating energy is needed to avoid the frost formation in the heat exchanger. This phenomenon is furthermore magnified in colder climates [Kragh et al. 2007] where excessive periods of colder temperatures endure. Although simple electric frost protection coils are widely used all over Europe, alternative systems exist such as ground-source air heat exchanger (GSHE), ground-source brine heat exchanger (GSBHE), hygroscopic heat exchanger (rotor systems, and improved plate heat exchanger systems), disbalancing the airflows, etc.
Although the disbalancing of the airflows or stopping the ventilation unit for defrosting is not useable for extended cold periods [Kragh et al. 2007] the use of other described alternative systems have to be considered as direct electricity use for frost protection in typical ventilation units can play a significant role in primary energy demand of the net zero and nearly zero energy buildings (nZEBs).

This paper concentrates on GSBHE systems comparing the simulation results with measured data from first Estonian net zero energy building, described in [Mauring et al. 2013]. Additionally theoretical net energy demand for frost protection in cold Estonian climate is calculated based on historical weather data for range of effecting parameters (ventilation air flow, frost-protection set point temperature) and is analysed in the context of overall energy demand of nZEBs.

2. Material and methods

2.1 Description of studied climate dataset

As a typical country bordering the Baltic Sea, Estonia is divided to two climatic zones – e.g. coastal area and inland area where conditions differ due to influence of nearby sea. The more detailed spatial division and climatic differences are given in [Kalamees and Vinha 2004]. The studied building is located in the town of Põlva at the South-East part of Estonia where more continental climatic conditions occur along with lower temperatures, deeper and longer lasting snow cover compared to coastal areas [Raik 1967 cited in Kalamees and Vinha 2004]. Based on national Test Reference Year for energy calculations the long- term average dry bulb temperature for inland part of Estonia in December is -2,5°C, in January -3,0°C and in February -5,2°C [Kalamees and Kurnitski 2006], however long-term average daily minimum values for each month from November to March are below -10,0 °C reaching -14,3 °C for January [Kalamees 2006].

In more extreme years the air temperature falls below -30 °C occasionally, staying frequently below -15 °C for several days [Estonian Meteorological and Hydrological Institute 2002] based on measurements in Tõravere station. For detailed analysis of variability of frost protection energy demand this measured sub-daily weather dataset for time period from 1970 to 2000 was used. The hourly data from measured data with sub-daily (3 hour) time steps was generated using linear interpolation between measured time steps.

Outdoor dry bulb temperature was used from the weather dataset to calculate the net energy demand of the frost protection system.

2.2 Description of studied building and ventilation system

The studied building has three stories, total net floor area of 305 m², external envelope surface area of 864 m² and enclosed volume of 1586 m³. The building was planned and realized according to international passive house concept to achieve the average yearly net heating demand of 15 kWh/(m²*year) [Passivhaus Institute 2012]. To further lower the energy demand, the studied building was equipped with split solar thermal system combined with ground source heat pump with vertical boreholes. Additionally an 90 m² photovoltaic solar (PV) system was built to cover the total final energy demand of the building making it net zero energy building. The more detailed description is given in [Mauring et al. 2013]. In table 1, estimated final energy demand (electricity) of the building is given.

The building has balanced mechanical ventilation system with PHI certified passive house ventilation unit (Paul Novus 300 with exhaust side heat recovery efficiency 93% according to PHI certification system) [Passivhaus Institute 2009]. Fresh air with no additional heating is supplied to living room and bedrooms and then exhausted from kitchen, bathrooms, etc. The airflows have been reduced to limit the risk of overly dry air during the winter season. The average airflow rate measured during the startup of the ventilation system is 280 m³/h, which corresponds to average air change rate of 0,4 h⁻¹. On-site measurements showed that CO₂ levels are low enough to further lower the airflows if needed.
Table 1. Estimated final energy (electricity) consumption and production of the studied building.

<table>
<thead>
<tr>
<th>Category</th>
<th>Electricity use / production, kWh/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated electricity production by solar PV (photovoltaic) system</td>
<td>10120</td>
</tr>
<tr>
<td>Total electricity demand of the building</td>
<td>10356</td>
</tr>
<tr>
<td>..including electricity demand of GSHP (vertical ground source heat pump)</td>
<td>2149</td>
</tr>
<tr>
<td>..including estimated electricity demand of technical installations</td>
<td>2000</td>
</tr>
<tr>
<td>(ventilators, pumps etc.)</td>
<td></td>
</tr>
<tr>
<td>..including estimated electricity demand of domestic appliances, lighting</td>
<td></td>
</tr>
<tr>
<td>..including estimated electricity demand of technical installations</td>
<td>6207</td>
</tr>
</tbody>
</table>

The frost protection of the ventilation unit is solely by sub-soil brine heat exchanger. The system features 226 m (with 40 mm diameter) of plastic pipe buried horizontally in the depth of approx. 1.0 to 1.2 m and connected to Paul Sole Defroster unit SD-550, which controls the fluid flow speed of the system according to air-temperature before the ventilation unit.

2.3 Measurements

After completion in December 2012 the studied building has been equipped with extensive monitoring system to gather information about indoor climate and performance of building system as well as exterior wall as a part of on-going joint research project between two universities in Estonia. In the context of this study the ventilation system is equipped with temperature and relative humidity sensors (Ø5mm×51mm, measurement range: -40°…+100°C and 0…100%, accuracy: ±0.3°C and ±2%) to measure supply, extract, exhaust air parameters and additionally air parameters before and after frost protection system prior the ventilation unit.

2.4 Simulation procedure of GSBHE system

The net energy demand for regular frost protection and its variability over long term time period was calculated using statistical programming package R. A simplified hourly power estimations were calculated based air heat capacity using equation 1. Hourly power estimations were integrated for annual net heat demand values.

\[ P = \dot{V} \times c \times \rho \times (T_e - T_{sp}) \]  \[1\]

Where  
P – average hourly net power demand for preheating external air (W);  
\( \dot{V} \) – volumetric air flow (m³/h)  
c – heat capacity of air (1,006 kJ/kgK);  
\( \rho \) – air density (1,225 kg/m³);  
\( T_e \) – dry bulb temperature of external air (K);  
\( T_{sp} \) – setpoint temperature for frost protection (K).

The simulation of GSBHE system was carried out with calculation software PHErde (provided by Passivhaus Institute). The system configuration along with soil characteristics were input according to on-site conditions and details. For comparison of measured and simulated values a synthetic weather dataset was created from on-site measured average hourly values (for study period) and national Test Reference Year (hours outside study period). The dynamic simulation was carried out to acquire the temperature values after the GSBHE system. The length of the study period was determined according to external air temperatures when preheating would be required.
3. Results

3.1 Calculated net energy demand variability for frost protection

Average calculated long-term net energy demand for frost protection corresponding to airflow and frost protection set point described in the studied building is approx. 900 kWh annually. The net energy demand shows the energy physically needed for preheating the external air if no GSBHE is used or if direct electric preheating is used. In the case of properly dimensioned GSBHE this energy demand is omitted. The variability of net energy demand for frost protection is given in the Figure 1. It can be seen that depending on yearly differences the net heat demand varies in the range between 240 kWh and 1946 kWh annually.


As estimated long-term average total energy demand of the building (heating, DHW, domestic and auxiliary electricity) is 10356 kWh, a direct electric preheating of external air can play considerable role in total energy and primary energy demand. For studied building the direct electric frost protection could account for 8.7% of total electricity use for average year. For colder years this percentage will be even higher because the room heating energy is produced with high efficient heat pump system. When omitting the consumption related electricity use (domestic appliances, lighting etc) the potential energy use of electric frost protection will be approx. 21.7% of the energy demand for heating, DHW and auxiliary electricity.

This signifies the use of alternative frost protection systems in low-energy and nearly zero energy buildings. Although the used GSBHE system in studied building avoids this surplus energy consumption it has to be acknowledged that this system has limited power output and in the case of higher frost protection demand (through higher volume flow rates or higher set point temperatures) the selection and dimensioning of the frost protection system has to be done carefully.

The effect of higher volume flow rate and set point temperature are given in figures 2 and 3. The estimated net frost protection energy demand for higher volume flow rates (0.6 h-1 and 0.8 h-1 accordingly) are given in figure 2. Compared to baseline situation the energy demand increases significantly.

The estimated net frost protection energy demand for lower and higher set point temperatures (-3 as baseline scenario and -6 °C, 0 °C and +3 °C accordingly) are given in figure 3.
3.2 Measured and simulated performance of GSBHE system

The monitoring of dry bulb air temperature before and after GSBHE system started after setup and initial start-up of the GSBHE system as well as monitoring system. Initial stability issues with monitoring system were discovered and therefore results for full heating period of 2013/2014 are described in this paper excluding the measurements from the previous heating period. Monitoring results for time period between 01.12.2013 and 24.03.2014 are given in Figure 4 for each 5-minute time step.

It can be seen that although external dry bulb air temperature falls and stays frequently below -10°C the air temperature after the GSBHE system stays approximately between -1°C and +1°C during the coldest periods. At the beginning and at the end of the heating period the air temperatures after the GSBHE system are higher fluctuating between +2°C and +4°C. There are 3 irregular peak
measurements for single time steps, however these are related to manual shutdown of ventilation system during which the standing air warmed up in the ventilation ductwork.

Theoretical energy demand avoided by GSBHE system according to equation 1 based on measured air temperatures was 658 kWh for analysed heating period. Additionally approx. 43 kWh of electricity was used for the circulation pump – so overall energy avoided by GSBHE system was 615 kWh.

![Graph](image1)

**FIG 4.** Measured air temperatures before (black solid line) and after (red dotted line) subsoil brine heat exchanger at 5 min intervals for whole heating period of 2013/2014

The measured temperatures before and after GSBHE system were averaged to hourly values in order to compare them to preliminary simulated values. These hourly temperatures along with simulated temperatures after the GSBHE system are given in figure 5.

![Graph](image2)

**FIG 5.** Measured average hourly air temperatures (black solid line – measured air temperature before GSBHE system, red dotted line – measured air temperature after GSBHE system) compared to simulated hourly temperatures (blue dashed line).
Although the pattern of hourly fluctuation of simulated values follow the measured values, the measurements do not correspond well to the simulated fluctuation amplitudes. Further calibration and fine-tuning of PHErde calculation model was performed after preliminary calculations (according to actually measured brine flow speeds, etc.), but calculation model could not be fully validated as can be seen from figure 5. This can be related to ground temperature modelling simplifications in PHErde tool and lack of possibility to include detailed solar radiation effect on ground surface and subsoil temperatures. Therefore, a multiyear retrospective simulation of GSBHE system is not currently possible to assess the long-term performance of such systems in Estonian climate.

4. Discussion

The theoretical calculation results given in figures 1, 2 and 3 show that net energy demand for the frost protection of the ventilation unit can account for significant part of total energy demand of the building even if the volumetric air flow rate and set point temperature for frost protection is lower than in historical practices. The higher airflow rates and higher set point temperatures will increase the net energy demand significantly. This means that in the context of nearly zero energy buildings where the overall energy demand is limited the frost protection of MHRV unit cannot be realized with direct electric heating coil. Alternative systems, such as ground-source air heat exchanger, ground-source brine heat exchanger, hygroscopic heat exchanger (rotor systems, and improved plate heat exchanger systems) and special systems utilizing double heat exchanger configuration etc are technically possible as stated in [Kragh et al. 2007].

The studied building features GSBHE system, which enables energetically effective frost protection without direct electric heating. This system was dimensioned and realized according to calculations with specific software models (PHErde), however the measurements from first full heating period show that calculations underestimate the real performance of the GSBHE considerably. The measurement results show that for entire heating period of 2013/2014 the system provided enough preheating energy for the ventilation unit even for excessive periods with air temperatures between -10°C and -17°C.

Due to simplifications in specific software tools, the validation of calculation model and further performance analysis in even more extreme temperatures were not possible. As a future work we are trying to propose and implement enhancements to calculation procedures involved in GSBHE performance calculation software PHErde or develop a separate calculation method for such systems.

5. Conclusions

The performance of the ground source brine heat exchanger system of the first certified passive house in Estonia was monitored and assessed during the first full heating period after construction. The system performed well providing frost protection for the mechanical ventilation system without any problems. The measured values showed that mathematical simulation model used for dimensioning the system underestimated the system performance, which means that the calculation routines have to be further developed to achieve better match with the measured values. Thereafter a long-term retrospective analysis with historical climate data of cold Estonian climate can be performed.

Theoretical calculations of net energy demand for frost protection with different ventilation air flows and preheating set point temperatures showed that when utilizing typical electric preheating coil for frost protection a considerable energy demand can be expected which can contribute significantly to total energy demand of nearly zero energy building. Therefore, in cold climate, an alternative frost protection has to be used. Utilization of hygroscopic heat exchanger in MHRV unit enables lower set point temperatures for external air preheating independently from the volumetric airflow rates. However, when using GSHE or GSBHE systems, the power output is limited and therefore the dimensioning of these systems has to be carried out very carefully to match planned airflow rates ventilation unit requirements.
6. Acknowledgements

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References


Classification of building envelopes for solar energy applications

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KEYWORDS: Solar energy, Building envelopes, Solar radiation, Solar heat, PV, Solar map

SUMMARY
Buildings are suitable as support structure for solar energy applications. The solar radiation on the envelope is depending on the orientation and tilt, as well as the geographical location and the time of the day and year. In order to utilize solar energy as solar heat and/or electricity, the envelope of the buildings can be categorized in different levels.

Category 1 is the south facing roofs that receives the highest radiation, which includes tilts between 10-65° and the orientation from south-east to south-west. Category 2 includes the horizontal roofs and for the lower tilts (<30°) also east and west orientations. For very low tilts (<5°) also north facing roofs can be included. Category 3 includes south facing facades and low tilts for north facing roofs.

The potential of solar heat and solar electricity from the envelope of the buildings can be calculated and compared with the demand in the building depending on numbers of floors and category of irradiation. The ratio between suitable roof area and building floor area gives information about the potential of supplying energy within the building and the possibility to distribute the excess energy to a heating network or the electrical grid. Defining of categories can be a tool for potential calculations as well as structuring building types, blocks or areas according to utilization of solar energy. A Solar Map can also be used and one example is the solar map in Lund.

1. Introduction
The building envelopes can be used for heat- or micro power production and the energy may be used within the building and decrease the demand of the supplied energy to the building, as well as fed in the district heating network or the electricity grid. There is a large opportunity and challenge to transform buildings from just using energy to minimize the demand and also deliver more energy than needed over a year.

The solar radiation on the building envelopes can be converted to heat with solar collectors or to electricity by using photovoltaics (PV). In existing buildings the best surfaces should be used for installations and new buildings should be designed in order to optimize the output from the solar energy applications. There is not one solution for what is optimised, it differs depending on investment cost of the installations, the value of the solar energy, the possibility to use the energy directly within the building as well as the possibility for selling, taxes, incentives and supporting systems etc.

For each single building the decision support can be different regarding the economics, which controls the optimization of the size and design of the solar energy installation.

2. Solar radiation on building envelopes
The seasonal variation of the solar radiation increases with the distance to the equator and the more important is the tilt of the surface facing the sun. The tilt is here describing the angle between the
solar energy installation and the horizontal plane. The optimal tilt for the total irradiation is varying during the year. The optimal tilt per month for Lund, Sweden, for a south facing surface, is shown in figure 1.

**FIG 1.** The optimal monthly tilt (inclination angle from horizontal) for solar radiation on a south facing surface in Lund, Sweden. (PVGIS 2013) (PVGIS © European Union, 1995-2013)

As the radiation is varying during the year, the main importance of the tilt is during summer and figure 2 shows the variation of the monthly total radiation for the south facing optimal angle (40°) as well as a horizontal plane and a vertical surface facing south in Lund.

**FIG 2.** The monthly solar radiation in Lund for the optimal tilt 40 degrees, horizontal plane and 90 degrees tilt towards south (south facing facade) (PVGIS 2013) (PVGIS © European Union, 1995-2013)

The variation over the year is large as seen in figure 2. For the yearly optimal tilt 40° (towards south in Lund, Sweden), only about 10% of the yearly irradiation occurs during the 4 winter months: November to February. On the other hand about 65% of the annual solar radiation is obtained during the 5 spring- and summer- months; April to August and 75% of the yearly radiation during half the year from April to September.

The variation of the radiation for all tilts and angles for real weather data from Jönköping during 1961-1990 is shown in figure 3, as percentage of the maximum yearly radiation. By comparing solar radiation direct towards the south, the decrease is only about 5% for radiation towards southeast and
southwest. With increased angles from south, the optimal radiation is obtained on decreased tilts from horizontal, and for radiation towards east and west directions; the horizontal radiation is the maximal.

**FIG 3.** Total radiation depending on different azimuths and tilts in percentage of maximum annual radiation. Average for southern part of Sweden (Kjellsson 2000).

Figure 3 can be used in order to classify different surfaces according to level of radiation. The figure shows the relative radiation in percentage of the maximum radiation and the levels are divided in 10% ranges. A higher radiation means more output from the solar energy installation and also increased yield in economic terms.

The best 10% can be classified to Category 1 or “Very good radiation” and should be used first according to yield. In the figure 3 it is the central area including most of the used roof slopes and the orientation from south-east to south-west.

Category 2 may be called “Good radiation” and includes also the horizontal roofs and for the lower tilts (<30°) also east and west orientation. For very low tilts (<5°) also north facing roofs can be included.

Category 3 – “Less good” also includes south facing facades and low tilts for north facing roofs.

Finally, the rest may be categorized as not suitable for solar applications, at least not when optimizing the yield.

The corresponding maximum values depend on the actual location and varies in Sweden. The values for the different categories are calculated for the maximum radiation between about 1000 – 1200 kWh/(m².year), see table 1.
### TABLE 1. Limits and mean of radiation for three categories based on 10-percentage levels of maximum yearly radiation.

<table>
<thead>
<tr>
<th>Total maximum yearly radiation (kWh/(m², year))</th>
<th>Yearly radiation (and mean) in Category 1 (kWh/(m², year))</th>
<th>Yearly radiation (and mean) in Category 2 (kWh/(m², year))</th>
<th>Yearly radiation (and mean) in Category 3 (kWh/(m², year))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max.</td>
<td>90-100% of max.</td>
<td>80-90% of max.</td>
<td>70-80% of max.</td>
</tr>
<tr>
<td>1000</td>
<td>900 - 1000 (950)</td>
<td>800-900 (850)</td>
<td>700-800 (750)</td>
</tr>
<tr>
<td>1100</td>
<td>990 -1100 (1045)</td>
<td>880-990 (935)</td>
<td>770-880 (825)</td>
</tr>
<tr>
<td>1200</td>
<td>1080-1200 (1140)</td>
<td>960-1080 (1020)</td>
<td>840-960 (900)</td>
</tr>
</tbody>
</table>

The economics and the yield from a solar energy application on a specific place are depending on the maximum radiation level, so the limit differs. Other limits may be used, as the actual economic circumstances vary in time. Anyhow it is of importance to investigate the most suitable areas.

The global irradiation for the optimal tilt for Sweden varies between 1200 kWh/(m², year) for the south of Sweden and some parts in the east of Sweden (north of Stockholm and Gotland), to the lowest figure of about 900 kWh/(m², year) in the very north parts.

The maximum annual radiation is received with a 2-axis tracking system, which is possible to use especially for PV. The increase of radiation is in the order of 500 kWh/(m², year) compared to optimal tilt, but the cost for the movable support structure is much higher compared to fixed mounting supports and it is not an option for integrating in the envelope in buildings. One possible application may be to use tracking systems horizontal roofs.

### 3. Utilization of solar energy in buildings - combination of surface area, tilt and orientation

The envelopes of buildings have good opportunities to be used for solar energy installations. The roofs on many buildings have suitable tilts, which is between 20-55° and large areas. The orientation is to all directions, but in order to get the best radiation the most suitable is from southeast to southwest.

The roofs on single-family dwellings are suitable due to the large area compared to the floor area. For multiple-story buildings the ratio between the area of the roof and the area of the building’s total floor area decreases with increased numbers of floors. This ratio can be calculated and indicates the possibility of utilization of solar energy within the building.

A typical single family building in the south of Sweden has gabled roof with a tilt of around 30°, which means that half of the roof can be classified to Category 1, if the roof is oriented between south-east and south-west. An ordinary size can be 130 m² floor space which means that the suitable tilted roof size can be 75 m².

If the whole roof is used, the ratio between the roof and floor area can be defined to 58%. This ratio can be used in order to compare the potential of producing heat or electricity, with the demand in the building.

The majority of the multifamily buildings constructed within the “Million building program” in Sweden have horizontal roofs, which means category 2, as described above. Comparing 4 and 8 floors respectively and calculating with the whole roof area, the ratio between roof and floor area is 25% and 12% respectively. In reality, one solution is to put a gabled roof upon the flat roof, which means
that half of the roof can be in the category 1, if the orientation is OK. The ratio between suitable roof and floor area will be 14% and 7% for the 4 story and the 8 story buildings respectively. If the façade is oriented to the south, this can also be used but in category 3, which means less output/m². In high rise buildings this can be very large suitable areas.

Another possibility is to keep the horizontal roof and put supporting structures and tilt the solar devices. In order to maximize the output and minimize the shading, there must be distances between the rows. One rule of thumb is a distance between the fronts in each row of 3 times the module width, which means that only about 30% of the roof area can be used, although in category 1.

Finally here are many more considerations that must be taken into account in a building. Different kind of obstacles may be placed on roofs, which reduce the area and gives shadows.

If the building has fixed solar shading devices to the south, this may also be used for solar applications. The area is not so large but the radiation is in the best category for south facing shadings. In office buildings without solar shading there can be overheating problems, but after installing solar shading they can both save energy and produce electricity in the same time.

Shed roofs oriented to the south are the most efficient design for solar applications, see figure 4. Many new buildings are constructed with shed roof, but the importance of south orientation is not often considered.

![FIG 4. The suitable area for solar applications on gabled roofs is about half compared to shed roofs.](image)

Comparing to the gabled roof, the whole area can be used (if no shading devices are placed on the roof), which means that the ratio between the roof and the floor area for a single store building and the tilt about 30° is 115%, see table 2. Normally the ventilation pipes are mounted on the roofs and for gabled roofs, they can be designed so the outlet is situated on the north side of the roof, but on shed roofs they may cause shading on the solar applications.

\[ \text{TABLE 2. The ratio between suitable roof area and building floor area, for different roof design facing south and number of floors.} \]

<table>
<thead>
<tr>
<th>Examples of buildings</th>
<th>Ratio between suitable roof and building floor area (%)</th>
<th>Category of irradiation for the south facing roofs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabled roofs (30° tilt), 1 floor</td>
<td>58</td>
<td>1</td>
</tr>
<tr>
<td>Gabled roofs (30° tilt), 4 floors</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>Gabled roofs (30° tilt), 8 floors</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Flat roof, 4 floors</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>Flat roof, 8 floors</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Shed roof (30° tilt), 1 floor</td>
<td>115</td>
<td>1</td>
</tr>
</tbody>
</table>

One way of using the category definition is to compensate the lower radiation with an increased area. Roughly 10% extra area is needed for category 2.
4. Comparing possible production solar heat and solar electricity with energy demand

4.1 Solar heat

Solar heat is mainly used in buildings for domestic hot water and for heating the building. In Sweden the normal system produce up to 50-60% of the yearly demand for domestic hot water. For optimal orientations the systems may produce between 400 and 650 kWh/m\(^2\) solar collector (m\(^2\) roof area), depending on system design. In combined systems, solar heat can also be used for heating the building in spring and autumn. Depending on the heat demand in the building the solar heat contribution varies. Normally there is almost no contribution with solar heat during the coldest days.

The heat demand for domestic hot water varies a lot depending on the users, and in new energy efficient buildings it may be 20 kWh/m\(^2\) (heated area) for single family dwellings and 25 kWh/m\(^2\) for multifamily dwellings (Feby 2012). For existing buildings this figure may be higher and a common average figure is 30 kWh/m\(^2\) (heated area). When calculation for the existing buildings it may be possible to save 15 kWh/m\(^2\) (heated area) with solar heat and the solar collectors will need an area on the roof of about 5-7 m\(^2\) on a single family dwelling and about 3-5 m\(^2\)/flat on a multifamily dwelling.

On single family dwellings there is normally no problem to find the requested area but for multi-floor buildings the area may be limited. For an 8-floor building with gabled roofs that has a ratio between suitable roof and the floor area of 7% as indicated in table 2, an average area of a flat with 60-70 m\(^2\) correspond to a roof area of 4-5 m\(^2\), which is enough for a solar collector system for domestic hot water. It means that it covers the south facing roof more or less completely. For higher buildings the area is not enough and for lower – it is more than needed. For shed roofs, the area is almost the double, so this may cover up to 16 floor building.

For combisystems, that also heat the building, the requested area/dwelling are about the doubled compared to only heating domestic hot water systems. The combisystems (as well as domestic hot water systems) include heat storage for a few days but are not delivering substantial heat during the winter months, due to the low radiation as seen in figure 2.

Another design possibility is to use a local or central district heating network, which links the buildings together with a central unit for heat supply. In this case the best oriented roofs can be used for solar collectors and for new constructions the normal roof material can be replaced with solar collectors. For local district heating network a storage tank must be used, but in a large district heating network for a city, the solar heat can be delivered in the system without any storage tanks.

4.2 Solar electricity

The efficiency of photovoltaics (PV) is varying depending on the type. The common way of defining the size of PV modules are the photovoltaic power capacity. It is defined as the maximum power output under standardized test conditions (STC) in “Wp” (Watts peak). A rough figure for Swedish conditions is that the annual output is 1 kWh/Wp. The area conversion from power to m\(^2\) is shown in figure 4.
The most used PV modules are made of crystalline silicon cells but thin film cells are increasing. The module efficiency for single crystalline silicon is between 13-19% and for multi crystalline silicon 11-15% (EPIA 2011). Thin film PV modules vary between 7-13% (IEA 2013).

In a PV system there is also losses in the inverter, that is used for changing from direct current (DC) to alternate current (AC), as well as cables and due to high temperatures. For the further calculations the average figure of 15% efficiency has been used.

In Sweden the reference value for calculations of the demand of house-hold electricity in energy efficient buildings is 30 kWh/(m² (heated area), year) (FEBY 2012). The actual variation is very high and in dwellings there is also a demand for electricity for common purposes which may very significantly from single family dwellings with only a circulation pump to multi-family dwellings including e.g. elevators, lightning, heat recovery systems and laundry rooms.

PV on gabled roofs on single-family dwellings, which have a ratio between the roof and the floor of 58%, may cover the yearly demand of house-hold electricity. When calculating with 15% efficiency of the PV, the annual output from the PV-plant will be 150 kWh/m² roof area and compared to floor area this correspond to about 87 kWh/(m² (heated) floor area, year), almost 3 times the calculated demand of 30 kWh/m² (heated area). This means that 5 000-10 000 kWh electricity can be produced every year from the roof on an ordinary single family building. As PV-cells are very sensible to shading it might not be possible to use the entire roof area and the suitable area might decrease.

If the suitable roof area is large compared to the demand for household electricity, the PV can also be used for heating domestic hot water and heating the building, preferable with a heat pump. The price for PV has decreased rapidly during the last years and this solutions have became economical interesting.

For multifamily dwellings the suitable roof area is lower as discussed for solar heating, and the facades may be used.

PV-modules can also be used as a building component in other places like balcony railings, solar shadings and as architectural elements, when the energy production is not the decisive design factor.

Depending on the economical context all produced solar electricity can be deliverad to the grid, but in Sweden it is normally more economical to use the electricity within the building and decrease the amount of bought electricity. Depending on the number of floors and the actual demand, there is also a large potential of to produce electricity to the grid from the roofs of buildings.
The potential of using existing buildings for production of solar electricity in a city scale can be analyzed by using solar maps. A “Solar Map” for the whole municipality of Lund was launched in 2013, giving information of about 50 000 roofs with the potential of production of solar electricity by using the roofs, divided in four categories regarding irradiation levels. The solar map is available on internet and can be used as information to the house owners but also act as a benchmark for politicians, decision makers, investors etc. to define possibilities, strategies and goals (Solkartan Lund, www.solkartan.se).

The Solar Map can be used for analyzing the potential of producing solar electricity for single buildings, but also for comparing different blocks including similar buildings, comparing different blocks and types of buildings.

5. Conclusions

The potential of using buildings for production of heat and electricity is very large. There are although a lot of specific parameters that must be considered and the radiation on suitable surfaces is one important factor. By developing categories for levels of solar radiation on the surfaces, the potential of energy from the envelope of the building can be calculated and be developed to include building blocks, areas with types of buildings and whole cities.

The buildings can be transformed from only using delivered energy to be producer of heat and electricity, saving delivered energy or distribute heat and/or electricity to the network and grid. Old buildings can be refurbished and the most suitable surfaces can be defined, while new buildings can be constructed in an optimal design.

It is important to decrease the supplied energy to buildings and this can be done with a combination of improved energy efficiency and using the envelope for production of solar heat and solar electricity.

6. Acknowledgements

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References


PVGIS © European Union, 1995-2013 (visited 2013-12-12)

Indoor environment in four newly build low energy houses in Fairbanks, Alaska

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KEYWORDS: HVAC, Indoor air quality, Cold climates, Residential buildings, CO2 concentration, Ventilation rates

SUMMARY:
In cold climates living inside the heated space requires considerable amounts of heat. With the intention to decrease the heating demand, people are insulating their homes and make them more air tight. With the natural infiltration being brought close to zero there has been an increase of a new problem which is poor indoor air quality (IAQ). During summer 2012 four student homes were built in Fairbanks, Alaska as a part of Sustainable Village project. The aim of this project is to promote sustainable ways of living in the Arctic and to study new technologies and their applicability in the cold north. This paper presents the results of an IAQ survey performed in the homes during two weeks in December 2012. During this survey the air temperature, relative humidity (RH) and CO2 concentration were measured in all occupied bedrooms along with monitoring of the ventilation units. The results have shown noticeable differences in IAQ between the four houses caused by different technical solutions. The ventilation rates were reduced by occupants or by frost protecting strategy of the ventilation units and the RH inside the living space was often very low. It is assumed that by introducing more advanced controls of the HVAC systems, better defrosting strategy and moisture recovery from the exhaust air the IAQ can be improved with minimum extra energy demand.

1. Introduction
Climate in the Arctic regions is cold so living inside the heated space requires quite some energy particularly during the long winters. With the intention to decrease the energy use for heating, people started insulating their homes more and making them more air tight (Kalamees 2007, Pan 2010). Consequently the natural infiltration was limited which led to reduced air change. Insufficient air change causes that the concentrations of various pollutants (including CO2) generated indoors are increasing which may have a negative effect on human performance or even health (Wargocki, Wyon et al. 2000, Seppanen, Fisk et al. 1999). CO2 it is often used as an indicator of IAQ. According to EN 15251 (Dansk Standard 2007) new buildings should have the indoor CO2 concentration lower than 500 ppm above outdoors. ASTM Standard D6245 suggests CO2 concentrations lower than 650 ppm above outdoors. ASHRAE 62.1 (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2004) recommends 700 ppm above outdoors as an upper limit.

Another indoor environmental challenge in cold climates is humidity. In poorly ventilated buildings the moisture generated indoors may be too high for a poor air change which leads to high indoor humidity and may cause mold growth and house dust mite infestation (Pirhonen, Nevalainen et al. 1996, Emenius, Korsgaard et al. 2000). On the other hand proper air change in such dry climate often leads to extremely low indoor humidity which affects the comfort of the occupants as well (Reinikainen, Jaakkola et al. 1992).
To cope with risk of poor IAQ, ventilation systems were introduced to buildings. These systems can provide the buildings with required air change in more energy efficient way as they allow use of heat exchangers (HEs). Some HEs also allow the moisture recovery which may help to solve the low humidity issue, but the reliability and hygienic safety is considerable. In the cold and dry outdoor climate in HEs condensation and subsequent frost formation may arise and eventually put the entire system out of order. Preheating of supply air may be applied to cope with this issue; however, such solution is in cold climate with long winters very energy demanding. Alternatively, smarter heat recovery units may be used like the one used in Low Energy House in Sisimiut, Greenland (Vladykova, Rode et al. 2012).

1.1 Sustainable Village

In summer 2012 four student homes were built in Fairbanks, Alaska as a part of Sustainable Village (SV) project. The project was funded by University of Alaska Fairbanks (UAF) and contracted with Cold Climate Housing Research Center (CCHRC). The aim of this project is to promote sustainable ways of living in the Arctic and to study new technologies and their applicability in the cold north (Cold Climate Housing Research Center ). Different energy efficient technologies were combined to create unique but still affordable homes. The homes have similar layouts and each of the homes accommodates 4 students; however they differ in used technologies. There are two types of heating systems used in SV: I) hydronic floor heating and II) unique forced air heating which combines delivery of heat and fresh air BrHEAThe in combination with a standalone heater (Cold Climate Housing Research Center ). Three types of ventilation units were installed: I) Zehnder ComfoAir 350. This unit uses counter flow flat plate HE with an 800 W electric pre-heater to protect the HE from freezing. If the preheating is not sufficient (the outside air is too cold) the unit reduces the supply flow rate which puts the house into slight underpressure. II) Venmar EKO 1.5 HRV. The HE in this unit is a flat plate cross flow type. Unlike the Zehnder, Venmar units use recirculation cycle as a frost protection strategy. During recirculation cycle, the unit blocks the fresh air supply and exhaust and recirculates the air inside the house. III) Venmar EKO 1.5 ERV. The only difference from the HRV version is the type of HE. This unit uses cross flow flat plate energy exchanger which apart from heat also allows moisture recovery. Configuration of the homes is shown in Table 1.

Table 1. Description of the homes and systems

<table>
<thead>
<tr>
<th>House:</th>
<th>Birch House</th>
<th>Tamarack House</th>
<th>Spruce House</th>
<th>Willow House</th>
</tr>
</thead>
<tbody>
<tr>
<td>North - West</td>
<td>BrHEAThe +</td>
<td>Hydronic floor</td>
<td>BrHEAThe +</td>
<td>Hydronic floor</td>
</tr>
<tr>
<td></td>
<td>pellet stove</td>
<td>heating</td>
<td>Steffes heater</td>
<td>heating</td>
</tr>
<tr>
<td>North - East</td>
<td>Zehnder ComfoAir 350</td>
<td>Venmar EKO 1.5</td>
<td>Venmar EKO 1.5</td>
<td>Venmar EKO 1.5</td>
</tr>
<tr>
<td></td>
<td>Reception</td>
<td>HRV</td>
<td>HRV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electric preheating +</td>
<td>Recirculation</td>
<td>Recirculation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Supply air flow reduction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The overall energy performance of each house is being continuously monitored by the CCHRC and UAF. Additional to the CCHRC and UAF monitoring there was a survey of (IAQ) performed in the homes during two weeks in December 2012. During this survey the air temperature, relative humidity (RH) and CO₂ concentration were measured in all occupied bedrooms. Additionally the temperature in all four connections to the ventilation units was measured. This paper presents the results of this survey which goal was to identify any possible issues with IAQ especially in relation to different ventilation units installed in the houses and to evaluate the performance of these units.
2. Methods

The survey was performed over the course of three weeks in December 2012. Due to the malfunction of the ventilation unit in the Tamarack house during the last week of measurements only the data obtained during the first two weeks were used for IAQ analysis. During this period the Tamarack, Birch and Willow houses had been fully occupied by 4 people whereas the Spruce house was only occupied by 3 persons. Therefore only 3 bedrooms were monitored in the Spruce house. The variables monitored and the equipment used are described below.

2.1 Air flows

The fresh air intake into the houses was measured by means of The Energy Conservatory Exhaust Fan Flow Meter (TECEFM) at the beginning of the survey. Before the measurements the ventilation units were balanced it can therefore be assumed that supply and exhaust air flows are equal. The measured values were compared with the requirements given by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2004) and BEES (Alaska Housing Finance Corporation. Research Information Center 2002).

2.2 IAQ

Onset HOBO loggers U12 were used to measure air temperature and RH inside the houses. The logging frequency was set to 2.5 min. The HOBO loggers were combined with CO₂ sensors Vaisala with a range of 0 – 5000 ppm. The sensors were placed far from the bed so the measurements were not affected by being too close to the breathing zone of a sleeping person and far from the air inlets.

With the outdoor CO₂ concentration in Fairbanks 400 ppm, the recommended indoor concentration according to ASTM Standard D6245 is 1050 ppm, according to ASHRAE 62.1 (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2004) 1100 ppm and according to EN 15251 (Dansk Standard 2007) 900 ppm. Because the occupied period is of main concern, night only (10 p.m. – 8 a.m.) concentrations were taken into account when evaluating the CO₂.

The indoor humidity and temperature were evaluated for the entire measurement period as they do not only affect the comfort of the occupants, but also have effects on the eventual mould growth and overall heat loss (higher indoor temperature = higher transmission heat loss).

2.3 Ventilation units

The temperatures of all four air streams connected to the ventilation units were measured by temperature sensors TMC6-HD from Onset connected to HOBO loggers U12. In houses with BrHEAT the system, the temperature of the air right after the heater was also measured to identify the periods when the heater was on. The sensible heat efficiency of the heat exchangers for the periods with fresh air supply (no recirculation) was calculated according to (Eq.1.)

\[ \varepsilon = \frac{T_{sa} - T_{fa}}{T_{ra} - T_{fa}} \times 100 \, [%] \]  

Where \( T_{sa} \) is temperature of the supply air to the house (K), \( T_{fa} \) is temperature of the cold fresh air (K), and \( T_{ra} \) is temperature of the return air from the house (K).
3. Results

3.1 Air flows

The measurements showed that three homes would fulfill the local ventilation requirements under normal operation of their ventilation system; however their actual air change was reduced by either occupants or frost protecting strategy. FIG 1 shows the correlation between the actual ventilation rate and amount of night time when the CO₂ concentration in bedrooms was above 1100 ppm.

![Graph showing correlation between ventilation rate and CO₂ concentration in bedrooms](image)

3.2 IAQ

The night CO₂ concentrations in each home along with the limits recommended by European and American standards are shown in FIG 2.

![Graph showing cumulative percentage distribution of CO₂ concentrations in bedrooms](image)
Relative humidity measured in the bedrooms is shown in FIG 3. From there it is seen that the house with lowest air exchange (Willow) has the highest relative humidity. However the house with the highest air exchange (Tamarack) does not have the lowest relative humidity possibly as a result of the moisture recovery potential of the heat exchanger.

FIG 3. Relative humidity in all occupied bedrooms within the Sustainable Village (the X and values in the boxes are arithmetic averages)

The average temperature in most bedrooms was within the range 21.5 – 31.0 °C suggested by the Harbin study (Wang, Wang et al. 2003) to satisfy 80% of occupants. However according to the interviews with the occupants the large temperature swings leading to occasional overheating in Spruce and Birch house have caused some discomfort.

FIG 4. Temperature distribution in bedrooms. The boxes describe the lower and upper quartiles, the bands inside the boxes are medians, X and values in the boxes are mean values and the ends of the whiskers represent 1st and 99th percentiles.
3.3 Ventilation units

3.3.1 Venmar HRV
The average sensible heat efficiencies of the heat exchangers were 70.7 % and 76.6 %. The hot air heater used for heating of Spruce house does not have a modulating heat output meaning that there is either 0 or 5 kW of heat being introduced to the air stream which causes large fluctuations in temperature of the air delivered to the rooms and consequently fluctuations in room temperatures. In average the heater turned on and off 14 times a day and was on for 58% of the time.

3.3.2 Venmar ERV
The average sensible heat efficiency of the heat exchanger when the unit was in air exchange mode was 76.5 %. The moisture recovery rate was not measured.

3.3.3 Zehnder
The average sensible heat efficiency of the heat exchanger was 71.7 % when measured after the electric preheater. The combination of 100% air exchange with no recirculation, hot air heating and no moisture recovery or humidification made the Spruce house the house with lowest indoor humidity, but also considerably low CO$_2$ concentration.

The hot air heater was on for 60% of the time and in average turned on and off 19 times every day.

4. Discussion

4.1 Air flows
In case of Birch house the low ventilation rate was due to low fan speed selected on the control panel by the users which can be fixed by reprogramming the controller of the unit in a way that it runs on higher speed. The ventilation rates in the other three houses were reduced significantly either by a) defrosting of the heat exchangers or b) by users selecting the recirculation mode manually on the control panel (one of the unit’s operation modes is “20 min/h” in which the unit supplies fresh air for 20 minutes and then recirculates for 40 minutes). Reduced air change led to increased concentrations of indoor pollutants (such as CO$_2$). Possible solution for the homes where the Venmar units are installed could be an increase of the ventilation rate during periods when defrosting is active so that the reduced air change would be high enough to meet the requirement. To avoid unnecessary increase of the heat consumption, the increase of ventilation rates in all homes should only take place during occupied hours.

4.2 IAQ
The lowest CO$_2$ concentrations were measured in the Tamarack house which has the highest ventilation rate. Even that is however lower than recommended (due to defrosting) which can be the reason that in average 25 % of a night time the CO$_2$ concentration was above 1100 ppm recommended by ASHRAE. We believe that adjusting the ventilation systems to provide the required ventilation rates will help to eliminate the problems with elevated CO$_2$ concentrations. However the occupant’s interaction with the systems can significantly affect the final results. Increasing the ventilation rates will increase the heating demand of the houses considerably. Variable air flow systems should be considered for the future projects to achieve good indoor air quality and lower energy use.

The occupants of the Birch house have been complaining about low humidity which according to the measurements is the lowest from all four houses (86% of the time below 25% RH). This house has the second largest air exchange and does not have moisture recovery which in combination with the hot
air heating gives a cause to such a low humidity. It can be expected that increasing the air flows up to a required levels will decrease the humidity even more. Moisture recovery, as demonstrated in the Tamarack house seems to have a potential for maintaining higher RH and thanks to the mass transfer potentially having higher energy recovery efficiency (this however needs to be further investigated). Air humidification or indoor plants may also help to solve the problem with too low humidity, but on the other hand may be very energy demanding and introduce new challenges such as mold growth. Bedroom temperatures varied more in homes with hot air heating than in homes with floor heating which led to discomfort in occupants. The reason for such variation is that the hot air heaters do not have modulating power output and are controlled by a thermostat placed in a reference room (corridor). Therefore there are periods when the heat is delivered to bedrooms even though they do not need it and vice versa.

4.3 Ventilation units

The efficiency of the heat exchangers was in a range from 70.7 % to 76.6 % which is comparable to 68 % found in experimental heat exchanger in LEH Sisimiut (Vladykova, Rode et al. 2012). Increasing the air flows to meet the required air change might however cause that the efficiency will change. The effect of frequent switching of the hot air heaters in BrHEAThe systems on a lifetime of the device is considerable. Modulating the power output of the air heaters would have a positive effect on the temperature fluctuations inside the houses as well as on the switching frequency. Better control (possibly demand based) of the air flows would mean that the rooms would be ventilated sufficiently during all the time. Such control may bring energy savings and improve the air quality at the same time as the air flow will be reduced during unoccupied periods.

5. Conclusions

The houses in sustainable village are a great presentation of various ventilation systems and demonstrate quite well how important is the proper ventilation for healthy and sustainable homes. The measurements showed that there are significant differences in IAQ in the four houses. These are partially attributable to variations in HVAC systems and occupant interactions with these systems. The ventilation rate, even though it fulfills the ASHRAE standard requirements under standard operation, gets reduced either by the occupants or by the frost protecting strategy (recirculation). With the ventilation rate too low, the concentration of CO₂ along with other pollutants increases which may have an effect on comfort and performance of the occupants. In order to meet the requirements also during the Arctic winters system refinements and occupant education is recommendable. Higher ventilation rate brings another issue which is too low humidity. To deal with this phenomenon moisture recovery proved to be efficient and despite being considered as incapable of working in our climate showed some good promise.

Zoning which would allow occupants to set their own room temperature would increase the comfort and could also decrease the heat demand thanks to set backs during unoccupied and night hours. Unfortunately zoning in hot air heating requires great deal of research and development before it is introduced to highly energy efficient residential buildings.

6. Acknowledgements

This study was generously supported by the Otto Mønsted and Idella foundation. Undertaking this study was only possible thanks to great collaboration with CCHRC and UAF. We would like to thank the occupants of the homes for their patient collaboration.
References


Low-energy mechanical ventilation: a case study of two new office buildings

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KEYWORDS: Mechanical ventilation, low-energy, ventilation, indoor climate, specific fan power

SUMMARY:
In 2010 an internationally renowned company initiated an architectural competition for two new office buildings to be constructed in Denmark. The design objectives were to construct a sustainable office building according to Danish low energy class 2015, with a good indoor climate and with as little energy consumption as 41.1 kWh/m²/year including heating and all building services with no use of renewable energy such as PV-cells or solar heating. One of the key means of reaching the objectives was to implement mechanical ventilation with low pressure loss and therefore low energy consumption. The project consists of two buildings, building one is 6 stories high, and building two is 4 stories high. The buildings have a gross area of 50,500 m² including underground parking. The ventilation and indoor climate concept was to use mechanical ventilation together with mechanical cooling and fan-assisted natural ventilation for free night cooling, hence minimizing the energy consumption for cooling. The paper describes the initial ventilation requirements and the implemented ventilation system. The specific fan power, SFP, with maximum air flow rate was measured to be 0.9 kJ/m³ to 1.2 kJ/m³, with an average of 1.1 kJ/m³. The yearly mean SFP based on estimated runtime is approx. 0.8 kJ/m³. The case shows the un-locked potential that lies within mechanical ventilation for near-zero energy consuming buildings.

1. Introduction

Mechanical ventilation has been the most widely used principle of ventilation over the past 50 years, but building services, including ventilation, represents a growing share of the total energy consumption. In the EU, HVAC systems accounts for 48% of the building sector energy consumption (Perez-Lombard et al. 2008) and, of this, fans accounts for 15-50 % depending on the type and design of the system (Wouters et al. 2001, Perez-Lombard et al. 2011). To bridge the widening gap between the demand for fossil fuel reductions and the demand for improved indoor climate, other principles of natural and hybrid ventilation systems have emerged (Delsante 2002), intended to reduce the energy consumption for ventilation, specifically the power consumption of fans in mechanical systems. However, these alternative systems have many other flaws, e.g. ventilation heat losses, uncontrollable ventilation air supply and high risk of draught (Hviid 2010).

Meanwhile, little has been done to improve the performance of mechanical ventilation systems. The specific fan power (SFP), which expresses the ratio of power consumption to air flow rate of the ventilation system, is far from optimal. Terkildsen (2013) quotes four guidelines from the past 15 years that recommend 1.0 kJ/m³, yet data from Hvenegaard (2007), Jagemar (2003), and Nilsson (1995) shows SFP-values of 2.5-3.5 kJ/m³ with newer systems around 2.0-2.5 kJ/m³. Only a few custom-designed systems comply with the guidelines. Berry (2000) reported a custom-made air handling plant with the specific fan power of 0.5 kJ/m³. Hviid & Svendsen (2012) came as low as 0.6 kJ/m³ with a prototype low pressure ventilation system, using custom build liquid-coupled indirect heat exchangers, diffuse ceiling inlets and low pressure dampers. In simulations, Terkildsen &
Svendsen (2013) came as low as 0.33 kJ/m³ with an conventional mechanical ventilation system using different pressure reducing technologies like bypass of heat recovery unit, diffuse ceiling inlets, active electrostatic filtration and optimized pressure/flow control.

The discrepancy between guidelines and practice is mainly due to the industry focus on minimising space for building services, but it is also due to the low innovation focus in the ventilation industry to develop low-pressure solutions. This paper describes the ventilation system and the design process and the energy measurements on the completed system, thereby documenting the feasibility of conventional mechanical ventilation systems for realised low-energy buildings.

2. Design process

The core design team consisting of architects and engineers started from scratch with an integrated design approach where all stakeholders were included before the first lines were drawn. This approach, depicted on FIG 1, formalises the process by setting up initial design goals that are specific and measurable which enables concrete and continuous evaluations throughout the entire construction period. The expectations among the different stakeholders were aligned to match design goals that were sound, economically viable and socially responsible. These design goals formed the sustainability profile which the finalised building had to comply with. The profile was highly transparent and boosted the awareness of the different focus areas which the design team had to contribute to and comply with when the solutions were implemented.

By doing this, the design team was able to adjust the design pro-actively in order to combine the demands of the client with low energy consumption and a highly sustainable profile. The design outcome was a state of art building with indoor climate class I and II according to EN 15251.

The means of achieving low-energy consumption encompassed a few elements: optimised building form, a façade optimised for daylight and sufficiently high insulation level, low energy electrical lighting and low pressure VAV ventilation system. Especially the ventilation was under close review because badly designed ventilation would make it impossible to apply the highest indoor climate class with low overall energy consumption.

It was of particular interest to the client that there was no use of renewable energy sources such as PV-cells or solar heating, and that all solutions were proven and commercially available on the market.

\[\text{FIG 1. Integrated design process}\]
3. Building

The project consists of two buildings, building one is 6 stories high, and building two is 4 stories high. The buildings have a gross area of 50,500 m\(^2\) including underground parking. The ventilation and indoor climate concept was to use i) mechanical mixing ventilation together with mechanical cooling and ii) fan-assisted natural ventilation for free night cooling. In this manner, the energy consumption for cooling was minimised.

The core of each building is an atrium. At the ground floor and first floor the common facilities are located. The rest of the building floors are office spaces mainly along the outer façade. Rooms with none or less daylight requirements, e.g. service rooms, shafts, cafés and meeting rooms, are located between the perimeter spaces and the atrium.

3.1 Ventilation system

**FIG 2. Principle of main building ventilation system; balanced mechanical day time ventilation and night cooling by operable façade windows and exhaust ventilation**

The energy consumption of the ventilation system is related to the ventilation rate, resistance to the airflow, efficiency of the fan and motor, and operation time.

In mechanical systems, the fan power is approx. proportional to the ventilation rate cubed. Consequently, the first step was to minimise the ventilation rate demands, i.e. use low-emission building materials and exploit the fact that passive cooling means were implemented from the very first design phase.

The second step was to minimise flow resistance. This was achieved by planning the optimal duct routing, thus reducing the duct lengths. The central atrium was planned to function as non-ducted extract route. Plant rooms were located centrally. FIG 3 and FIG 4 depict parts of the ventilation routing while FIG 5 is more schematic.

The initial design pressure drop of the duct system was chosen to be maximum 150 Pa as a compromise between keeping the size of the air handling units down while still having an SFP value of 1.1 kJ/m\(^3\) at maximum flow.

The design duct pressure loss was achieved with the following design criteria: Design pressure gradient of <0.4 Pa/m in general with, as additional constraint, maximum airspeed of 5 m/s in the main ducts.
For comparison the rule of thumb recommended by Nilsson (1995) and ASHRAE (2007) is 1.0 Pa/m; it is 0.8 Pa/m by Schild et al. (2009) while Hvenegaard (2007) accepts 1.5-2.0 Pa/m for systems with moderate operation time (offices).

The latter condition of 5 m/s was imposed because losses in bends and fittings are proportional to the air velocity squared. The break-even point of pressure gradient versus air speed was in this case Ø630 mm.

The air terminals were replaced by diffuse ceiling ventilation (Fan et al. 2013). Air is supplied in the plenum above the acoustic ceiling and distributed through cracks to the room below. The inlet velocity is very low and with no fixed jet direction, hence the term diffuse. The diffuse ceiling, which measured 5 Pa at 100 \% airflow and 1-2 Pa at 30 \% airflow, is employed in the office spaces to reduce the pressure losses of conventional mixing terminals (approx. 30 Pa) and to increase draught-free comfort.

![FIG 3. 3D view of ventilation system in Navisworks](image1)

![FIG 4. 3D view of floor section in Navisworks](image2)

With low-pressure ventilation systems, it is prudent to consider the motor, fan and drive efficiency because it can decrease significantly if the combination of airflow and pressure rise is not near the combinations giving peak efficiency. To avoid oversizing, smaller air handling units were installed in parallel two and two. At low load one unit shuts down, thus increasing flexible operation while maintaining fan efficiency. To recover heat, the air handling units were equipped with rotary heat exchangers with an efficiency of 80\% or better.

### 3.2 Passive cooling strategy

The passive cooling strategy is four-legged with leg 1-3 depicted on FIG 2:

1. Automatic façade openings
2. Mechanical supply ventilation from the main air handling units to rooms with no façade and rooms on ground floor (safety reasons)
3. Mechanical exhaust from the atria
4. Cooling of IT-racks by room air

The first three legs of the passive cooling strategy reduced the energy consumption for night cooling considerably, from the initial all mechanical ventilation solution with 1-2 ACH (SFP = 0.5 kJ/m³) to the final hybrid strategy with SFP = 0.11-0.125 kJ/m³.

The fourth leg cools the IT-racks on each floor by simple mechanical exhaust with air supply from adjacent rooms. FIG 5 depicts this as red markings.

This makes it possible to turn off the main ventilation system outside office hours, while still cooling the racks with room temperature air supply. Depending on current building heat demand, the generated heat is either exhausted or distributed to the atrium depending on the current building heat demand which utilises the excess heat in a sensible manner and increases the overall building energy efficiency.

![FIG 5. The ventilation system layout.](image)

4. Results

The design pressure drops of the 19 air handling units with ductwork are 450 Pa to 550 Pa. This is the pressure drop from outdoor air intake to inlet to the office with full design air volume. In comparison, Hvenegaard (2007) reported the mean pressure drop from 100 mechanical ventilation systems in operation to be approx. 1400 Pa.

The energy efficiency, i.e. the specific fan power, is depicted on FIG 6. The figure shows measured values on the finalised installation at maximum flow rate. Systems for night cooling and exhaust systems have very low SFP values because of very short duct routing.
FIG 6. The specific fan power of the different air handling unit at maximum flow rate.

From FIG 6, the yearly mean specific fan power can be derived. SFP_{year} is a key performance indicator which is comparable across buildings and expresses the practical ventilation system efficiency. The results are shown in TABLE 1, however, the runtime can only be estimated at this current stage.

**TABLE 1. Yearly mean specific fan power [SFP_{year}]**

<table>
<thead>
<tr>
<th></th>
<th>Building one</th>
<th>Building two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime ventilation**</td>
<td>0.80 kJ/m³</td>
<td>0.79 kJ/m³</td>
</tr>
<tr>
<td>Night cooling hybrid systems</td>
<td>0.125 kJ/m³</td>
<td>0.11 kJ/m³</td>
</tr>
</tbody>
</table>

* Time and flow weighted average SFP_{year} calculation: \( q_{v1} \times SFP_1 \times t_1 + q_{v2} \times SFP_2 \times t_2 + \ldots / q_{v1} \times t_1 + q_{v2} \times t_2 + \ldots \) where \( q_v \) = air handling unit air flow, \( t \) = runtime and indices 1, 2, ..., n equals mode1, 2, ..., n; as an example mode 1 = 50%, mode 2 = 75% etc.

** Ventilation during office hours, axial fans not included as they operate at night

In TABLE 2 the SFP is weighted by maximum flow rate. These results are not biased by the estimation of runtime, thus they are useful for evaluating the performance of the ventilation system before the final completion of the building.

**TABLE 2. Flow weighted specific fan power of max flow rates [SFP_{max}]**

<table>
<thead>
<tr>
<th></th>
<th>Building one</th>
<th>Building two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime ventilation**</td>
<td>1.08 kJ/m³</td>
<td>1.03 kJ/m³</td>
</tr>
<tr>
<td>Night cooling hybrid systems</td>
<td>0.15 kJ/m³</td>
<td>0.14 kJ/m³</td>
</tr>
</tbody>
</table>

* Flow weighted SFP_{max} calculation: \((q_{v1} \times SFP_1 + q_{v2} \times SFP_1 + \ldots) / (q_{v1} + q_{v2} + \ldots)\) where \( q_v \) = air handling unit air flow and indices 1, 2, ..., n equals mode1, 2, ..., n; as an example mode 1 = 50%, mode 2 = 75%.

** Ventilation during office hours, axial fans not included as they operate at night
4.1 Energy consumption

The total calculated primary energy demand is 40.5 kWh/m²/year for the two office buildings.

Allowed primary energy demand is 41.1 kWh/m²/year according to the Danish building code low-energy class 2015. The main thermal properties of the building envelope are listed in TABLE 3.

The distribution of the energy demand is depicted on FIG 7. It shows that the fans consume 23% of the total energy consumption.

<table>
<thead>
<tr>
<th>Component</th>
<th>U-value</th>
<th>g-value</th>
<th>Visual transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curtain wall facade</td>
<td>Total 0.65 W/m²K</td>
<td>g = 0.51</td>
<td>71%</td>
</tr>
<tr>
<td>-glazing to floor ratio 30 %</td>
<td>Opaque = 0.15 W/m²K</td>
<td>and ext. solar shading</td>
<td></td>
</tr>
<tr>
<td>-glazing to façade ratio 60 %</td>
<td>Transparent = 0.8 W/m²K</td>
<td>shading</td>
<td></td>
</tr>
<tr>
<td>Atria skylight: triple layer glazing</td>
<td>1.0 W/m²K</td>
<td>g = 0.27</td>
<td>60%</td>
</tr>
<tr>
<td>Roof</td>
<td>0.10 W/m²K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement walls</td>
<td>0.15 W/m²K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement floor slap</td>
<td>0.10 W/m²K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIG 7. Primary energy demand in % - Total energy demand 41 kWh/m²/year with no renewables.

5. Conclusion

The market for energy-efficient ventilation focuses on natural and hybrid solutions, leaving mechanical ventilation side-lined with a reputation of being energy-consuming and noisy. This paper shows a case where the design of conventional mechanical ventilation systems:

- was managed by a team of engineers, architects and contractors that understood their common goals, and agreed and adhered to a shared design process
- followed existing guidelines with some additional pressure-reducing technologies like diffuse ceilings and parallel air handling units
- was measured to be very energy efficient with an all units average SFP value of 1.0-1.1 kJ/m³ (0.8 kJ/m³ at yearly average airflow) compared to the Danish building code maximum allowed
SFP of 2.1 kJ/m³. The energy use in this case is higher than custom best practice research systems with SFP as low as 0.6 and 0.33 kJ/m³, but if these research systems were scaled to the same size as these buildings (one building has max. airflow approx. 180,000 m³/h), they would take up significantly more building space

- the low pressure ventilation system is likely to be as low noise and it is low energy, resulting in less problems with noise
- low energy ventilation systems can help reduce energy demand in low energy buildings and subsequently reduce or remove the need for renewables. In other instances the reduced energy for ventilation can be “invested” in a less energy efficient layout or more freedom in the architectural expressions

6. Acknowledgements

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References


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KEYWORDS Industrial buildings, energy balance calculation, building simulation, nearly-zero-energy buildings, air tightness, infiltration, energy transport via ground

SUMMARY
After 2020 all buildings in Europe have to be conceived and executed as "nearly-zero-energy buildings". For industrial buildings this poses an enormous challenge as their current energy standards are far behind and little research exists in this field. Due to few experiences the energy performance of industrial buildings is mainly still assessed with the same methods as residential buildings. This research project reviews the applicability of such methods for the industrial building sector using transient building simulation linked with a finite-difference ground model and air-flow network modelling. Required leakage data of typical light steel building components is measured in an air tightness test stand. The focus lies on air infiltration and thermal losses through large concrete slabs.

The main findings were that the current infiltration rating methods do not represent the variety of industrial buildings as inside temperature, building height and leakage distribution are not recognized. For zero-energy buildings it will further be required to introduce a monthly based method for infiltration rating to respect the irregular availability of renewable energy during the year. Further it is shown that vertical slab insulations are more reasonable for large slabs as energy gains by summer overheating can better be stored under the building when no horizontal insulation exists. For large slabs under low heated buildings this storing effect is an important saving potential. It is identified that current ISO standards are often not applicable for assessing industrial buildings.

1. Introduction
The adopted European directive on the energy performance of buildings sets a “nearly-zero-energy standard” for all buildings erected in Europe after 2020 (European Union, 2010). For the residential building sector this seems to be an ambitious but feasible goal as many new dwellings already reach a high energy standard and many lighthouse projects with this standard exist. Office buildings also caught up as many companies appreciate representing them as “green companies”. But for industrial buildings no such high standards were built yet except some special single cases. In matters of energy saving these buildings still lag behind even if they have to meet the nearly-zero-energy requirements as soon as others. Reasons are not only the high pricing pressures in this sector but also a lack of technical solutions and holistic low-energy building concepts.

In the past many European countries did not even distinguish between the energy performance rating of industrial and residential buildings at all. First steps were made in the last years by implementing different requirements, assessment data or usage profiles in the energy rating methods as e.g. in the Méthode de calcul (2012) in France or the DIN V 18599 (2011) in Germany.
In spite of these first steps many parts of energy balance calculation methods are still based on the findings for residential buildings. For office buildings, schools or other similar buildings these methods may partially be applicable. But industrial buildings not only contain of different building components as for example light steel envelopes and dome -or skylights in the roof. They also have a very different building shape (large and flat). And further their usage is completely different as inside temperatures can range between 12 °C and 20 °C (partially with long night and weekend setbacks) and large open sectional doors can have a significant impact on the energy performance as well.

All these aspects have to be respected for future concepts. Especially when buildings shall be supplied by renewable energy it is crucial to know more exactly when which energy demand exists for a building. Thus current international energy balance methods were checked for their application for industrial buildings. Therefore the building simulation package TRNSYS and the air-flow network simulation TRNFLOW were mainly used. The focus of this project was on the air tightness of light steel building envelopes and the thermal losses via large concrete slabs on grade.

2. Air Tightness of Industrial Buildings

The air tightness of a building is important to reduce energy losses caused by infiltration during the heating period. In many European countries the infiltration during the year is calculated according to the static approach in EN ISO 13789 (2008). This method calculates the infiltration by reducing the \( n_{50} \) value with a factor \( e \). It shall reduce the infiltration as the difference pressure during the year is far lower than the 50 Pa generated during a fan pressurization test. This factor \( e \) is based on simulations carried out for residential buildings and can be chosen from a table dependent only on the wind shielding and the number of exposed facades.

Actually the difference pressures and therefore the infiltration depends significantly on other parameters such as building height, shape of the building, leakage distribution and very important the inside temperature (Younes et al., 2011), (University of Wisconsin Madison, 2009). This is neglected completely in EN ISO 13789 (2008), so it can be assumed that the factors obtained in simulations for dwellings do not fit for large industrial buildings.

Further it is clear that the infiltration is not constant during the whole year. Due to buoyancy it considerably depends on the difference temperature between in -and outside which obviously varies between summer and winter. Future zero-energy buildings will surely be supplied by renewable energy, often based on solar energy. As solar energy is not constantly available during the year it is important to know when the energy losses by infiltration and therefore the energy demand occurs.

To check the applicability of the current method for future industrial buildings in simulations, input data describing the leakages of typical industrial buildings is required. This leakage data was measured in a new built tightness test stand.

2.1 Measurements in an Air Tightness Test Stand

In an air tightness test stand joints of standard connections used in typical light steel industrial buildings were measured. In detail the connections at the eaves, the verge, wall and slab and connections to accessories as well as between vapour barriers were analyzed. Figure 1 shows two different test set-ups. On the left side the connection between stapled vapour barriers was measured, on the right the joint between a concrete slab and a trapezoidal light steel wall was analyzed. The specimen had a length of 3 m.

A detailed description of the test stand cannot be given here but figure 2 shows the general set-up principle. The measurement in the test stand basically works like a blower door test of a whole building. A fan blows air into a tight box where the test items with the isolated joint are installed.
By the fan action a difference pressure between inside and outside the box is induced and measured by a manometer. At the same time the air flow into the box is measured by an anemometer. This air flow complies with the flow through the isolated joint between the building components. For every detail at least seven different pressure stages were measured.

**FIG 1. Measurement of the joint between two vapour barriers (left) and between slab and wall (right)**

The measurement results showed a relatively consistent leakage distribution all over the building envelope. Leakages in the roof usually comply with those in the wall which influences the following simulations of air infiltration.

2.2 Simulation of Infiltration in an Air-Flow Network

The leakage data gained in the measurements could now be used for the simulations of air infiltration through the envelope of typical industrial buildings. For this the air-flow network model TRNFLOW was used which allows modelling every single crack of a building based on the measured leakage coefficients and flow exponents from the test stand.

The software TRNFLOW is coupled with the transient building simulation TRNSYS to create an interaction with the building. The simulations were carried out using time steps of 15 minutes. For detailed information about the network model it is referred to (University of Wisconsin Madison, 2009) and (Weber et al., 2003).

Figure 3 and 4 show simulation results for different buildings all having the same $n_{50}$-value of 1.0 h$^{-1}$. For a better interpretation the infiltration is averaged for every month. All results show a clear dependency on the season. Due to stack effects caused by high temperature differences the infiltration is significantly higher in winter than in summer. For the chosen climate (German reference climate: city of Potsdam) the influence of strong winds in March is also visible.

For the simulations $C_p$-values generated by the $C_p$-generator by TNO (Knoll and Phaff) were used. These values required for estimating the pressure difference at the building envelope were chosen for a moderate shielding.
In figure 3 industrial buildings with different building heights and different minimum inside temperatures are compared. A maximum temperature limit during summer was not set as industrial buildings usually do not have cooling devices. The impact of both parameters height and inside temperature on the infiltration is considerable. With an increasing height the wind velocity rises, which causes a higher pressure difference and therefore a higher infiltration. Further the stack effect increases with the building height and causes the same effect.

A buoyancy driven infiltration rise is also caused by a higher inside temperature. The importance of this effect can be seen when summer and winter months are compared. In winter the inside temperature has a clear impact on the infiltration. When the temperature difference disappears in summer, both curves merge again.

Figure 4 shows the influence of the building size. Here a rather small industrial building (1000 m² ground area) is compared to a building with the same length/width ratio and the same height but a larger ground area (10000 m²). The infiltration of the larger building is clearly lower than for the small one. The reason is the different roof/wall ratio and respectively a different leakage distribution. The simulations show that the variations between different industrial buildings are huge and general assumptions for an infiltration are not possible.
Thus the current method according to EN ISO 13789 (2008) does not seem to be appropriate for the assessment of infiltration losses of these diverse industrial buildings.

### 2.3 Losses via Open Doors in Industrial Buildings

In residential buildings and many office buildings the losses via open doors are negligible as doors are small and opening times are short. But for logistic or production buildings the energy losses through open sectional doors can amount for a considerable part of the total energy demand. The higher the insulation standard of a building is, the more important such ventilation losses get. But in current energy balance calculations losses via open doors are not considered. It is of course hard to estimate already during the design stage how long the opening times will be and the user behaviour can surely vary a lot in practice. But for zero-energy building design it will not be possible to neglect it anymore.

To show the influence of this deciding parameter, transient simulations of the air flow through large sectional doors were carried out. For this purpose TRNFLOW was used again considering the air flow with a discharge coefficient according to Dascalaki (1995), (University of Wisconsin Madison, 2009).

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**FIG 5.** Additional energy demand by infiltration via open doors for 1 h opening time per working day

Results for the simulation of a 2000 m² large warehouse, located in Potsdam (Germany) are displayed in figure 5. It shows the additional heating demand during a year (monthly mean values) caused by an open sectional door of 4.80 m x 3.50 m with north orientation. The calculations assume that the door is opened for 1 h per working day distributed into short periods over the whole working shift. The inside temperature of a building is obviously a deciding parameter for the infiltration through an open door. Simulations only represent single sided ventilation. Opening two opposite doors can of course increase the infiltration by draft.
3. Energy losses via ground

Industrial buildings are usually built with a large slab on grade. These slabs can go up to some thousands of square meters, thus it is obvious that the thermal transport under industrial buildings differs significantly from the conditions under small dwellings. For appraising thermal losses via soil in Europe the EN ISO 13370 (2008) is often used for all kinds of buildings. To evaluate its applicability for large slabs on grade, simulations using the type 49 (Solar Energy Laboratory, 2012), a finite-difference model for ground modelling implemented in TRNSYS, were carried out. This transient 3D ground model was also utilized in IEA-Task 34/43 and testing results in comparison with other models were overall good (MCDowell et al., 2009). Figure 6 shows the mean heat flow density through the slab of a small residential building with 20 °C inside temperature averaged per month. The heat flow was once simulated using the finite-difference model interacting with the building simulation model and once calculated according to EN ISO 13370 (2008). For the simulations the fourth year is shown which has an almost steady state.

![Small Dwelling (12 m x 7 m = 84 m²), 20 °C](image)

**FIG 6. Heat flow density acc. to EN ISO 13370 versus transient simulations for a small building**

The insulated slab shows a very good compliance between both models during the heating period. For an uninsulated slab the deviations are bigger, while the simplified EN method is up to 20 % on the safe side. In summer the heat flow is underestimated for both slabs as the EN ISO 13370 does not recognize the overheating of a building during summer in an appropriate way. Storage effects are only recognized by a periodic shift of about 1-2 months. In general the static method seems to be appropriate for such small buildings especially for insulated slabs where storage effects matter less.

Figure 7 shows the mean heat flow density through a large slab under an industrial building having a lower inside temperature of 15 °C. The storage effect in summer is directly visible. For uninsulated slabs or slabs with a vertical footer insulation it is even clearly bigger; in the middle of the slab temperatures of 20 °C and more arise directly under the slab in summer. Until december the mean ground temperature under the slab still exceeds the low room temperature of 15 °C. Due to this energy gains can still be used until the turn of the year. Only in January first losses through the slab occur but they are still less than with a horizontal insulation. Only in March and April the losses through a slab without a horizontal insulation are bigger than with a short footer insulation. Using a horizontal insulation (holohedral or even a horizontal edge insulation) prevents the energy storing in summer. Besides the missing summer overheating protection this causes higher energy losses during the heating period and thus corrupts the total energy performance of a building.
In particular for zero-energy buildings supplied by renewable energy it is important to use the stored energy in months with few solar radiation (November – February). In March and April the higher losses by an only vertically insulated slab can easily be balanced by solar energy gains, which are already available in spring. Further a solution without a horizontal insulation saves costs and avoids design problems due to high loads on industrial buildings slabs.

4. Conclusions

The comparison of building simulations for industrial buildings with current appraisal methods showed that there are still lacks in their applicability to future low-energy industrial buildings. For a reasonable infiltration analysis the current static method is not sufficient. The infiltration should at least be determined dependent on the building height and the inside temperature. Further it should be based on monthly values and not averaged for the whole year. Moreover the infiltration losses via large open doors should be recognized in production and logistic buildings as it will not be possible to neglect these losses in future zero-energy building concepts.

In addition it was shown that horizontal insulations under large slabs can prevent storing energy from summer in the ground. Therefore vertical insulations seem to be the best solution for large industrial buildings. Unfortunately the thereby caused high U-values are partially not allowed by national energy balance regulations. For energy saving reasons this should be changed in the future. Further the possibility to use transient building simulation software for official energy performance certificates instead of static methods would be desirable. This would allow respecting the various parameters of industrial buildings better even if no universally valid methods yet exist.

5. Acknowledgements

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Experimental investigations of heat transfer in Thermo Active Building Systems in combination with suspended ceilings

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KEYWORDS: Thermo active building systems, suspended ceilings, heat capacity

SUMMARY:
Thermo Active Building Systems (TABS), described as radiant heating or cooling systems with pipes embedded in the building structure, represent a sustainable alternative to replace conventional systems by using source temperatures close to room temperatures. The use of suspended ceiling in office buildings to cover acoustic requirements hinders the use of TABS. To measure the reduction of the heat capacity, several experiments are performed in a room equipped with TABS in the upper deck and mixing ventilation. The heat transfer is measured for different suspended ceiling covering percentages, occupancy scenarios and ventilation rates. The gained results indicate that the heat capacity coefficient of the ceiling surface is reduced by around 30% when the suspended ceiling covering is 70% of the total ceiling area, and 45% when the covering area is up to 87%. The results also demonstrate that the ventilation rate has a high influence on the convective heat capacity. When the ventilation rate is increased from 1.7 h\(^{-1}\) to 2.9 h\(^{-1}\), the heat transfer coefficient increases up to 16% for the same occupancy and suspended ceiling layout.

1. Introduction

Global energy-related CO\(_2\) emissions from human activities have continuously increased over the past years. Buildings account for around 32% of the total energy consumption of the countries members of the IEA, and it is in the provision of heating, cooling and ventilation where most of the energy is consumed (International Energy Agency 2013). Therefore the building sector must address the reduction of economic and environmental costs of energy used by means of technology developments, market strategies and government policies.

In this context, Thermo Active Building Systems (TABS), commonly described as radiant systems with pipes embedded in the building structure, recently appeared as a new alternative to cool or heat a space. The main difference with other radiant systems is that they benefit from the thermal storage capacity of the building structure. Due to the heat absorption of the thermal mass, the energy is stored and released over an extended period of time reducing the peak loads and temperature fluctuations.

These systems have been successfully implemented in mainly multi-storey office buildings where the benefits of the energy storage can be distributed from storey to storey (Schmidt 2004). Frequently office buildings require the installation of suspended ceilings to cover the acoustics requirements. However, the fulfillment of these requirements compromises the thermal performance of TABS by impeding the convective and radiant heat to be transferred to the space.
Previous researches have investigated the cooling capacity of TABS when the suspended ceiling is either totally or partially covered with acoustic ceilings. Contrary to what was expected, the results of the study performed by E. Pitarello (2008) shows that it is feasible to combine both techniques and still fulfil thermal and acoustic requirements. As a matter of fact, it was discovered that when covering up to 80% of the ceiling, the cooling capacity was only lowered by around 25-30%.

Another study performed by H. Peperkamp and M. Vercammen (2009) investigates the cooling capacity reduction in relation with the covering percentage and the sound absorption of suspended ceilings. The study concludes that there is no noticeable reduction in the average sound absorption of the 500Hz to 4Hz band when the covering area is reduced from 100% to 80%.

The same embedded pipes can be used for both heating and cooling scenarios but until now, only cooling scenarios have been investigated in detail. Therefore this work investigates the heat transfer from heated ceilings for different suspended ceiling covering percentages and different occupancy scenarios.

2. Experimental Methods

2.1 Test facility

The experiments took place in a thermo active test facility with an internal area 21.6 m². The test facility includes a room surrounded by a thermal guard to control the outside conditions of the room. FIG 1 shows the exact geometry of the room and its surrounded guard.

![Guard](image)

**FIG 1. Front and plan view of the test facility with its corresponding dimensions**

The upper deck consists of prefabricate hollow concrete slabs with integrated PEX pipes, that contains water at the desired flow rate. The height of the deck is 270 mm and the diameter of the pipes is 20 mm, positioned at 50 mm from the bottom of the deck as displayed in FIG 2.
During the investigations the temperature of the guard was set to be the same as the room temperature so that adiabatic conditions could be applied to room, walls and floor.

### 2.2 Suspended ceiling

A suspended ceiling was installed in the test facility at a height of 2.7 m from the floor. It consisted of 600x600x15 mm mineral wool tiles mounted on wooden beams. Three main suspended ceiling layouts were implemented varying in covering percentage (87%, 70% and 53%) as shown in FIG 3.

![FIG 3. 87%, 70% and 53% suspended ceiling covering layouts](image)

### 2.3 Equipment

A flow unit was used to provide the required supply water temperature at a constant flow (0.1 kg/s) to the upper deck pipes. A flow meter “Danfoss Mass 1100, DN10” measured the mass flow in the upper deck as an analog signal in the range of 0-20mA corresponding to 0-720kg/h.

In order to ensure the circulation of air at the desired temperature, two fans were positioned inside the guard. The temperature of the guard is controlled by a power controller with a 0-10V signal in order to obtain the desired conditions outside the room; in this case, adiabatic conditions were simulated.
A cooling coil was used to provide ventilation to the room. The temperature was controlled with a PID control system. The air was supplied to the room by a LCA ceiling diffuser.

Concerning internal loads, a double person office was simulated, by using two black barrels as dummies (100 W each), two desktop computers in stand-by mode (68 W each) and two lamps (36 W each) hanging 0.9 m from the upper deck. The total heat load during occupied hours was 18.84 W/m².

A LabVIEW application was used to measure and control the data collected by an Agilent 34970A data acquisition unit (data logger). Type TT (Copper/constantan) thermocouples measured absolute temperatures through a build-in function in the data logger, while thermopiles made of either three or five serially connected thermocouples measured temperature differences.

A micromanometer from Furness Controls model FCO510 measured the pressure drop across an orifice from Fläkt model EHBA-012-1 in the supply and exhaust ducts.

2.4 Measurements

The same temperature sensors were used during all the measurement series. Some of the sensors were placed during the construction process so that it was possible to measure the temperature of the concrete deck and the guard, as well as the fluid temperature. Surface- and air temperatures were measured in several locations in the occupied area and the plenum.

Steady state conditions were used during all the experiments. The heating investigations consisted of two series (series “a” and series “b”) of 8 experiments each. Both series were identical except from the fan speed, and therefore the air flow supplied to the room. Experiments number 1a to 8a corresponded to a low ventilation rate (1.7 ± 0.1 h⁻¹) while experiments number 1b to 8b corresponded to a high ventilation rate (2.9 ± 0.1 h⁻¹).

The defined ceiling covering percentages (87%, 70% and 53%) and a non covered layout were tested as well as occupancy/ non-occupancy scenarios.

Each experiment lasted a minimum of 4 days in order to ensure steady state conditions. The data was measured within intervals of 30 seconds and the average of the data collected the last 12 hours of experiment was used for the heat capacity calculations.

2.5 Heat transfer

Energy balance of the deck is assumed. The flows composing the energy balance of the upper deck are defined in Eq. (1)

\[ q_{\text{fluid}} = q_{\text{down}} + q_{\text{up}} + q_{\text{guard}} \]  

Where  
- \( q_{\text{fluid}} \) heat flow between the pipes and the deck (W/m²)  
- \( q_{\text{down}} \) heat flow through the ceiling surface (W/m²)  
- \( q_{\text{up}} \) heat flow through the floor (W/m²)  
- \( q_{\text{guard}} \) heat losses through the sides of the deck (W/m²)

The sides of the decks are insulated to minimized heat loss to the thermal guard, \( q_{\text{guard}} \). This heat loss has been measured in previous studies demonstrating that it only accounts for around 2-3% of the total heat flows (Weitzmann 2004). In the current investigation, \( q_{\text{guard}} \) is thus neglected.

To obtain the heat flow through the ceiling surface of the upper deck, it is necessary to analyze first the heat flow through the floor and the heat flow between the pipes and the deck.

Temperature sensors located across the plywood layer used as floor covering make possible to calculate \( q_{\text{up}} \) through Eq. (2).
\[ q_{up} = \frac{1}{R_{floor\ covering}} \cdot \Delta T_{floor\ covering} \]  

Where  
\[ R_{floor\ covering} \] thermal resistance of the floor covering (m²K/W)  
\[ \Delta T_{floor\ covering} \] temperature difference across the floor covering (K)

The heat flow from the fluid to the deck can be calculated by multiplying the properties of the fluid and the temperature difference between supply and return as shown in Eq. (3).

\[ q_{fluid} = \frac{m \cdot C_p \cdot (T_{return} - T_{supply})}{A_{deck}} \]  

Where  
\[ m \] fluid mass flow rate (kg/s)  
\[ C_p \] fluid heat capacity (J/kgK)  
\[ T_{return} \] fluid return temperature (K)  
\[ T_{supply} \] fluid supply temperature (K)  
\[ A_{deck} \] area of the deck (m²)

The heat flow through the ceiling surface can be found through Eq. (1), (2) and (3), as simplified in Eq. (4).

\[ q_{down} = q_{fluid} - q_{up} \]  

Eq. (5) is used to calculate the heat capacity coefficient trough the upper deck.

\[ U_{hc} = \frac{q_{down}}{(T_{fluid} - T_{room})} \]  

Where  
\[ U_{hc} \] heat capacity coefficient through the ceiling (W/m²K)  
\[ T_{fluid} \] average temperature of the fluid (K)  
\[ T_{room} \] room temperature (K)

The thermal capacity of a heated ceiling can also be expressed as the ratio of heat flow through the ceiling to the temperature difference between the ceiling surface and the room as specified in Eq. (6).  
\[ h_{ceiling} \] is the total heat transfer or heat exchange coefficient of the ceiling surface including radiation and convection.

\[ h_{ceiling} = \frac{q_{down}}{(T_{ceiling\ surface} - T_{room})} \]  

Where  
\[ h_{ceiling} \] heat transfer coefficient of the ceiling (W/m²K)  
\[ T_{ceiling\ surface} \] surface temperature of the deck (K)

For the calculations, the room temperature is considered as the average between air temperature and mean radiant temperature. The temperature of the fluid is the average water temperature between supply and return.
3. Results

The heat flow through the ceiling surface as a function of the temperature difference between the fluid and the room is illustrated in FIG 4. The graph classifies the data according to the setup of the experiment but there is no distinction on whether internal loads are included or not. Two trend-lines are created to distinguish the results; each of the trend-lines corresponds to one series of experiments. For an equal temperature difference between the fluid and the room, the resultant heat flow is in average 2 W/m² larger in the high air flow series than in the low flow ones. The tendency also indicates that the experiments performed without suspended ceilings result in a larger heat flow as function of the temperature difference. And, as expected, the opposite occurs for the layout where 87% of the ceiling area is covered; in this case the results are clearly below their respective trend.

![Graph showing heat flow through the ceiling surface](image)

**FIG 4. Heat flow through the ceiling surface, q\text{down}, as function of the temperature difference between the operative temperature in the room, and the mean fluid temperature in the deck**

FIG 5 combines the results of the heat capacity coefficient calculated based on Eq. 5 as function of the covering percentage and the results of the heat transfer coefficient defined in Eq. 6. In this figure, the experiments conducted with and without occupancy are not sorted since the differences between occupancy- non-occupancy layouts are not in any case larger than 5%. The heat capacity coefficient of the ceiling is reduced by 30% when the suspended ceiling covering rate is 70% of the total ceiling area. The reduction is increased to 55% when the covering rate is up to 87% of the ceiling area. It is also observed that series “a” results into a heat capacity coefficient up to 14% lower than series “b”.

At the same time, the results of the heat transfer coefficient shows a variation between series “a” and series “b” which is up 16% when the ceiling is not covered. The heat transfer coefficient of series “b” for non covered layouts is up to 6.3 W/m²K, whereas the same value for series “a” is 5.3 W/m²K. At the same time, the results for a covering rate of 87% show a heat transfer coefficient of 3.1 W/m²K and 2.7 W/m²K for series “b” and series “a” respectively.
4. Conclusion

This project investigates the heat transfer of thermo active building systems in combination with suspended ceilings. The gained results show that the combination of suspended ceilings and TABS is a real alternative to conventional heating or cooling systems, especially for low energy or passive buildings where the heating and cooling demands are reduced.

The different layouts investigated show that both the covering rate and the ventilation rate have a great influence on the results. Those experiments conducted with a high ventilation rate result in up to a 16% higher heat transfer coefficient between the ceiling surface and the room than the same experiments performed with a low ventilation rate. The ventilation enhances the convective heat transfer between the ceiling surface and the room and therefore it is assumed that the variation between series correspond to an increase on the convective heat transfer coefficient.

Regarding differences between the results obtained in this project and previous investigations, it can be concluded that, as expected, the cooling capacity of the ceiling is higher than the heating capacity. The cooling capacity coefficient is reduced by 30% when using a suspended ceiling covering rate of 80%, whereas the heating capacity coefficient is reduced by the same range when using a covering rate of only 70%. This proves that the decline on the thermal performance is larger in the heating case.

It can be conclude that the thermal performance of TABS in combination with suspended ceilings is still acceptable for covering rates up to 70%. Coverings larger than that will considerably compromise the performance of the systems.
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References


Estimating the input parameters of lumped building thermal models on the basis of standard design values

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KEYWORDS: building simulation, lumped parameters, estimation of input parameters

SUMMARY: This paper focuses on testing whether the input parameters of lumped parameter building thermal models could be estimated in advance on the basis of the known geometry and envelope composition of the building. The study was performed using a virtual test family house insulated in a low-energy standard. Two variants of the house were defined: a light one, made of timber structure, and the a heavier one, made of perforated brick blocks with external insulation. The reference results were calculated using a complex building energy simulation model. Then, simulations using four logical structures of lumped parameter models were conducted. The values of the lumped parameters in these models were estimated on the basis of available information on the test building, i.e. on the basis of basic drawings and known composition of building components. The results achieved on the lumped models were then compared with the reference solution. The results of this study show that input parameters of lumped parameter building thermal models can be estimated in advance only on the basis of standard information on the building.

1. Introduction

This paper deals with lumped parameter thermal models of a building. The lumped parameter thermal models divide building components into a small number of temperature-uniform parts on which heat balance is set. Thus, the lumped parameter models extensively reduce the number of unknown values which in turn considerably increases the speed of calculation. The general goal of such models is to exclude the variables with negligible influence, but at the same time maintain the physical nature of the problem and ensure reasonable accuracy. Since the input parameters to lumped models aggregate several aspects together, their interpretation can be ambiguous.

Lumped parameter thermal building models can be used for various purposes. (Nielsen, 2005) used a simple lumped model to develop a building design tool. (Kämpf, et al., 2007) developed a model which was used for calculations at the district level. (Huijbregts, Z., et al., 2012) used a lumped hygrothermal building model to study the impact of global warming scenarios on museum buildings. (Prívara et al., 2011) used a simple lumped parameter room model to implement an advanced predictive controller of a heating system in a real building.

Model predictive control seems to be one of the most promising real applications of building lumped models. The identified lumped parameter building thermal model could be used to determine optimal set-point trajectories and optimize control of heating and cooling systems. Therefore, tons of literature about lumped building thermal models deal with the issue of applying system identification techniques using measured data. However, installation of sensors is labor-intensive, collection of a sufficient dataset needs some time and measurements cannot be performed in advance. This paper therefore tests whether the input parameters of lumped parameter models could be estimated on the basis of the known geometry and envelope composition of a building.
2. Lumped parameter thermal building models

Buildings are usually composed of:
- external components (walls, roof), all together marked with a lower index “ext”;
- transparent components (windows), marked with a lower index “w”;
- internal components (internal load bearing wall, partitions, ceiling, ground floor), all together marked with a lower index “int”.

As a starting point for the derivation of lumped parameter models, the following “parent” building thermal model is used, see Figure 1. (Hudson and Underwood, 1999) or (Gouda et. al, 2000) introduced similar model structures.

![Model composed of several one-node branches](image)

**FIG. 1: Model composed of several one-node branches**

This model has already been simplified because of the first order description of building components. Parallel paths in this model establish: one state for internal environment, two states for external components (external walls, roof), four states for internal components (partitions, internal load bearing wall, ceiling, floor on the ground) and two fast heat transfer paths representing the windows and ventilation. The model structure reflects the typical building components which have already been introduced. There is one missing, yet important aspect in the parent model. The model does not contain the heat transfer path through the floor on the ground to the external environment.

Lumped parameter models can be understood as even more simplified versions of the parent model depicted in Figure 1. Four lumped models are presented below (see Figure 2 and Figure 3). None of the lumped models decouples radiative and convective parts of heat gains. It corresponds to the very high value of the coupling conductance $K_0$ of the parent model. The internal temperature in the lumped models should be understood as a temperature composed of the internal air temperature and the mean radiant temperature of internal surfaces. Some error can therefore occur in the ventilation heat flow path.

The lumped model which is hereinafter designated as models 4 preserves the topology of external and internal components. The model 2 and the model 3 are reduced version of the model 4. In the model 3, it is assumed that the thermal capacity built in external building components is negligible or easily accessible from the internal node. The model 2 replaces six parallel branches by just two branches and only one of these contains a capacity node. This model could well represent an office room with a glazed façade, i.e. a room where only negligible thermal capacity is built in external building.
components. The model 1 could be seen as a special case of the model 2 with the infinite value of thermal conductance between the internal node and the capacity node.

Heat storage in model 1 is modeled using only one capacitance which is immediately accessible for the purpose of storing the heat gains, i.e. the temperature of internal mass is in equilibrium with the internal temperature. A similar one-node approach can be found in (Burmeister and Keller, 1998) and (Antonopoulos and Koronaki, 1998). The structure of model 2 was used by (Nielsen, 2005) to develop a simple building design tool.

**FIG. 2: Thermal circuit for the model 1 and model 2**

The structure of model 3 was introduced by (Laret, 1981). (EN ISO 13790, 2008) and (EN ISO 13792, 2012) contain the first order analogy of the model 3 (capacity \( C_i \) is neglected). Model 4 logically combines the model 2 and model 3. (Kramer, 2012) used almost identical model structure and found it adequate even for the purpose of simulating heavy weight historical uninsulated buildings. The identical model structure was also presented in (Masy, 2007).

**FIG. 3: Thermal circuit for the model 3 and model 4**

### 3. Case study

#### 3.1 Virtual test house

The virtual test house simulates a new family house corresponding to the low-energy standard. Two distinct variants of the house were defined: a heavier one, made of perforated brick blocks with an external insulation (V1) and a light one, consisting of a timber structure (V2). The detailed description of the house is not given here due to the lack of space. The reference simulation results were calculated using a complex thermal model of the virtual test house (Staněk, 2013). In order to reduce the complexity of the problem, following assumptions were used:

- One zone model was considered.
- Free-floating situation was simulated, i.e. thermal response of the building was driven by climatic conditions only. The simulation used the 2010 real measured data from the weather station in Prague Karlov.
- Air change rate was assumed to be constant during the whole year (0.3 h⁻¹).
• The floor on the ground was assumed to be adiabatic.
• Solar heat gains were calculated in advance using a separate solar model.

3.2 Estimation of input parameters

3.2.1 Standard design values

The transmission thermal conductance of a building component is defined as thermal transmittance multiplied by the corresponding area \((K = UA)\). By way of analogy, thermal capacitance can be calculated as the areal heat capacity multiplied by the corresponding area \((C = \kappa A)\). Table 1 contains the values of basic input parameters for the case of virtual test house.

Table 1: Standard design values

<table>
<thead>
<tr>
<th></th>
<th>(K_{ex}(\text{W/K}))</th>
<th>(K_{in}(\text{W/K}))</th>
<th>(K_{v}(\text{W/K}))</th>
<th>(C_{ex}(\text{J/K}))</th>
<th>(C_{int}(\text{J/K}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>67,7</td>
<td>66,2</td>
<td>39,6</td>
<td>(8,0 \times 10^7)</td>
<td>(7,2 \times 10^7)</td>
</tr>
<tr>
<td>V2</td>
<td>(2,5 \times 10^7)</td>
<td>(2,9 \times 10^7)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2.2 Position of temperature nodes in the parent model

There are some methods for the calculation of connecting conductance between the internal environment and the capacity node in one-node wall models, for details see (Mathews, 1994) and (Gouda, 2002). This case study uses a simpler approach. The proposed method situates the capacity node in the center of capacitance (analogy with the center of gravity). See the example of a two-layer wall depicted in Figure 4, where \(\kappa_1 (\text{J/(m}^2\text{K)})\) denotes the areal thermal capacity of the layer 1, and \(\kappa_2 (\text{J/(m}^2\text{K)})\) denotes the areal thermal capacity of the layer 2. In this case, the center of capacitance is located in the distance \(x_{cap} (\text{m})\) from the internal surface of the wall.

\[
x_{\text{cap}} = \frac{\kappa_1 x_1 + \kappa_2 x_2}{\kappa_1 + \kappa_2}
\]

FIG. 4: Center of capacitance for a two-layer wall with a corresponding thermal network.

3.2.3 Input parameters in lumped models

In simplified models, the input parameters have to be further lumped. In this study, thermal conductances and thermal capacitances acting in parallel are simply summed up. Thermal capacitances are considered as total values without any reductions. Estimated values of input parameters for the first three models are summarized in Table 2. In the model 1, the thermal capacity \(C_i (\text{J/K})\) is assumed to be a sum of contributions from air, furniture, windows, internal building components and external building components. In the model 2, the thermal capacitance \(C_{int} (\text{J/K})\) is assumed to be a sum of conductances which constitute the thermal link between internal temperature node and center of capacitance in a relevant building component of the parent model. In model 3, the thermal
capacitance $C_{\text{ext}}$ (J/K) is assumed to be equal to thermal capacitance $C_{\text{int}}$ from the model 2 and conductance $K_{\text{ext},1}$ is assumed to be equal to $K_{\text{int}}$ from the model 2.

Table 2: Estimated values of input parameters of the models 1,2,3

<table>
<thead>
<tr>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_i$ (J/K)</td>
<td>$K_{\text{int}}$ (W/K)</td>
<td>$C_{\text{int}}$ (J/K)</td>
</tr>
<tr>
<td>V1 $1,53 \times 10^8$</td>
<td>2470</td>
<td>1.52×10³</td>
</tr>
<tr>
<td>V2 $5.37 \times 10^7$</td>
<td>1319</td>
<td>5.27×10³</td>
</tr>
</tbody>
</table>

Estimated values of input parameters for the model 4 are summarized in Table 3. The thermal capacity $C_{\text{ext}}$ (J/K) is assumed to be the contribution from external building components. The thermal capacity $C_{\text{int}}$ (J/K) is assumed to be the contribution from internal building components. Conductances $K_{\text{ext},1}$ and $K_{\text{int}}$ (W/K) are calculated as the sum of conductances between the internal temperature node and the capacity node in a relevant building component of the parent model.

Table 3: Estimated values of input parameters of the model 4

<table>
<thead>
<tr>
<th>$K_{\text{ext},1}$ (W/K)</th>
<th>$K_{\text{int}}$ (W/K)</th>
<th>$C_i$ (J/K)</th>
<th>$C_{\text{int}}$ (J/K)</th>
<th>$C_{\text{ext}}$ (J/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1 715</td>
<td>1758</td>
<td>9.57×10⁵</td>
<td>See Table 1.</td>
<td></td>
</tr>
<tr>
<td>V2 125</td>
<td>1193</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3 Simulation results

The free-floating internal temperature calculated using lumped parameter models was compared with the free-floating internal temperature calculated using the reference numerical model. The reference internal temperature was calculated as the weighted mean from the mean radiant temperature of all surfaces and the internal air temperature. The standard values of convective and radiative heat transfer coefficients were used as weights (3 W/(m²K) and 5 W/(m²K)).

For the sake of clarity, only the time-period between the 180th and 195th day is expressed in figures. Three variants are depicted: the reference course calculated using the reference numerical model (designated as “ref”), the course calculated using the estimated values of input parameters (designated as “estim”), and finally the course calculated using the optimized values of input parameters (designated as “optim”). Optimization process starts from the already estimated values of input parameters and attempts to find the values which are more appropriate. In this study, only thermal conductances have been assumed to be variable. Thermal capacities have been fixed to their total values. Goodness of fit was the objective function to be maximized.

FIG 5: Model 1 – Free-floating temperature.
As seen in Figure 5, the model 1 did not reproduce the daily dynamics correctly. The case calculated using the estimated inputs reached slightly higher values of daily means than in the reference case. Optimization determined the necessary correction of about 22 W/K (see Table 4) and it was similar for all other lumped models. As seen in Figure 6, the model 4 using the estimated values of input parameters resulted in reasonably good estimates of the free-floating temperature in case of the brick house (V1). In case of the wooden house (V2), the daily amplitude was overestimated. The capacity $C_{int}$ was not sufficiently accessible to dampen the internal temperature fluctuation, i.e. the thermal conductance between the internal environment and the capacity node was underestimated. After its optimization, the model 4 showed very good compliance with the reference case. It should be noted that the objective function was found to be very flat (see Figure 7). Rather different parameter sets thus can lead to very similar prediction of the internal temperature. Estimated and optimized values of time constants are summarized in Table 5.

Table 4: Estimated vs. optimized values of parameters of the model 1 and model 4

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{ext}+K_v+K_w$ (W/K)</td>
<td>$K_{ext,1}$ (W/K)</td>
</tr>
<tr>
<td></td>
<td>estimated</td>
<td>optimized</td>
</tr>
<tr>
<td>V1</td>
<td>173,5</td>
<td>196,2</td>
</tr>
<tr>
<td>V2</td>
<td>194,5</td>
<td>125</td>
</tr>
</tbody>
</table>

Table 5: Estimated vs. optimized values of time constants in hours for all models

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Estimated</td>
<td>244</td>
<td>0,10</td>
<td>261,4</td>
</tr>
<tr>
<td></td>
<td>Optimized</td>
<td>216</td>
<td>0,06</td>
<td>226,8</td>
</tr>
<tr>
<td>V2</td>
<td>Estimated</td>
<td>89</td>
<td>0,18</td>
<td>100,1</td>
</tr>
<tr>
<td></td>
<td>Optimized</td>
<td>79</td>
<td>0,07</td>
<td>83,1</td>
</tr>
</tbody>
</table>

FIG 6: Model 4 – Free-floating temperature.

FIG 7: Model 4 – the shape of objective function (conductance $K_w+K_v$ was fixed to optimized value).
4. Discussion

Resulting differences between the reference solution and simplified models could be classified as differences in daily dynamics, differences in long-term dynamics, and systematic differences in annual mean values. The last type of error was common to all simplified models and hopefully was the result of the user uncertainty in modeling.

The values of connecting conductances between the internal environment and capacity nodes are important for good representation of daily dynamics. If the thermal conductance is too low (i.e. accessibility of the thermal capacitance behind conductance is poor), the internal temperature fluctuates too much. Unfortunately, the internal temperature amplitude is extremely sensitive to correct setting of the connecting conductance. The center of capacitance method led to fairly good estimates of accessibility in case of the brick house. This was not the case of the light wooden house, where the accessibility was set too low. Therefore, the evident question is: how could the estimation of thermal conductances between the internal environment and capacity nodes be improved. Another open question is, whether the lumped thermal capacitances should be to some extent reduced. This study was performed on the basis of total values of thermal capacitances. However, at least in case of the wooden insulated house, it is evident that the total value of the thermal capacity is not used to dampen the oscillation of the daily temperature swing.

Model 1 was not able to capture the internal temperature dynamics neither on the basis of estimated values nor after optimization of parameters. The total value of the building thermal capacity made it possible to reproduce longer dynamics, but the values of daily dynamics were reproduced very poorly. However, the daily means in the optimized model 1 were rather accurate. This is an important conclusion, as it means that the energy needs of insulated buildings could be estimated quite accurately and quickly even with this very simple dynamic model. The substantial advantage of the model 1 consists in the fact that the input parameters are standard design values.

5. Conclusions

The structure of all lumped parameter models investigated in this paper was derived from a typical topology of building components. Firstly, a parent thermal model was derived from this topology. Then, four lumped thermal models were derived by further reducing the parent model. The values of parameters in lumped models were estimated as the sum of thermal conductances or capacitances acting in parallel in the parent model. Thermal conductances in lumped models were derived from the position of capacity nodes placed in the parent model. A simple method to estimate the node position was used. Thermal capacitances in lumped models were assumed to be total values without any reductions.

The case study was performed using a virtual test family house insulated in a low-energy standard in free-floating conditions. It was observed that accurate representation of daily swings in the internal temperature is difficult. The daily amplitude of the internal temperature was very sensitive to the correct setting of thermal conductances connecting the internal node and other capacity nodes. It seems that these thermal conductances can only be roughly estimated in advance from drawings. With the exception of the first order model, all other lumped models using the estimated values of input parameters showed good compliance with the reference model (goodness of fit close to 90 %). It is therefore concluded from that the estimation of input parameter values based on the known geometry and envelope composition led to satisfactory results.

There are some open questions relating to future work:

- Under which conditions can the parent model be replaced by a lower-order model without significantly reducing accuracy? Why do simplified lumped models perform well; and under which conditions do they not work so well?
- What is an accurate lumped model of heat transfer through the slab on the ground?
• Which additional parts should be added to a lumped parameter building thermal model in order to accurately describe the HVAC system dynamics?

References


Reliability of meta-modelling in robust low-energy dwelling design

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Staf Roels, Professor

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KEYWORDS: meta-modelling, probabilistic design, reliability

SUMMARY:
In building design, energy demand and life-cycle costs are commonly calculated based on deterministic stationary or dynamic simulations. However, many contributing parameters are inherently uncertain, resulting in potentially unreliable performance predictions. To overcome this, a probabilistic design method is recommended to take uncertainties into account. Such an uncertainty-based optimisation often requires many simulations, making it extremely time-consuming. Here, meta-modelling can be of high interest. A meta-model aims to mimic the original numerical model with a simplified fast model. However, the simplicity of the meta-model - some aspects of the original model are inherently neglected - might affect the reliability of the results. This topic is investigated in this paper by means of a case study of robust cost optimisation of a low-energy dwelling. To maximise calculation efficiency, the meta-model has to be trained on as few samples as possible, taking into account meta-model reliability. Hence, a meta-modelling procedure is proposed and result reliability is investigated for meta-models based on different sample sizes. It is concluded that meta-models can be reliably used in probabilistic design and built with a reasonable sample size.

1. Introduction

Building performance optimisation typically uses deterministic simulations to select the best performing design according to one or more performance indicators, such as energy demand, life-cycle cost, … As many contributing parameters are inherently uncertain, such deterministic optimisation not necessarily leads to the best performing design. Therefore, probabilistic performance optimisation is recommended to take these uncertainties into account. The global framework of probabilistic design is described in section 1.1. Unfortunately, such a probabilistic design often requires significant simulation effort. To reduce calculation time, meta-modelling is of high interest as the original model is replaced by a fast simplified equation-based model, as described in section 1.2.

Because meta-model reliability is essential in probabilistic design, this paper investigates this aspect with a simplified robust cost optimisation of a low-energy dwelling. For that purpose, optimisation is performed on both the original model and several meta-models, differing in sample size.

The case study is described in section 2, the results are shown in section 3. The main observations and recommendations with respect to meta-model reliability are summarised in section 4.

1.1 Probabilistic design

In design problems, contributing input parameters can be divided into three categories. Design parameters, such as the thermal resistance of a wall, the type of ventilation system, … are fully controllable and their values are to be selected. Inherently uncertain parameters, such as the impact of workmanship, the actual ventilation rate value, … are uncontrollable by the designer. Finally, scenario parameters deal with future, for example economic or climate, scenarios. By ascribing these parameter
categories to a different layer in a multi-layered sampling scheme as shown in FIG 1, all design options are subjected to the same uncertainties and a direct comparison for several future scenarios is enabled.

This multi-layered scheme, combined with sampling efficiency and convergence control (Janssen 2013), is proposed in Van Gelder et al. (2014) as a global probabilistic design method. In this method, first all potential design options are chosen with for example a full factorial scheme of the design parameters. Then a small multi-layered scheme is created by independent sampling of both uncertainty and scenario parameters, preferably uniformly filling the probability space. To start the Monte Carlo loop, the first design option and first scenario are selected. The small uncertainty sample is run in the model and enlarged until the desired outputs are converged. After that, the next scenarios are analogously run and more scenarios can be added until convergence of the design options or until all potential scenario values are calculated. Then, one can continue with the next design option. If all design options are converged, the outputs can be evaluated. This methodology requires execution of numerous Monte Carlo simulations, which may easily become computationally (too) expensive. The latter barrier can be overcome by use of meta-models, which mimic the original time-intensive model with a simpler and faster surrogate model.

FIG 1. Probabilistic design method.

1.2 Meta-modelling

1.2.1 General aspects

Meta-models, also known as surrogate models, have the intention to mimic the original model but at a highly reduced calculation time. While for extreme cases, the original model might take days for one simulation, the meta-model only needs a fraction of this calculation time.

FIG 2 shows how to build such a meta-model based on several sample sets in order to enable cross-validation and to control calculation efficiency (Van Gelder et al. 2013b). First, all input parameters need to be sampled in a small scheme and run in the original model. Initially at least two sets are needed: one as training set to build the model, the other as validation set. Then a k-fold cross-validation is performed to control the reliability with validation indicators, which indicate how well the original model is approximated. This means that each sample set is once used as validation set, while the other sets act as training sets, resulting in as many validation indicator values as available sample sets (i.e. k). The coefficient of determination $r^2$, indicating the overall fit, and the maximal absolute error MAE can be used as indicators, among others. Sample sets are added until convergence of the minimal, maximal and average values of the selected validation indicators is satisfactory.
1.2.2 MARS method

In this paper, cubic multivariate adaptive regression splines (MARS) (Friedman 1991, Jekabsons 2011) are used as meta-modelling method because of their good approximation ability and their fast calculation (Van Gelder et al. 2013b). Due to the use of hinge functions, model complexities can be taken into account. MARS models are of the form

$$ y = \sum_{i=1}^{m} c_i B_i(x) $$  

Where 
- $y$ estimated output parameter
- $x$ input parameter vector
- $m$ amount of basis functions $B_i$, which can be a constant, a hinge function or a product of two hinge functions
- $c_i$ weight factors

2. Case study

To exemplify the probabilistic design method and to investigate the meta-model’s reliability, a simplified case study of a semi-detached dwelling is used as shown in FIG 3. The dwelling has a floor area of 140 m², an uninsulated basement and overhangs for sun shading. Several low-energy design options are compared to select the most cost effective and robust option, with a comfortable indoor climate as auxiliary constraint. Therefore, both energy demand and maximal temperature are simulated, and net present costs are calculated afterwards.

2.1 Output parameters

Following the European standard EN ISO 15459, the net present cost of all energy-related dwelling components is calculated over 30 years with a cost-calculation tool developed in research project IWT TETRA BEP 2020 (Verbeeck et al. 2013). The net energy demand is therefore simulated with a building energy simulation (BES) model (see section 2.3), which can be replaced by a meta-model (see section 2.4). Furthermore, the maximal temperatures in the dwelling are simulated with the BES model as well to be able to penalise those design options with a potential overheating risk.

Dwelling owners need confidence in selected design options as they require guaranteed net present costs for their investments in energy efficiency and indoor climate. Ideas from robust design are therefore incorporated by optimising mean performance and minimising spread (Zang et al. 2005).
That way, designs that best resist the uncertain and scenario parameters can be selected. Therefore, effectiveness $\varepsilon$ and robustness $R_p$ indicators were defined and illustrated in previous research (Van Gelder et al. 2013a). For a positive output parameter $y$ to be minimised, the indicators are:

$$
\varepsilon(x) = 1 - \frac{y_{50}(x) - y_{\text{min}}}{y_{50} - y_{\text{min}}}
$$

$$
R_p(x) = 1 - \frac{y_{50,P/2}(x) - y_{50,P/2}(x_n)}{y_{50,P/2} - y_{50,P/2}}
$$

Where $P$ user specified percentage of included sample points

$y_q$ $q^{th}$ percentile of distribution of $y$ under full uncertainty

$y_q(x_n)$ $q^{th}$ percentile of distribution of $y$ after selecting design options $x_n$

$y_{\text{min}}$ simulated minimal $y$ value which is not an outlier, whereby an outlier is defined as a sample point smaller than $y_{75} - 1.5(y_{75} - y_{25})$

Effectiveness $\varepsilon$ thus describes how the deviation between median performance and optimal performance ($y_{\text{min}}$) improves compared to the design under full uncertainty. Robustness $R_p$ is analogously determined as the improvement the performance spread of a design option makes in proportion to the spread under full uncertainty. According to these definitions, a solution with an effectiveness and robustness of one is the best possible, while negative values are to be avoided.

### 2.2 Input parameters

The design parameters considered in this paper are listed in TABLE 1. For each parameter, several

**TABLE 1. Stochastic input parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distribution*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DESIGN</strong></td>
<td></td>
</tr>
<tr>
<td>Infiltration rate at 50 Pa</td>
<td>Dis(0.6, 1, 1.4) /h</td>
</tr>
<tr>
<td>Ventilation system (and heat recovery)</td>
<td>Dis(exhaust, balanced 70% rec., balanced 80% rec.)</td>
</tr>
<tr>
<td>U-value wall</td>
<td>Dis(0.1, 0.15, 0.2, 0.25) W/m²K</td>
</tr>
<tr>
<td>Window type</td>
<td>Dis(1.29 W/m²K &amp; g = 0.631, 1.31 W/m²K &amp; g = 0.551, 0.7 W/m²K &amp; g = 0.407)</td>
</tr>
<tr>
<td>Sunscreen type</td>
<td>Dis(none, 30% transmission)</td>
</tr>
<tr>
<td><strong>SCENARIO</strong></td>
<td></td>
</tr>
<tr>
<td>Nominal energy price evolution</td>
<td>Dis(-1.5 %, 2.3 %, 10 %)</td>
</tr>
<tr>
<td><strong>UNCERTAINTY</strong></td>
<td></td>
</tr>
<tr>
<td>Set temperature occupancy day zone</td>
<td>Nor(21,1.35) °C</td>
</tr>
<tr>
<td>Set temperature absence day zone</td>
<td>Dis(15°C, no reduction)</td>
</tr>
<tr>
<td>Set temperature occupancy night zone</td>
<td>Nor(19,2) °C</td>
</tr>
<tr>
<td>Internal heat gains</td>
<td>Uni(100,500) W</td>
</tr>
<tr>
<td>Air change rate day zone</td>
<td>Wei(0.6576,4.67) /h</td>
</tr>
<tr>
<td>Air change rate night zone</td>
<td>Wei(1.7847,4.67) /h</td>
</tr>
<tr>
<td>Workmanship error infiltration rate</td>
<td>Nor(1,0.1)</td>
</tr>
<tr>
<td>Workmanship error U-value wall</td>
<td>Nor(1,0.1)</td>
</tr>
<tr>
<td>Workmanship error heat recovery</td>
<td>Nor(1,0.1)</td>
</tr>
</tbody>
</table>

* Explanation of the symbols used:

Dis(a,b,c): discrete distribution with equal probability for a, b and c

Uni(a,b): uniform distribution between a and b

Nor(μ,σ): normal distribution with mean value $\mu$ and standard deviation $\sigma$

Wei(λ,k): Weibull distribution with scale factor $\lambda$ and shape factor $k$
low-energy design values are studied. To make probabilistic design with the original model feasible for this paper, calculation time is reduced by selecting only a limited set of design parameters and values. All combinations of these design values result in 216 design options.

As we are interested in the net present costs, the energy price evolution is of major interest. By considering this parameter as a scenario parameter, we are able to study the optimal results for each potential evolution. Three discrete values are considered, as shown in TABLE 1.

The inherently uncertain parameters, also listed in TABLE 1, deal with user behaviour and workmanship. The user behaviour variability is inspired by a measurement campaign of 70 new dwellings in Flanders (Belgium) (Staepels et al. 2013). 100 uncertainty layer values are sampled in sets of 20 with a maximin Latin Hypercube scheme (Husslage et al. 2008). In this case, this is sufficient for convergence as the maximal variation of the studied output percentiles is less than 6%. For simplicity in this paper, every design option and scenario combination is thus subjected to the same 100 samples, resulting in 64,800 simulation combinations.

Note that for clarity, in this case study, many other parameters are considered deterministic, such as occupancy profiles, climate and investment and maintenance costs.

2.3 Dynamic building energy model

The dwelling is modelled with two thermal zones and simulated in a transient BES tool developed in Modelica (Baetens et al. 2012) for the reference climate year of Uccle, Belgium (Van Gelder et al. 2013a). The adjacent dwelling is considered at a constant temperature of 19 °C. To simulate the heat demand, an ideal heating system is assumed, which is controlled using simplified occupancy and temperature profiles. A ventilation system is incorporated in the model with or without heat recovery. In summer, the heating system and heat recovery are switched off. To optimise the summer comfort, temperature of the day zone exceeds the user dependent comfort temperature, the air change rate is doubled for the next six hours or until the occupants leave the dwelling. This algorithm simulates the user behaviour to achieve a comfortable indoor climate.

2.4 Meta-models

Meta-models are built for both heat demand and maximal indoor temperature as described in section 1.2. The discrete distributions of the design parameters are transformed into uniform distributions to make other design options possible as well. All parameters are sampled together and both a sample size of 100 and 20 with up to ten sets of these sample sizes are used to build the models, as shown in FIG 4 and FIG 5. One can see that the model reliability increases with the total number of samples. Out of all presented models, four are selected to study the resulting reliability:

- reference meta-model: this is considered as the reference model as it is based on 10 sets of 100 runs and is the most reliable out of the available models.
- meta-model 1: this model is built and validated on 2 sets of 100 runs and is considered as sufficiently reliable.
- meta-model 2: this model is built and validated on 10 sets of 20 runs, thus containing as many samples as meta-model 1, and the indicators are clearly converged.
- meta-model 3: this model is built and validated on 5 sets of 20 runs and is the model containing the minimal number of samples to create a reliable meta-model according to FIG 4 and FIG 5.

3. Results

As described in section 2, an optimisation is performed of the net present cost effectiveness and robustness. For that purpose, Pareto fronts are calculated. Those design options where the indoor temperature may rise above 28° C are penalised to avoid the risk on overheating. The cumulative
FIG 4. Minimal, average and maximal $r^2$ and MAE cross-validation indicators of the heat demand meta-model for different number of sets and samples.

FIG 5. Minimal, average and maximal $r^2$ and MAE cross-validation indicators of the maximal indoor temperature meta-model for different number of sets and samples.

FIG 6. Cumulative distribution functions for net present cost for all 216 design options (left). Robustness $R_{95}$ and effectiveness $\varepsilon$ of net present cost (right). The design options with an overheating risk are indicated in grey. The Pareto front options are indicated with their design option numbers.

FIG 7. Comparison of outputs reference meta-model and BES model: effectiveness $\varepsilon$ net present cost (left), robustness $R_{95}$ net present cost (middle) and maximal indoor temperature (right). 5% deviation intervals are indicated with grey lines.
TABLE 2. Pareto front design options of dynamic BES model.

<table>
<thead>
<tr>
<th>Design option n°</th>
<th>Infiltration rate at 50 Pa</th>
<th>Ventilation system (and heat recovery)</th>
<th>U-value wall</th>
<th>Window type</th>
<th>Sunscreen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>1.4/h</td>
<td>balanced 80% rec.</td>
<td>0.15 W/m²K</td>
<td>1.29 W/m²K</td>
<td>30% transm.</td>
</tr>
<tr>
<td>187</td>
<td>0.6/h</td>
<td>balanced 80% rec.</td>
<td>0.10 W/m²K</td>
<td>0.7 W/m²K</td>
<td>30% transm.</td>
</tr>
<tr>
<td>188</td>
<td>1/h</td>
<td>balanced 80% rec.</td>
<td>0.10 W/m²K</td>
<td>0.7 W/m²K</td>
<td>30% transm.</td>
</tr>
<tr>
<td>189</td>
<td>1.4/h</td>
<td>balanced 80% rec.</td>
<td>0.10 W/m²K</td>
<td>0.7 W/m²K</td>
<td>30% transm.</td>
</tr>
<tr>
<td>196</td>
<td>0.6/h</td>
<td>balanced 80% rec.</td>
<td>0.15 W/m²K</td>
<td>0.7 W/m²K</td>
<td>30% transm.</td>
</tr>
<tr>
<td>197</td>
<td>1/h</td>
<td>balanced 80% rec.</td>
<td>0.15 W/m²K</td>
<td>0.7 W/m²K</td>
<td>30% transm.</td>
</tr>
<tr>
<td>198</td>
<td>1.4/h</td>
<td>balanced 80% rec.</td>
<td>0.15 W/m²K</td>
<td>0.7 W/m²K</td>
<td>30% transm.</td>
</tr>
<tr>
<td>207</td>
<td>1.4/h</td>
<td>balanced 80% rec.</td>
<td>0.20 W/m²K</td>
<td>0.7 W/m²K</td>
<td>30% transm.</td>
</tr>
</tbody>
</table>

TABLE 3. Comparison effectiveness and robustness indicators of Pareto front design options. Grey italics indicate values which are not in the considered Pareto front.

<table>
<thead>
<tr>
<th>Design option n°</th>
<th>BES model</th>
<th>Reference meta-model</th>
<th>Meta-model 1</th>
<th>Meta-model 2</th>
<th>Meta-model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ε</td>
<td>R95</td>
<td>ε</td>
<td>R95</td>
<td>ε</td>
</tr>
<tr>
<td>126</td>
<td>0.043</td>
<td>0.438</td>
<td>0.051</td>
<td>0.463</td>
<td>0.056</td>
</tr>
<tr>
<td>135</td>
<td>0.038</td>
<td>0.418</td>
<td>0.049</td>
<td>0.445</td>
<td>0.057</td>
</tr>
<tr>
<td>187</td>
<td>-0.171</td>
<td>0.540</td>
<td>-0.179</td>
<td>0.545</td>
<td>-0.176</td>
</tr>
<tr>
<td>188</td>
<td>-0.108</td>
<td>0.528</td>
<td>-0.113</td>
<td>0.536</td>
<td>-0.110</td>
</tr>
<tr>
<td>189</td>
<td>-0.067</td>
<td>0.515</td>
<td>-0.070</td>
<td>0.525</td>
<td>-0.067</td>
</tr>
<tr>
<td>196</td>
<td>-0.084</td>
<td>0.517</td>
<td>-0.089</td>
<td>0.521</td>
<td>-0.087</td>
</tr>
<tr>
<td>197</td>
<td>-0.018</td>
<td>0.505</td>
<td>-0.022</td>
<td>0.511</td>
<td>-0.021</td>
</tr>
<tr>
<td>198</td>
<td>0.025</td>
<td>0.493</td>
<td>0.020</td>
<td>0.501</td>
<td>0.022</td>
</tr>
<tr>
<td>207</td>
<td>0.025</td>
<td>0.467</td>
<td>0.018</td>
<td>0.483</td>
<td>0.023</td>
</tr>
</tbody>
</table>

distribution functions (CDF) of all design options, needed to calculate ε and R95, and the Pareto front options of the BES-model optimisation are shown in FIG 6 and listed in TABLE 2.

When comparing net present cost effectiveness ε and robustness R95 and maximal indoor temperatures between BES model and reference meta-model, slightly deviating values are found, as shown in FIG 7. Although these deviations become slightly larger when fewer samples are used to build the meta-model, very similar Pareto fronts are obtained, as presented in TABLE 3. Only one option (i.e. 135) appears that was not in the original Pareto front. But this design option is very similar to option 126, as only the U-value changes (0.2 W/m²K). On the other hand, options 196 and 207 do not appear in the meta-model Pareto front, but they are almost equal to the other options and are still close to the Pareto front. Note that the optimal ε values are very small due to the fact that most effective solutions result in overheating risks.

Similar observations remain when comparing Pareto fronts per scenario. Those results are not explicitly presented here. When comparing Pareto fronts from meta-models built on fewer samples than meta-model 3, larger deviations are found. Moreover, design options with an overheating potential might be selected as this risk is unreliably detected. FIG 4 and FIG 5 show that these meta-models are indeed less reliable as they have low r² values and large maximal errors.

4. Conclusions

As illustrated in section 3, meta-models can be reliably used in probabilistic design of low-energy dwellings as output distributions and effectiveness and robustness are sufficiently mimicked and very similar Pareto optimal design options are found. This allows performing a generally time-consuming probabilistic design as presented in section 1.1, but now in only a fraction of the original time. The
presented method uses multi-layered schemes to classify parameters by their physical meaning as this enables the comparison of numerous design options and scenarios.

In order to reliably and time efficiently build a meta-model, a model procedure based on replicated sample schemes was proposed in section 1.2. Small schemes are preferred as it is seen that meta-model build on those schemes perform as well as the others, but less samples are needed.

5. Acknowledgements

The authors are very thankful for the funding of the Flemish government and companies for the IWT TETRA BEP2020 project (Verbeeck et al. 2013) and participating inhabitants for the related measurement campaign. Many thanks to Liesbeth Staepels to develop the cost-calculation tool according to the European standard EN ISO 15429. They would like to thank Bart Husslage and Gijs Rennen from the Tilburg University as well for sharing their MATLAB code for calculation of maximin sampling schemes (Husslage et al. 2008).

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The first year’s results from the first passive house in Estonia

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KEYWORDS: nZEB, passive house, hygrothermal performance, indoor climate, overheating.

SUMMARY:
A single-family detached passive house has been designed in cooperation with Austrian architects and built in Estonia. This paper presents and analyzes the thermal comfort and hygrothermal performance of the building envelope of this house during the first year after construction.

Results showed high temperature readings in most of the rooms, achieved mainly due to large windows with southern exposure and the small heat loss of the building envelope. Due to the high indoor temperatures, the relative humidity decreased to quite low levels. Humidity in the externally insulated cross-laminated timber panels was observed to be high, causing condensation and risk for mould development. This was caused by drying out of the constructional moisture and the high diffusion resistance of the wood fiber sheathing board. The indoor humidity loads were high indicating that the design of passive houses indoor humidity loads cannot be decrease. In summary, while planning buildings with high energy efficiency, more focused attention should be paid to the performance of the building service systems and moisture safety already in the preliminary stages of design.

1. Introduction

In the European Union (EU), buildings account for 40% of total energy consumption (2002/91/EC, 2002; 2010/31/EU, 2010). The 2010 EU directive on energy performance of buildings encourages the transition from fossil fuels to renewable energy sources in the building sector and underlines the importance of reducing energy dependency and greenhouse gas emissions in the EU. Europe has adopted an ambitious vision for the energy efficiency of its buildings. By the end of 2018 all new public buildings must meet nearly zero-energy building (nZEB) requirements.

The aforementioned directive describes nZEB-s as buildings with very high energy performance in terms of net energy consumption. The nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, preferably produced on-site or nearby. In line with the EU directive, Estonian new energy performance regulations entered into force on 9.1.2013, establishing primary energy requirements for new and renovated buildings (RT I, 05.09.2012, 2010). The requirements and corresponding energy certificate classes are shown for three building types out of nine in Table 1.
TABLE 1 Energy performance certificate classifications (A-D) and corresponding maximum values of energy performance values (kWh/(m²⋅a)) for three different types of buildings.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B Low energy building</th>
<th>C Minimum requirements for new building</th>
<th>D Minimum requirements for major renovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detached house</td>
<td>50</td>
<td>120</td>
<td>160</td>
<td>210</td>
</tr>
<tr>
<td>Apartment building</td>
<td>100</td>
<td>120</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>Office building</td>
<td>100</td>
<td>130</td>
<td>160</td>
<td>210</td>
</tr>
</tbody>
</table>

In addition to national requirements, there are several internationally recognized energy-performance levels. The Passive House (PH) standard (PassivhausInstitut, n.d.) is one widely known energy performance standard. The PH standard requires thick insulation, minimized thermal bridges, airtightness, insulated glazing and heat recovery ventilation. For PH standard, the quantitative requirements are: annual specific net energy demand for heating at less than or equal to 15 kWh/(m²⋅a) and total primary energy for space heating, domestic hot water and household appliances at less than or equal to 120 kWh/(m²⋅a).

In Estonia, the renovation of a kindergarten with PH components marked the country’s first experience with PH concepts (“Kindergarten ‘Kaseke,’” 2009). The first complete and certified PH in Estonia is a detached house located at Metsa 5a in the town Põlva, designed by Austrian architects and constructed by Estonian designers (Reinberg et al., 2013). Based on calculations, it achieves the annual basis “plus-energy” building classification in the Estonian legislation.

This paper presents and analyzes the thermal comfort and hygrothermal performance of the building envelope of the aforementioned PH during the first year after construction.

2. Methods

2.1 Studied house and structures

The PH concept has been fully implemented, in addition to utilizing extensive passive and active solar techniques. The design and construction of the house has taken into account the characteristics of Estonia’s cold northern climate. For example, large transparent areas are concentrated toward the south, since the south façade windows have a favorable contribution from the sun and have potential to yield a positive heat balance over the heating season.

The house includes two stories (FIG 1, FIG 2) and a basement with total net floor area of 305 m². The building envelope surface area is 864 m² and has an enclosed volume of 1586 m³, corresponding to a compactness factor (A/V) of 0.55 m⁻¹ for the building.

The exterior walls feature an original design (FIG 3 left) with 94 mm thick cross-laminated timber (Kreuzlagenholz, KLH) block elements as the static layer and 400 mm cellulose insulation with external thermal insulation composite systems (ETICS). This house is the first building in Estonia based on KLH block elements, in addition to its other unique attributes.

Customization of the building design was necessary to accommodate the cold climate. Whereas a well-insulated undrained, rendered wooden exterior wall (see FIG 3 left) could be a good solution for a PH built in Austria, this option could result in serious moisture damage (Samuelson et al., 2008) and biological growth (Johansson, 2011) in a cold climate. Therefore, a new solution was proposed (FIG 3 right): the exterior wall was constructed with ventilated cavities covered mainly by rendering boards and partly by vertical solar collectors. Also the roof solution was changed: it was insulated with wedge shaped EPS insulation (380 mm – 550 mm).
FIG 1  View from SW direction (left) and the sections (middle, right) from the house.

FIG 2  The plans of the first (left) and the second (right) floors.

FIG 3  Exterior wall and roof structures, as originally designed (left), and as constructed (right, with measurement point for hygrothermal performance of exterior wall with temperature and relative humidity (t&RH6, t&RH7, t&RH8, t&RH9) sensors).
2.2 Measurements

Upon completion of house construction in December 2012, an extensive monitoring system was installed to continuously assess the indoor climate and performance of building systems and the exterior wall. The hygrothermal performance of exterior wall was measured on the northern façade with temperature and relative humidity sensors (Ø 5 mm × 51 mm, measurement range: -40°…+100°C and 0…100%, accuracy: ±0.3°C and ±2%) and heat flux plates (Hukseflux HFP-01-05, measurement range ±2000 W/m², accuracy: ±5%). Measurement results were recorded with a computer (Modbus RTU protocol). The indoor climate was measured with portable sensors (measurement range: -20°…+70°C and 10…95%, accuracy: ±0.35°C and ±3%).

3. Results

3.1 Indoor climate

To provide an overall view of the indoor climate, we analyzed the correlation of the indoor temperature and relative humidity (RH) with the outdoor temperature. Using green dots, the correlation of the hourly indoor temperature with the outdoor temperature outside the northern bedroom with east-facing window is displayed (FIG 4 left). Using black dots, the correlation of the average daily indoor temperature with the average daily outdoor temperatures outside the aforementioned room is displayed (FIG 4 left). This represents average thermal conditions in one room, and is depicted in FIG 4 right with a curve.

The correlation of indoor RH on the outdoor temperature was also analyzed, using a similar method as employed for the room temperature. In FIG 5 left, the average indoor RH values from one room are divided by the average outdoor air temperature. Based on each indoor RH sensor and the corresponding outdoor temperature, the daily average value was calculated to form the black dotted line. Each individual curve in FIG 5 right represents, for each room, the average value of the daily indoor RH and the corresponding average daily outdoor temperature.

The internal moisture excess was selected to characterize indoor humidity loads. FIG 6 left presents the daily moisture excess in one room during whole measurement period, and the black dotted line represents the weekly average moisture excess in on 90% criticality level (design level). FIG 6 right presents the moisture excess during the winter period: the average value was 3.1 g/m³, and the design value corresponding to 90% critical moisture level was 5.2 g/m³.

Carbon dioxide (CO₂) concentrations were used to assess the indoor air quality. CO₂ concentrations at 500 ppm and 800 ppm above the outdoor concentration (400 ppm) correspond to the indoor climate category (ICC) target classifications of average (II) and third (III), as shown in FIG 7.

![FIG 4 The dependence of the indoor temperature on the outdoor temperature in the north bedroom on the second floor with east-directed window (left) and the comparison of all rooms (right).](image-url)
3.2 Hygrothermal performance of exterior wall

The hygrothermal performance of the exterior wall was measured at different positions inside the 400 mm thick cellulose insulation (see FIG 3 right):

- on the internal edge of the insulation: between the insulation and the KLH;
- in the middle of the insulation;
- on the external edge of the insulation: between the insulation and the 12 mm thick wood fiber sheathing board (Kronopol DP50).
FIG 8 shows the temperature (left) and RH (right) inside the 400 mm thick insulation of the exterior wall. The RH was over 80% until the beginning of the summer (until 1.06.2013). As the exterior walls were insulated in September 2012, high moisture content in the walls lasted for approximately ten months. In the summer, when very high moisture conditions in the exterior wall were determined, two additional temperature and RH sensors (RH 7-2 and RH 7-3) were placed inside the wall. The measurement accuracy of the original sensor was open to discussion. However, similar humidity readings in the new sensors RH 7-2 and RH 7-3 assured the authors of the accuracy of the original sensor: the drying out of constructional moisture (KLH and cellulose insulation) had caused condensation and favourable conditions for mould growth (FIG 9) inside the exterior wall. Based on a mathematical model of mould growth in wooden material (Hukka and Viitanen, 1999), the mould index was near 3, meaning that some growth could also be detected visually and new spores could form.

![FIG 8 Temperature (left) and RH (right) inside the 400 mm thick insulation of the exterior wall.](image)

![FIG 9 Temperature and RH between the cellulose insulation and the 12 mm thick wood fiber sheathing board (left) were suitable for mould growth, according to the mould growth index (right).](image)

4. Discussion

The first certified passive house in Estonia was designed by Austrian architects in cooperation with Estonian designers, including the involvement of the co-authors of this paper. The indoor climate and hygrothermal performance measures of the exterior wall of this building were monitored and analyzed.

The passive utilization of heat gains is an important factor in the design of a passive house. In the cold Estonian climate, literature review suggests that only windows with southern orientation could yield energy-positive results (NorthPass, 2010). At the same time, large south-facing windows need flexible
solar protection to avoid over-heating indoor climate. South-directed windows could not be the only reason of overheating in the house under consideration, since the north bedroom with east-directed window reached high temperatures as well (FIG 4 left). During the summer months, only the basement maintained the average indoor temperature within the targets of indoor climate category II (normal level of expectation, for new buildings: Predicted Percentage Dissatisfied, PPD \( \approx < 10\% \)).

Due to high temperatures, the indoor RH decreased to quite low levels. During the cold period \( t_e \leq +5^\circ C \), the indoor RH was below 20\% (FIG 5). The indoor RH was similar in all rooms.

The indoor humidity loads were similar to typical dwellings with high humidity loads: the average value of moisture excess during the winter period was 3.1 g/m\(^3\), and the design value of moisture excess was 5.2 g/m\(^3\) (FIG 6). This indicates that in design of passive houses indoor humidity loads cannot be decreased despite the ventilation keeps the indoor air quality within the limits of indoor climate category II recommendations (FIG 7).

Humidity conditions in externally insulated cross laminated timber panels (KLH) were high (FIG 9 left), due to the drying out of constructional moisture (KLH and cellulose insulation) and the high diffusion resistance of the wood fiber sheathing board. Careful hygrothermal design and moisture safety considerations should be paramount in the construction of highly insulated building envelopes (Mundt-Petersen, 2013; Vinha et al., 2013). Otherwise, water vapour condensation or favourable conditions for mould growth could develop (FIG 9 right).

5. Conclusions

The performance of the first certified passive house in Estonia was monitored and assessed during the first year after construction, including detailed analysis of the indoor climate and hygrothermal performance of the exterior walls.

High temperatures in most of the rooms were achieved mainly due to the southern exposure of the large windows and the fact that the adjustable solar protection devices were installed only in the middle of the current monitoring period (May 2013). As the heat loss through the building envelope was small compared to the thermal transmittance of the interior walls and floors, a high average indoor temperature was maintained throughout the house, including the bedroom on the northern side of the building. Due to the high temperatures reached, the indoor RH decreased to quite low levels. The high indoor temperatures indicate that the large windows with southern orientation need adjustable solar protection or heat accumulation devices to avoid over-heating.

Humidity conditions in the externally insulated cross-laminated timber panels (KLH) were elevated for long periods, raising concern for condensation and the risk of mould development. Although the original hygrothermally risky design of the exterior walls, which would have used external thermal insulation composite systems (ETICS) with a wooden structure, was upgraded to a less moisture-prone design based on advice of the co-authors and other Estonian experts, excess moisture still became a problem. This was mainly caused by the shortcomings in the constructional technology, such as no rain protection for KLH, no moisture safety protocol during the construction period, and the high diffusion resistance of the wood fiber sheathing board. In parallel with energy performance, also the hygrothermal properties of the building envelope and its impact on the indoor climate should be top priority in the design of passive houses.

A key to successful completion of construction projects is clear communication and follow-up between designers and building crew, to ensure that the revised construction guidelines would be fully incorporated in the blueprints. This could reduce problems such as the overheating and moisture build-up encountered in this project. In design of buildings with high energy performance, focused attention should be paid on the performance of building service systems and moisture safety should be taken into account already in preliminary stage of design.
6. Acknowledgements

This research was supported by the European Union through the European Regional Development Fund. The research has been conducted as a result of the “Reducing the environmental impact of buildings through improvements of energy performance, AR12059” (financed by SA Archimedes) and IUT1–15 project “Nearly-zero energy solutions and their implementation on deep renovation of buildings” (financed by the Estonian Research Council).

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LowEx Communities – Optimized Performance of Community Energy Supply System with Exergy Principles

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KEYWORDS: Low Exergy Communities; Exergy Analysis; Low Temperature Supply Structures; Low Energy Buildings; Renewable Energy Supply

SUMMARY
Communities are characterised by a wide range of heating and cooling energy demands. This energy is mainly provided by the combustion of fossil fuels, which is responsible for greenhouse gas (GHG) emissions. While a lot has already been achieved there are still large potentials in providing heating and cooling energy more efficiently. At the community level, different renewable energy sources are available. These energies are characterised by high fluctuations and different qualities: e.g. photovoltaics as electricity (high-exergy) or low temperature (low-exergy) heat from e.g. thermal solar collectors or waste heat from industry facilities. Low energy qualities are of particular interest, because the low exergy (LowEx) supply of thermal energy is very efficient. The application of exergy principles is especially important, allowing the detection of different available energy-quality levels and the identification of optimal contribution to an efficient supply. From this, appropriate strategies and technologies with great potential for promoting the usage of low-valued energy sources (LowEx) and a high share of renewable energies for heating and cooling of entire cities can be derived. The paper presents the key ideas of the just started international co-operative work in the general framework of the International Energy Agency (IEA), the EBC Annex 64: “LowEx Communities – Optimized Performance of Community Energy Supply System with Exergy Principles”

1. Introduction

The energy demand of communities for heating and cooling is responsible for more than one third of the final energy consumption in industrialised countries. Commonly this energy is provided by different fossil fuel based systems. These combustion processes cause greenhouse gas (GHG) emissions and are regarded one core challenge in fighting climate change. National and international agreements (e.g. the European 20-20-20-targets or the Kyoto protocol) limit the GHG emissions of the industrialized countries respectively for climate protection. Country specific targets are meant to facilitate the practical implementation of measures. While a lot has already been achieved, especially regarding the share of renewables in the electricity system, there are still large improvement potentials in the heating and cooling sector and on the community scale. Exploiting these potentials and synergies, demands for an overall analysis and holistic understanding of conversion processes within communities. Communities are characterized by a wide range of energy demands in different sectors, for instance heating and cooling demands, lighting and ventilation in the building stock. Different energy qualities (exergy) levels are required as heat or cold flows or as electricity and fuels.
2. Description of technical sector

2.1 The LowEx Approach

To optimise the exergy efficiency of community supply systems the so-called LowEx approach (LowExergy) can be utilised. Simplified the physical property “exergy” can be described as a product of energy and “energy quality” $q$ (carnot factor for thermal energy).

$$ Ex_0 = Q \cdot \left(1 - \frac{T_0}{T}\right) $$

As a part of the considerations of this project, the following simplifications will be used: The higher the temperature of a heat flow is above the temperature of the surroundings (reference temperature), the higher the energy quality. The LowEx approach entails matching the quality levels of energy supply and demand in order to optimise the utilisation of high-value energy resources, such as combustible fuels, and minimising energy losses and irreversible dissipation (internal losses).

To heat indoor spaces up to 20°C, heat has to be supplied at a temperature slightly higher than 20°C. An exergetic analysis shows that the required energy quality, the exergy fraction or quality factor $q$ for this application is very low ($q \approx 7\%$ only). If the production of domestic hot water is considered as heating water up to temperatures of about 55°C, the needed energy quality is slightly higher ($q \approx 15\%$). For operation of different household appliances and lighting, the highest possible quality ($q \approx 100\%$) is necessary. An adaptation of the quality levels of supply and demand could be managed by covering, for example, the heating demand with suitable energy sources, as there is available district heating with a quality level of about 30% (see FIG. 1).

![FIG 1: Application of LowEx approach for optimization of community demand adapted supply. The very efficient so called low exergy supply and use are of particular interest (see green boxes).](image)

2.2 Scope

The scope of the annex covers the improvement of energy conversion chains on a community level, using an exergy basis as the primary indicator. The fundamental idea follows the hypothesis that by optimising the exergy chains, the overall system performance can be improved and CO$_2$ emissions can
be reduced. In particular, the method of exergy analyses has been found to provide the most accurate and insightful assessment of the thermodynamic features for any process as well as offering a clear, quantitative indication of both the irreversibilities and the degree of correspondence between the resources used and the end-use energy flows. In comparison to plain energy analysis, exergy based system optimisation facilitates the integration of renewable heat and cold sources that are most often available at fairly low temperatures. The optimal integration of decentralised supply modules of heat and cold enables the realisation of smart bi-directional supply chains in the heat and cold supply systems similar to ‘smart-grid’ approaches for the electricity sector. For conducting investigations on community level system boundaries have to be de-fined. The exact definition of the boundaries of the area to be examined (building, group of buildings, block, quarter or community) depends on the objectives of the involved research project (see: Focus of involved research projects).

![Demand structures](image1.png) ![Potentials](image2.png)

**FIG 2**: The boundary of the systems which are studied. Demand structures of different buildings and buildings groups (left). Sources and supply structures (right) adapted for supply of demand side.

### 2.3 Challenges and objectives

The main objective of the annex is to demonstrate the potential of low exergy thinking on a community level as energy and cost efficient solution in achieving 100% renewable and GHG emission-free energy systems. The intention is to reach these goals by providing and collecting suitable assessment methods (e.g. holistic balancing methods). Furthermore it is planned to provide guidelines, recommendations, best-practice examples and background material for designers and decision makers in the fields of building, energy production/supply and politics. During the course of this activity, the aim is to develop and improve means for increasing the overall energy and exergy efficiency of communities through demand adapted supply and inclusion of renewable energy sources. Therefore the central focus of all considerations is thermal energy at different exergy levels. Electrical energy will be taken into account as auxiliary energy. Electricity from a renewable fluctuating supply should be discussed as a contribution to the heat and cold supply of a community if it is thermally stored (e.g. storage tanks or usage of the building mass) and used for heating or cooling purposes (e.g. heat pumps). Further objective within the international co-operative work is discussion on appropriate additional indicators, supplementing the exergy assessment. The discussions should be initialised to come to a common understanding of how to weigh high-exergy electricity for heating and cooling purposes under the preconditions of local availability. Another objective is the application of exergy analysis as a basis for providing suitable material for designers and decision makers in the fields of low exergy generation, low exergy distribution and low exergy consumption. Central challenges in achieving the objectives are the identification of the most promising and efficient technical solutions for practical implementation and aspects of future network management and business models for distribution and operation. Aspects of transition management and policy will ensure the feasibility. A close cooperation with related IEA Annexes and activities is planned.
2.4 Benefits

The advantages of the application of the LowEx approach in the holistic assessment of a community are diverse:

- Customers benefit in various ways. First of all, the use of low exergy sources ensures a good comfort level and a sustainable supply. Customers do not have to worry about maintenance, fuel supply and optimal operation of heating systems.
- The environment benefits from the exergy concept. The total GHG emissions in communities can be substantially reduced as a result of the use of more efficient energy conversion processes. This new concept supports the setup of sustainable structures and secure energy systems for future developments on the community scale.
- From an economical point of view, high price stability can be expected due to the use of locally available, renewable, or surplus heat energy sources. An additional advantage of this is a lower dependency on foreign fuel supplies. The high overall system performance that can be achieved by using low temperature sources would lead to reduced resource consumption and therefore lower costs for fuels. This would also increase price stability and could potentially provide heat at very competitive prices.

The following three main target groups of the proposed annex benefit in different ways from the annex:

- The energy supply and technology industry will get development ideas for future products, business models and services in the field of dynamic energy supply systems. With the breaking down of traditional centralized top-down solutions in energy supply, new fields of business can be created in combination with overall system improvement.
- Communities will profit from the improved and more differentiated understanding of their local potentials and supply options. Greater local energy autonomy and impulses for local economy can support communities in regaining strategic competence in long-term development issues in the energy sector.
- Academic, research and education fields profit from the project by gaining a more holistic system understanding and a more differentiated view of community energy systems. A better understanding is created on the interaction and potential synergies of the different system modules.

3. Focus of involved research projects

Following chapters contain the key ideas of the new international co-operative work in the general framework of the International Energy Agency (IEA), the EBC Annex 64.

3.1 Optimisation of demand profiles

Energy demands currently are commonly supplied by centralised or decentralised systems designed and optimised for single demand profile. Therefore, energy demands of several yet different building types should be combined to pave the way for utilisation of unused synergies within existing communal building and supply structures. The research activities in field of “Optimisation of demand profiles” are strongly focused on the demand of buildings as part of multifarious community supply systems. As part of the work, the previously developed the exergetic assessment methods from IEA ECBCS Annex 49 (Torío, Schmidt 2011) will be applied and further developed. The focus here is particularly on so-called LowEx system distribution and supply concepts of different building classes. For this reason the optimisation potentials of heating and cooling tasks of buildings as well as building groups as one part of multifarious community supply systems. The following (FIG 3) figure illustrates the application of demand-optimized supply. An example, the waste heat of a cooling system for the heating of low-energy building could be used. For a sports centre, the waste heat from an ice rink could be used for heating a swimming pool.
3.2 Optimization of supply profiles

Development and identification of concepts allowing a flexible supply of different demands with maximum share of local and renewable energy sources. Thereby chances for an efficient use of decentralized renewable-energy based systems such as CHP units, heat pumps and solar thermal collector fields as well as surplus heat (secondary energy) are enhanced. In this context, an all electrical supply and the use of heat pumps for the heating and cooling of the building stock is a promising option, too. Electrical energy from fluctuating energy sources will only be considered if they are thermally stored (e.g. storage tanks or usage of the building mass) and used for heating or cooling purposes (e.g. heat pumps). In this case only, an exergetic assessment is required and the signified contribution to greenhouse gas reduction is available.

FIG 4 shows that available local sources have to be established to allow cascading of exergy flows. For this the location of both sources and sinks are crucial.

3.3 Realisation and development of “model cities”

Development and identification of concepts allowing a flexible supply of different demands with maximum share of local and renewable energy sources. Thereby chances for an efficient use of decentralized renewable-energy based systems such as CHP units, heat pumps and solar thermal collector fields as well as surplus heat (secondary energy) are enhanced. In this context, an all
electrical supply and the use of heat pumps for the heating and cooling of the building stock is a promising option, too. Electrical energy from fluctuating energy sources will only be considered if they are thermally stored (e.g. storage tanks or usage of the building mass) and used for heating or cooling purposes (e.g. heat pumps). In this case only, an exergetic assessment is required and the signified contribution to greenhouse gas reduction is available.

FIG 5: Opportunities for approach for the required steps to identify of a model city.

3.4 Assessment methodology

The main objective is to collect and further development of existing (exergy) assessment methods. This step is used to identify the most appropriate method (e.g. Excel Tools or Simulations Tools) for each user group. Based on the respective method it should be possible to display various stages of planning or design of buildings, groups of buildings and community supply systems. In particular, the further development of approaches from previous ECBCS Annex 37(Ala-Juusela, 2003) and Annex 49 (Torío, Schmidt 2011) is pursued here. In addition to these objectives, it is possible to develop a simplified approach or to identify new approaches. All method should contribute to a more flexible, efficient and renewable energy supply in community systems.

FIG 5 contains a description of the various planning stages. It should be clarified that the higher the resolution the less can be represented in detail. This shows the need for simplification in the modeling of complex community supply systems.
4. Expected outcome and results from the project

The following results expected from the activities within the research activities within the framework of the International Energy Agency (IEA), the EBC Annex 64:

- Analysis concept and design guidelines with regard to the overall exergy performance of community supply and demand. This could include a possible classification of technologies in terms of performance, improvement potential and innovation prospects.
- Overview of the feasibility, efficiency potentials and impacts of integral energy system solutions for existing community settings, criteria for decision making in the project development phase.
- Analysis framework and open-platform software and tools for community energy system design and performance assessment.
- Summary of intelligent management and control strategies and system solutions for an efficient energy supply system at community level based on exergy principles.
- Set of existing and close to market systems and technological solutions and best integration into overall energy system design.
- Description and collection of good practices and examples of system concepts, technologies, management and control strategies for maximum share of renewable energy sources and maximum efficiency of the energy and exergy potentials available on a community scale.

The primary deliverable is an easy to understand and practical, applicable design guidebook for key people in communities. It is to contain an executive summary for decision makers and will cover issues on how to implement advanced supply technologies at a community level. Further it is focussed on how to optimise supply structures to ensure reduced costs for the system solution, while providing a high standard of comfort to the occupants of the buildings.

The dissemination of documents and other information is to be focussed on providing practitioners with research results. Methods of information dissemination are to include conventional means such as presentations at workshops and practice articles. The project homepage will be used extensively to spread information. Publications may be written in English and in the languages of the participants' countries. However, the translation of the key findings into English will allow for a broader distribution of knowledge. A communication platform will be developed using local networks and energy related associations. Regular workshops will be organised in all participating countries to show the latest project results and to provide an exchange platform for the target audience. Some of the workshops might be organised within the framework of national or international conferences or symposia.

5. Conclusions

Communities are characterized by a wide range of heating and cooling energy demands. This energy is mainly provided by the combustion of fossil fuels, which is responsible for greenhouse gas (GHG) emissions. National and international agreements limit the GHG emissions of industrialized countries, respectively, for climate protection. While a lot has already been achieved there are still large potentials in providing heating and cooling energy. At the community level, different renewable sources are available. These energies are characterised by high fluctuations and different qualities: e.g.
photovoltaic as electricity (high-exergy) or low temperature (low-exergy) heat from renewable energy sources. Low energy qualities are of particular interest, because the low exergy (LowEx) supply is very efficient. These described properties represent a major challenge. For solving these challenges, the identification of potential savings and synergies by performing holistic analysis of energy flows is necessary. The application of exergy principles is especially important, allowing the detection of different available energy-quality levels and the identification of optimal contribution to an efficient supply. From this, appropriate strategies and technologies with great potential for promoting the usage of low-valued energy sources (LowEx) and a high share of renewable energies for heating and cooling of entire cities can be derived.

In the framework of the new EBC project ‘Annex 64 on LowEx Communities – Optimized Performance of Community Energy Supply System with Exergy Principles’ advanced technologies have to be adapted and further developed to realize the identified potentials. For this reason, it is important to demonstrate the potential of low exergy thinking on a community level as energy and a cost efficient solution in achieving 100% renewable and GHG emission-free energy systems.

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Frosting limit in Air-to-Air Membrane Energy Exchangers

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KEYWORDS: heat exchanger, hydrophilic, hydrophobic, pressure drop, sensible effectiveness, latent effectiveness, frosting visualization

SUMMARY:
In this paper, three air-to-air membrane exchangers with (a) hydrophobic, (b) hydrophilic and (c) impermeable membranes are tested under a range of supply inlet air temperatures. The exhaust inlet conditions are ~22°C and ~45% RH, and the supply and exhaust airflow rates are 18.8 L/s. The frosting limit is defined as the supply air (i.e., outdoor) temperature below which frosting is observed in the exchanger after a specified time. The presence of frosting is determined by monitoring changes in effectiveness, pressure drop and visual inspection. The frosting limit is found to be approximately -1°C for the impermeable membrane exchanger and -6°C for the hydrophobic and hydrophilic membrane energy exchangers.

1. Introduction
Energy consumption in residential and commercial buildings makes up around 40% of the total energy use in Canada and 60% of the energy consumption in buildings is used for heating and cooling (Natural Research of Canada, 2009). Energy Recovery Ventilators (ERVs) are an essential part of heating, ventilating and air conditioning (HVAC) systems when designing energy efficient buildings, because they allow adequate outdoor ventilation air without excessive energy consumption. Membrane based energy exchangers are a new type of ERV that reduce energy use, while regulating relative humidity levels in buildings. In cold regions such as Canada or northern Europe, frost formation in the exchangers during the cold season decreases the performance of the equipment, and blockage of the air streams by frost may reduce the ventilation rate and decrease the indoor air quality (IAQ). Many researchers have studied frosting in air-to-air heat/energy exchangers, but frosting in air-to-air membrane exchangers has not been previously studied (Rafati Nasr et al., 2014). In this paper three different membrane energy exchangers are tested under frosting conditions to determine when frosting occurs for each exchanger. Additionally, different techniques to detect frost formation in the exchangers are compared. Frosting limit is defined as the temperature of the supply air inlet (at a specific exhaust inlet relative humidity) at which frosting is detected in the exchanger. In this paper heat exchanger or HRV refers to the exchanger with an impermeable membrane and energy exchanger or ERV refers to the exchangers with permeable membranes.

2. Test Facility
The three cross flow air-to-air exchangers were manufactured with identical geometries such that they all have the same surface area (FIG 1). The cores are made out of layers where the membrane is separated by corrugated aluminium foil spacers. For two of the exchangers, the polymer membrane
has a coating on one side, making that side more hydrophilic than the uncoated side. In one of these ERV exchangers the hydrophilic coating interfaces with the exhaust stream, while in the other exchanger the more hydrophobic surface is in contact with the exhaust stream. The third core is made with an impermeable polymer film with the same thickness as the polymer membrane used in the other two cores. This film blocks any water vapor, making it a heat recovery ventilator (HRV) with the same sensible performance, to compare it to the other ERV cores.

**FIG 1. Three different cores used in the frosting tests.**

FIG 2 shows the arrangement of the exchanger cores and the supply and exhaust air streams. Air is drawn from two environmental chambers at desired conditions (for the supply and the exhaust air inlets), and after passing through the exchanger, the air is discharged into the laboratory. Fans are used both upstream and downstream to ensure balanced flow through the exchanger core. In order to determine when frosting occurs in the exchangers, several air properties are measured at different locations in the test facility.

**FIG 2. Arrangement of (a) exchanger core and headers and sensors location, (b) Configuration of the thermocouples at the outlets and (c) the inlets of the exchanger.**

**Temperature:** The temperature of the air is measured using T-type thermocouples, which are calibrated over a temperature range of -30°C to 30°C. FIG 2 shows the configurations of the thermocouples at (b) the outlets and (c) the inlets of each stream.

**Flow rate:** Orifice plates are installed in the supply and exhaust ducts, both upstream and downstream of the exchanger, to determine the mass flow rate of dry air in each stream (ISO 5167-1, 2003).

**Visualization:** To observe frosting, a snake camera (endoscope) is installed at the exhaust outlet as shown in FIG 2 (a).

**Relative humidity (RH):** The relative humidity of each air stream is measured at the inlets and outlets of the exchanger, exactly where the temperature is measured. To achieve higher accuracy in measuring the humidity at very low temperatures, a chilled mirror dew-point sensor is used in the supply inlet side.

**Pressure drop:** Static pressure probes are placed before and after the core in each stream to measure the pressure drop across the exchanger (FIG 2 (a)).
3. Test Procedure

The experiments are designed based on the standard for testing air-to-air heat/energy exchangers (ASHRAE Standard 84, 2013). The performance of exchangers is evaluated using sensible effectiveness for HRVs and sensible and latent effectivenesses for ERVs.

3.1 Performance Evaluation

In this paper the performance of the exchangers is determined by their effectivenesses, and pressure drop, as described in (ASHRAE Standard 84, 2013). The nomenclatures in FIG 2 (d) are used in the remainder of the paper to designate locations.

Effectiveness: The effectiveness of an exchanger is calculated for the supply and exhaust streams from the following equations:

\[ \varepsilon = \frac{q_{\text{actual}}}{q_{\text{maximum}}} \]  
\[ q_{\text{actual}} = C_{SO}(X_{SI} - X_{SO}) \]  
\[ q_{\text{maximum}} = C_{\text{min}}(X_{SI} - X_{EI}) \]

Where:  
\( \varepsilon \) effectiveness  
\( q \) sensible, latent, or total heat or energy (kW)  
\( X \) dry-bulb temperature (K or °C) for sensible effectiveness, humidity ratio (g/kg) for latent effectiveness or enthalpy (kJ/kg) for total effectiveness  
\( C \) \( m \), \( C_p \) for sensible, \( \dot{m} h_f \) for latent or \( \dot{m} \) for total  
\( \dot{m} \) the mass flow rate of dry air (kg/s)  
\( C_p \) the specific heat of dry air (kJ/(kg·K))  
\( h_f \) the heat of vaporization of water (kJ/(kg·K))

The effectiveness in the supply side is more important and will be presented in this paper.

3.2 Mass and Energy Balance

Although tests with frosting or condensation may not meet the criteria for mass and energy balances, because of the continuous growth of the frost, in this paper, conservation of the mass flow rate of dry air and water vapour, as well as conservation of sensible and total energy for the HRV/ERVs according to (ASHRAE Standard 84, 2013) are satisfied in most tests.

3.3 Uncertainty

When conducting experiments it is important to determine the uncertainty in each measurement. The sensors are calibrated and the uncertainty of each sensor is determined according to (ASME, 2005). The uncertainty in the temperature measurements is ±0.2°C, in the relative humidity measurements is ±3% RH and in the pressure measurements is ±3-6 Pa. The uncertainty in the mass flow rates is ±2%, in the calculated sensible effectiveness is ±2% and in the latent effectiveness is ±5-8%. The higher uncertainty in latent effectiveness compared to sensible effectiveness is due to higher uncertainty in the humidity sensors compared to the thermocouples.

4. Results and Discussion

The three cores are initially tested under conditions with no risk of frosting, and then tests are conducted at low supply temperatures, with the possibility of frosting. In all of the experiments, the exhaust inlet conditions are maintained at 22°C and ~35-45% RH. The supply inlet temperature (\( T_{SI} \))
varies between 0°C and 11°C for the tests without frosting and between -10°C and 0°C for the frosting tests. The mass flow rate of dry air is ~23 g/s for both air streams.

4.1 Tests with no condensation or frosting
To make sure no condensation occurs in the test for HRV, the supply inlet temperature is 11°C. The mass flow rate of dry air in each stream is approximately the same, within uncertainty limits, which indicates negligible leakage in the test facility, and balanced flow through the HRV core. The effectiveness, as well as the pressure drop across the core, in each stream remain constant and the values for the two streams are approximately the same, again indicating equal flow rates.

Similar tests for the ERV with coating on the supply side (hydrophobic) and the ERV with coating on the exhaust side (hydrophilic) are performed. The sensible and latent effectivenesses in both these exchangers are constant as well. TABLE 1 presents a summary of results including the operating conditions and the performance parameters for the three exchangers. It can be seen that the sensible effectiveness of the hydrophilic ERV is 5% lower than the other two exchangers, but its latent effectiveness is slightly higher (within the uncertainty range), while the total effectiveness of both ERVs is the same.

TABLE 1. Summary of the performance tests of three exchangers without frosting.

<table>
<thead>
<tr>
<th>Type of exchanger</th>
<th>T_Ei</th>
<th>RH_Ei</th>
<th>T_SI</th>
<th>RH_SI</th>
<th>m_Dry</th>
<th>ΔP</th>
<th>ε_s</th>
<th>ε_l</th>
<th>ε_t</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRV</td>
<td>22.9</td>
<td>40</td>
<td>11.0</td>
<td>37</td>
<td>23</td>
<td>23</td>
<td>61</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hydrophobic ERV</td>
<td>23.1</td>
<td>55</td>
<td>4.5</td>
<td>39</td>
<td>23</td>
<td>24</td>
<td>61</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Hydrophilic ERV</td>
<td>21.2</td>
<td>46</td>
<td>1.0</td>
<td>35</td>
<td>23</td>
<td>24</td>
<td>56</td>
<td>31</td>
<td>45</td>
</tr>
</tbody>
</table>

4.2 Frosting Limits
Many parameters may affect frosting, including air inlet conditions, flow rates, exchanger effectiveness and design. In this research, the exchanger designs are similar, and air flow rates are kept constant. The two main air properties are T_SI and RH_Ei. T_Ei is kept constant in all experiments, and RH_SI does not play a significant role in the frosting.

The methods used to detect frosting are:
- measuring the change in pressure drop across the core;
- calculating the change in effectiveness of the exchanger and
- visual observation using a camera at the outlet of the core.

4.2.1 HRV
Several tests are performed under frosting conditions to determine the frosting limit for each exchanger. The supply side sensible effectiveness and pressure drop across the HRV over time are shown in FIG 3 for one test. The effectiveness stays approximately the same until 140 min, and then decreases by 2% over the last 30 min. The pressure drop on the exhaust air side increases gradually during the test, while the pressure drop on the supply side remains constant. This increase in pressure drop in the exhaust side is related to frosting, due to the high humidity and cold exchanger surface, which is consistent with the literature (Nielsen et al. 2009; Fisk et al. 1984). Photographs at the exhaust outlet show the formation of frost starting at an early stage of the experiment (FIG 4). After 10 min the amount of frost observed at the HRV outlet does not change with time, according to the photographs. It can be concluded that most of the frost is forming inside the core rather than at the outlet.

The exhaust side pressure drop is presented for all HRV tests, in FIG 5. The only case with no pressure change is the test with T_SI = -0.5°C. From the results presented in TABLE 2, the frosting...
limit of the HRV is determined to be $T_{SI} \approx -1^\circ C$ when $RH_{EI} \approx 45\%$ RH. The effectiveness results in TABLE 2 show a reduction in the average effectiveness with supply temperature, except for the test with $T_{SI} = -0.5^\circ C$. The higher average effectiveness in test 3 may be due to the condensation heat release in the exhaust air stream or an enhancement in heat transfer by the early stage of frosting (Fisk et al., 1984). However, this increase would be temporary and it is expected the effectiveness would decrease if left to frost for a longer period.

The following can be concluded from the experiments on the HRV:

- visual observation shows the presence of frost earlier than the change in pressure drop,
- pressure drop shows an increase in the amount of frost over time, while the photographs do not,
- supply side pressure drop does not change under frosting conditions and
- change in sensible effectiveness is minimal; it is not a good indication of frosting in this test.

### 4.2.2 Hydrophobic ERV

Based on the results from the HRV, the frosting limit in the ERVs is expected to be lower than $-1^\circ C$ for the same $RH_{EI}$. FIG 6 shows the pressure drop across the core for a test with $T_{SI} = -4.5^\circ C$ and
RH_{E3} \approx 49\% \text{ RH}. Again, frosting occurs only in the exhaust side of the ERV. This finding is important as it confirms that no frosting has occurred in the supply side, even with the use of a membrane in the exchanger.

The photographs in FIG 7 show a very small amount of frost at the outlet of the ERV. This amount does not change with time, although the pressure drop is still increasing. Again, it can be concluded that frost forms mostly in the middle of the core.

**FIG 6.** Pressure drop for the test with $T_{SI} = -4.5^\circ C$ and $RH_{E3} = 49\% \text{ RH}$ with the hydrophobic ERV.

**FIG 7.** Photographs of frost formation in the hydrophobic ERV.

Sensible and latent effectivenesses are shown in FIG 8. The sensible effectiveness reduces by 2\% at the end of the test, while latent and total effectivenesses stay fairly constant during the tests.

**FIG 8.** (a) Sensible and (b) latent effectiveness for the test with $T_{SI} = -4.5^\circ C$ and $RH_{E3} = 49\% \text{ RH}$ with the hydrophobic ERV.

Similar conclusions to those presented for the HRV can be extracted for the hydrophobic ERV, except for the frosting limit. A summary of the frosting tests for the hydrophobic ERV is presented in TABLE 3. There is a small variation in RH_{E3}, due to changes in the lab air conditions. This variation is the reason that frosting occurs during the test with $T_{SI} = -4.5^\circ C$, while no frosting occurs during the test with $T_{SI} = -5.8^\circ C$. Thus, it is predicted to observe frosting in the hydrophobic ERV at $T_{SI} \approx -6^\circ C$ when $RH_{E3} \approx 45\% \text{ RH}$. In addition, comparing the effectivenesses for the frosting tests with the results in TABLE 1, the sensible effectiveness is 1-2\% higher and the latent effectiveness is 2-4\% higher when frosting occurs, compared to the frosting test. These increases in effectiveness are likely due to condensation heat release and the presence of condensed water on the membrane surface which may increase moisture transfer.
TABLE 3. Summary of the frosting tests for the hydrophobic ERV.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$T_{SI}$ (°C)</th>
<th>$R_{SI}$ (% RH)</th>
<th>$T_{EI}$ (°C)</th>
<th>$R_{EI}$ (% RH)</th>
<th>$\varepsilon_s$ (%)</th>
<th>$\varepsilon_l$ (%)</th>
<th>$\varepsilon_t$ (%)</th>
<th>Frosting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-6.2</td>
<td>43</td>
<td>22.3</td>
<td>49</td>
<td>62</td>
<td>35</td>
<td>51</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>-5.8</td>
<td>46</td>
<td>22.1</td>
<td>44</td>
<td>62</td>
<td>33</td>
<td>51</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>-4.5</td>
<td>44</td>
<td>22.2</td>
<td>49</td>
<td>62</td>
<td>34</td>
<td>50</td>
<td>Yes</td>
</tr>
</tbody>
</table>

4.2.3 Hydrophilic ERV

Based on the performance results from the previous section, the frosting limit in the hydrophilic ERV is expected to be close to the hydrophobic ERV. A summary of the results for the hydrophilic ERV is provided in TABLE 4. The pressure drop and effectiveness is shown in FIG 9 in FIG 10 respectively. The increase in pressure drop confirms the formation of frost in the exchanger. The pressure drop however, stays fairly constant after 140 min in FIG 9. This may be an indication of a reduction in the frost growth due to changes in the sensible effectiveness, which would reduce the heat transfer between the two air streams. On the other side, the sensible effectiveness decreases by 2% during first 140 min and stays fairly constant thereafter, with no change in latent effectiveness. The photographs of the outlet are similar to the observations in the hydrophobic ERV and so are not shown.

TABLE 4. Summary of the frosting tests for the hydrophilic ERV.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$T_{SI}$ (°C)</th>
<th>$R_{SI}$ (% RH)</th>
<th>$T_{EI}$ (°C)</th>
<th>$R_{EI}$ (% RH)</th>
<th>$\varepsilon_s$ (%)</th>
<th>$\varepsilon_l$ (%)</th>
<th>$\varepsilon_t$ (%)</th>
<th>Frosting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-4</td>
<td>41</td>
<td>22.8</td>
<td>46</td>
<td>56</td>
<td>34</td>
<td>47</td>
<td>No</td>
</tr>
</tbody>
</table>

By comparing the results in TABLE 4, the frosting limit for the hydrophilic ERV is between -4 to -5.8°C when $R_{EI} \approx 45$% RH, which is a little higher than for the hydrophobic ERV. With further
analyse from the pressure drop graphs, the frosting limit is estimated at -5.5 °C. Although there is a little reduction in sensible effectiveness during the tests, the average sensible effectiveness of each test is the same as the test with no frosting, presented in TABLE 1. The average latent effectiveness is 3% to 5% higher with frosting than without frosting. This higher latent effectiveness might be the results of condensation in the exhaust air stream at low temperatures, which increases the moisture transfer through the membrane.

5. Conclusions

In this paper, three air-to-air membrane exchangers were tested under low supply inlet temperatures when the exhaust inlet conditions were ~22°C and ~45% RH, and the supply and exhaust airflow rates were 18.8 L/s. The frosting limit for the HRV is -1°C, and for both the hydrophobic and hydrophilic ERVs is around -6°C. In addition, the following points were concluded during this project.

- visual observation showed the occurrence of frosting sooner than pressure drop monitoring,
- the amount of frost throughout the test can be detected by an increase in the pressure drop, while the photographs from the outlet did not show this increase in the amount of frost,
- the pressure drop in the supply side did not change with frosting in any of the exchangers meaning that no frost formed in the supply side of the exchangers, and
- changes in effectiveness were not significant during the frosting tests, indicating that the effectiveness values did not show the initiation of frosting.

6. Acknowledgment

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References


Thermal comfort in summer in low energy buildings

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KEYWORDS: summer overheating, thermal comfort, low energy buildings

SUMMARY: The aim of this work is to analyse thermal comfort and overheating risks under Latvian climate conditions. Two cases were inspected: no cooling and heating applied indoors (temperature fluctuates due to free floating conditions) and cooling applied indoors. Results for 3 test houses significantly differ, despite the similar projected U-value for each external wall. Differences are analysed in detail. It is shown that the initial moisture on the external wall can significantly influence the thermal comfort in the room. Despite the temperate climate in Riga, Latvia, both the experiments and the calculations show that overheating risks are high in summer.

1. Introduction

By December 31, 2020, all the newly constructed buildings are to become the “nearly zero energy consumption buildings” according to (Directive of the European parliament and of the council 2010/31/EU). However, overheating risks can be observed for passive houses, especially in summer. A high indoor temperature combined with a higher relative humidity can influence the living conditions negatively, affecting human health. Therefore a comprehensive study of thermal comfort in passive houses is strongly recommended. Living conditions in summer have been widely researched. 207 across the England were chosen and summertime temperatures were analysed (Beizaee & Lomas 2013). A single Slovenian passive house was analysed and overheating risks in summer have been investigated in (Mlakar & Strancar 2011). In (Bravo & Gonzalez, 2013) thermal comfort in hot-humid climate has been analysed. (Brun & Wurtz & Hollmuller, 2013) applied a new free-cooling system in experimental houses with the aim to analyse summer comfort.

FIG 1. On the left: The test stands of houses. On the right: A cross-section of one test stand

Despite the countless researches dedicated to the thermal comfort in houses at the summertime, the research of houses having the same parameters (net volume, roof, floor, orientation, projected U-value of external walls), the only difference among the houses being materials used in external walls, has not yet been published. Such experiments have been done in Riga, Latvia, where five test houses have been built (see Fig. 1). Thermal comfort conditions in the three test houses were analysed in
(Ozolins & Jakovics & Ratnieks & Gendelis 2013). However, that publication focussed on the heat and moisture transfer on the walls as well as on the temperature distribution in the room. Moreover, at the time the experiments were not started yet in the houses placed in Riga (see Fig. 1). The experimental results obtained from the test stands were discussed in (Ozolins & Jakovics & Ratnieks 2013). However, this paper focussed on moisture risks on the walls. Small test houses were created in (Mlakar & Strancar 2013). However, in this case the net volume was significantly lower, projected U-values of external walls were not equal and the aim of the given paper was completely different. INCAS platform with several test houses was described in (Spitz & Mora & Wurtz & Jay, 2012). The aim of this work is to analyse thermal comfort and overheating risks under Latvian climate conditions.

2. Short description of test houses and measurements

This section provides a brief description of external walls of five test stands built in Riga, Latvia (see Fig. 1). Project homepage (EEM, 2011) provides a comprehensive image gallery of test stands as well as a detailed material description.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity [W/mK], μ [-], c_p×ρ [J/(m^3K)]</th>
<th>Material</th>
<th>Thermal conductivity [W/mK], μ [-], c_p×ρ [J/(m^3K)]</th>
<th>Material</th>
<th>thermal conductivity [W/mK], μ [-], c_p×ρ [J/(m^3K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind protection slab, 0.03 m</td>
<td>0.034, 1, 59500</td>
<td>Wind protection slab, 0.03 m</td>
<td>0.034, 1, 59500</td>
<td>Plywood, 0.02 m</td>
<td>0.17, 700, 75000</td>
</tr>
<tr>
<td>Stone wool, 0.02 m</td>
<td>0.036, 1, 33200</td>
<td>Stone wool, 0.125 m</td>
<td>0.043, 1, 33200</td>
<td>Stone wool, 0.2 m</td>
<td>0.041, 1, 33200</td>
</tr>
<tr>
<td>Lime plaster, 0.015 m</td>
<td>0.7, 7, 1344000</td>
<td>Lime plaster, 0.015 m</td>
<td>0.7, 7, 1344000</td>
<td>Plywood, 0.02 m</td>
<td>0.17, 700, 75000</td>
</tr>
<tr>
<td>Aerated concrete, 0.375 m</td>
<td>0.072, 4, 255000</td>
<td>Aerated clay bricks, 0.44 m</td>
<td>0.175, 7, 595000</td>
<td>Fibrolite, 0.075 m</td>
<td>0.068, 2, 756000</td>
</tr>
<tr>
<td>Lime plaster, 0.015 m</td>
<td>0.7, 7, 1344000</td>
<td>Lime plaster, 0.015 m</td>
<td>0.7, 7, 1344000</td>
<td>Lime plaster, 0.015 m</td>
<td>0.7, 7, 1344000</td>
</tr>
</tbody>
</table>

In Table 1, the multi-layered external walls of each test house are characterized. For layers consisting of the stone wool effective λ is chosen taking into account the wood frame. Wood siding in front of walls for each test house was used to protect the walls from rain and solar radiation. Ventilated air layer with a thickness of 2 cm is located between the wood siding and the wall. The roof, floor, windows and doors of all test stands are similar. Triple-glazed window with solar heat gain coefficient 0.5 is built into the south-facing wall of each test stand. U-value is 0.72 W/m²K for the
window and width, height and height above floor are 1.2 m, 1.5 m and 1 m, respectively. It can be noted that the inner loads due to the measuring equipment were approximately 3 W/m² for each of the test stands. More information about test stands and materials used for each of the test houses is available in (EEM, 2011).

3. Results and discussions

The current section consists of 2 parts:

- thermal comfort analysis based on the measurements in the test houses;
- analysis of the long term overheating risks based on the numerical calculations.

Numerical simulation has been implemented by using software WUFI PLUS: room climate model for calculation of the inner climate conditions.

3.1 Thermal comfort under different exploitation conditions

![Temperature and Relative Humidity Graph](image)

**FIG 2. Outdoor temperature and relative humidity from June 1 to August 31**

Measurements were implemented in test houses with the aim to estimate the room comfort under different conditions: no heating and cooling applied indoors in June, i.e. $T_{in}$ and $T_{out}$ fluctuated by free floating conditions. In July maximal $T_{in}$ was set as $+24 \, ^\circ C$, i.e. cooling was ensured if indoor temperature rose beyond $24 \, ^\circ C$. In August neither heating nor cooling were applied. However, the difference between the interior conditions in August and June was created by covering the windows from outside in August with the aim to observe the role of the solar radiation through the window. Air exchange coefficient was approximately 0.5 1/h and the indoor relative humidity fluctuated by free floating conditions for all time period. The outdoor climate conditions are shown in Fig. 2. The data has been obtained from the meteorological station created in the test polygon. The maximal outdoor temperature was observed on August 8, when maximum of $T_{out}$ rose up to 33.6 $^\circ C$. The average $T_{out}$
was 19.2 °C, 19.1 °C and 18.2 °C in June, July and August respectively. The average $\varphi_{\text{int}}$ was 67 %, 71 % and 74 % in June, July and August respectively.

**FIG 3.** The measured indoor relative humidity compared to indoor temperature for 3 different test houses. Bounded regions are thermal comfort charts according to (ASHRAE Standard 55). Smaller region: comfortable. Larger region: still comfortable. On the left: room conditions in June when no heating and cooling was applied indoors. In the middle: room conditions in July when maximal $T_{in}$
was set at +24 °C. On the right: windows were covered in August, no cooling or heating applied indoors.

As it is shown in Fig. 3a, b, c, a high indoor relative humidity has been observed in case of the test stand of AER that can negatively influence human health. An explanation of high humidity is the high initial moisture for the aerated concrete that significantly influences the room conditions. The situation was not improved when the cooling was applied indoors. In the test stand of CER the room climate was significantly better (see Fig. 3d, e, f). For some time periods, the optimal thermal comfort was not ensured and circles slightly go out of optimal thermal comfort region due to the higher relative humidity (see Fig. 3e). When the windows were covered from the outside, the optimal comfort was also ensured almost throughout all days in August (see Fig. 3f). In case of the test house of PLY, a significantly lower relative humidity in the room (see Fig. 3g,h,i) was observed. However, a higher overheating was also observed, especially in June (Fig. 3g), when $T_{in}$ fluctuates by free floating conditions and solar influence through the windows was observed. The problem is solved when cooling is applied indoors (see Fig. 3h). When windows were covered, the optimal comfort climate was also observed (see Fig. 3i), except during some warmer days that can be seen in Fig. 2. It can also be concluded that a significant impact of different building components used on the external walls to the thermal comfort has been demonstrated. The amplitude of $T_{in}$ fluctuations was the lowest in case of the test stand of CER (Fig. 3d compared to Fig. 3g, Fig. 3f compared to Fig. 3i). It can be explained by higher volumetric heat capacity of aerated clay bricks incorporated in the external wall of CER that does not allow the heat to quickly transfer through the wall.

**TABLE 1. Average outdoor and indoor temperatures for 3 test houses**

<table>
<thead>
<tr>
<th></th>
<th>$T_{out}$</th>
<th>AER; $T_{in}$</th>
<th>CER; $T_{in}$</th>
<th>PLY; $T_{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>19.5</td>
<td>22.5</td>
<td>23.4</td>
<td>25.4</td>
</tr>
<tr>
<td>August</td>
<td>18.2</td>
<td>20.9</td>
<td>21.8</td>
<td>22.4</td>
</tr>
</tbody>
</table>

If we compare Fig. 3a to Fig. 3c, Fig. 3d to 3f, Fig. 3g to 3i, it can be seen that the average $T_{in}$ between the months of June and August does not differ as much as it can be expected. More precisely, in June the average $T_{in}$ was 3 °C, 3.9 °C and 5.9 °C higher than the average $T_{out}$ for the test stands of AER, CER and PLY respectively (Table 2). The difference between $T_{out}$ and $T_{in}$ is explained with the inner sources and solar radiation through the window. In August average $T_{in}$ was 2.7 °C, 3.6 °C and 4.2 °C higher than the average $T_{out}$ for the test stands of AER, CER and PLY respectively (Table 2). It can thereby be concluded that a covered window only partially decreases the overheating risks.

### 3.2 Overheating risks in a long term

Measurements for estimating overheating risks in different building constructions were described in a previous subsection. However, only one summer was inspected, and the outdoor climate conditions can differ during other years. Therefore it is required to analyse the overheating risks in low energy houses during a long term. At first, WUFI PLUS model will be verified and the results compared with the experimental data obtained.
FIG 4. Calculated indoor relative humidity against indoor temperature for 3 different test houses.

It is shown that the numerical results (Fig. 4) significantly differ from the measurements (Fig. 3 a, d, g). The differences in case of the test house of AER (Fig. 3a compared to Fig. 4a) are explained with a high initial moisture in aerated concrete that was not taken into account in numerical simulations. This moisture on the external wall promotes a higher indoor relative humidity, higher U-value and therefore lower indoor temperature. For the test stand of CER, the differences from measurements are lower (Fig. 3d compared to Fig. 4b). because the initial moisture for aerated clay bricks is not as high as for aerated concrete. For the test stand of PLY the range of in is similar both for measurements and numerical model (Fig. 3 g compared to Fig. 4c). However, the measured range of φ in is from 40-60 % despite the range of 40-50 % for numerical model.

FIG 5. Experimental results (solid line) against numerical results (dashed line). Windows were: (a) uncovered; (b) covered

In Fig. 5 the dynamics of measured T in are shown to verify the numerical model used in software WUFI PLUS. In June the numerical model is well fitted with measurements (Fig. 5a). However, measured T in is for approximately 1-1.5 °C higher than the one obtained by numerical model in August (Fig. 5b). One explanation of this displacement is the overheating on the loft that can influence the room temperature more significantly, when the solar influence through the window is negligible

Since the numerical model shows reliable results for estimating room temperature for the test stand of PLY, a detailed analysis of overheating risks will be made in a long term, using the climate data from
2006 to 2012 in Riga. It will be assumed that no heating and cooling is applied indoors in summer and solar influence through the window will be negligible.

![FIG 6. Calculated indoor temperatures for the test stand of PLY in a long term (2006-2012), solar influence through the window is negligible. (a) Standard room conditions that were applied on the real test house. (b) Inner loads 100 W due to the human activity. (c) Inner loads 100 W and increased air exchange from 0.5 to 1.5 1/h](image)

Numerical calculations show that room temperature could increase above +25 °C in August only in 2010 (see Fig. 6a). It means that the situation, when $T_{in}$ increases up to +29 °C (see measurement in Fig. 5b), is a rare phenomena at the given room conditions. However, $T_{in}$ can increase above +25 °C several times during the 7 year period that can cause uncomfortable room living conditions. In a real situation, humans can produce additional heat or inner source. For the sake of simplicity it has been assumed that the inner loads are constant 100 W. The results obtained based on this assumption show a completely different situation (see Fig. 6b). Rooms can overheat for a longer time periods in several summers. Even $T_{in}>30$ °C can be reached. An assumption about an increased air exchange up to 1.5 l/h improves the thermal comfort (see Fig. 6c). However, the overheating risks remain and uncomfortable room conditions are often a case during the time period of 2006-2012. A better solution could be the night ventilation.

### 4. Conclusions

In the current paper three test stands of houses were compared and the experimental measurements of room living conditions for different cases (no heating and cooling applied indoors, covered windows, cooling) were obtained. The experiments show that the thermal comfort was not ensured for the house with external wall mainly consisting of the aerated concrete blocks and insulation materials. The living conditions were absolutely uncomfortable due to the high indoor humidity. The reason was a high initial moisture in the aerated concrete and very slow drying process. Thermal comfort also was not achieved in the test stands with the external walls mainly consisting of wooden materials and insulation layer. However, cooling or covering of the window significantly improves the situation. The best interior living conditions were observed in the test stand mainly consisting of aerated clay bricks and insulation materials.

Long term simulations based on the “light” test stand mainly consisting of plywood and stone wool shows that overheating risks could be observed for several time periods and for several summers despite the assumption about the window covered from the outside.
Since the initial moisture significantly influences the thermal comfort in case of one test house, it presents an interesting challenge to observe, how much the interior living conditions will improve for several subsequent summers. Such measurements will continue.

5. Acknowledgements

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References


ASHRAE Standard 55. Thermal environmental conditions for human occupancy.
Investigation of the Indoor Environment in a Passive House Apartment Building Heated by Ventilation Air

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KEYWORDS: Low energy building, Passive House, warm air heating, thermal comfort, solar shading, field measurements, dynamic building simulation

SUMMARY:
Experience has shown that appropriate design of very low energy dwellings can be a large challenge and that the final design may result in insufficient heating in winter and overheating in summer. The 126 certified Passive House apartments (Ravnsborghusene) in Køge, Denmark are a low energy building project finished medio 2012. The design challenge was met with a concept of air heating that is individually controlled in every room. It also applies external solar shading. This study used indoor climate measurements and dynamic simulations in one of these apartment buildings to evaluate thermal comfort and the performance of the air heating system and solar shading. Thermal comfort category B according to ISO 7730 was obtained in the building during field measurements, indicating that the air heating system was able to maintain comfort conditions in winter, when the outdoor temperature had been unusual low for a longer period. The dynamic simulations also indicated that air heating during winter can provide a comfortable thermal environment. Dynamic simulations also demonstrated that during summer, apartments with automatic external solar screens had no serious overheating, whereas in apartments with south oriented windows, static shadings by the balcony overhangs and low ventilation rates, resulted in excessive hours of overheating.

1. Introduction

From the Kyoto agreement in 1997 to the 2009 EU energy and climate package, the aim has been to reduce energy consumption of new and existing buildings. In the design of low energy buildings focus is to reduce the energy consumption. This may lead to design loads that are sensitive to variations in climatic conditions, user behaviour and changes during the building process. The Passive House concept focuses on very low energy consumption for heating by efficient thermal insulation and utilization of the passive heat in the building. Here passive use of the solar load, occupants, electrical appliances etc. contributes considerably to heat up the space. Once the heating requirement is sufficiently low, the conventional water based heat distribution systems can be omitted and the dwelling heated by ventilation air alone. This may reduce the costs without compromising the indoor environment (Ellehauge et. al. 2008). However, recently published results found that poor design of air heating systems without individual control in each room and inadequate solar shading created problems with insufficient heating in winter and overheating in summer (Larsen 2011). These experiences from the first passive houses in Denmark have resulted in more detailed criteria on the space heating systems and on the performance of the indoor environment and namely thermal comfort. The current proposal for the future Building Regulations in Denmark, the current low energy class 2020, forbids the use of air heating alone and sets up concrete requirements for maximum acceptable indoor temperatures (Energistyrelsen 2013). But what if an air heating system is correctly dimensioned and gives occupants the possibility to control the room temperature individually and if the building has
an effective, external solar shading? Would the thermal indoor environment then meet the best indoor climate category A? This study focuses on evaluating the air heating system and solar shading systems of a newly constructed low energy apartment building, based on field measurements and dynamic simulations. The studied apartments are part of 126 certified Passive House apartments (Ravnsborghusene) in Køge, Denmark which were finished medio 2012.

2. Building description

The investigated apartment building is one out of nine certified Passive House apartment buildings. Each apartment building consists of 14 apartments spread over an eastern and a western section (see FIG 1). The eastern section consists of four floors with four 4-room apartments and four 2-room apartments. The western section comprises six 3-room apartments divided into three floors. The gross area of the east and west section is 689 m² and 490 m², respectively.

FIG 1. South east view of the investigated apartment building (left) and floor plan (right)

The apartment building is ventilated and heated by air from two centralized and balanced ventilation systems with heat recovery and pre heating coil. The supply air is heated by individual water based heating coils installed before each room inlet. The coil in each room can be individually controlled by thermostats. The heating system is based on three air to water heat pumps (AWHP) that supply heat to two domestic hot water tanks and a buffer tank. Automatic external solar screens are installed only at the east and west oriented windows. All 14 apartments have balconies towards east, west and south. These balcony overhangs operate as static shading.

3. Field measurements

3.1 Methods

Short and long term measurements were conducted to evaluate the thermal comfort and ventilation rates in the apartments.

3.1.1 Thermal comfort

Thermal comfort as well as local thermal discomfort was categorized according to ISO 7730 (2006), based on short term measurements. The purpose of the short term measurements was to evaluate if the air heating provided at specific locations in the living room was sufficient, during an unusual cold period where the outdoor temperature was approximately -8 °C. The average long term outdoor temperature in Denmark in January is -0.3 °C, the outdoor design temperature -12 °C and the design indoor air temperature is 20 °C. The short term measurements were conducted on January 25th 2013 in
each apartment on the 2nd floor, at three locations in the living rooms R1, R4, R8 and R11 (see FIG 1). The selected locations represented the approximate positions where occupants would stay for long time periods. At each location air temperature, air velocity, plane radiant asymmetry and relative humidity were measured at the heights 0.1 m, 0.6 m and 1.1 m during a minimum period of three minutes. A clothing insulation value of 1.0 clo and a metabolic rate of 1.2 met were assumed to best represent the average occupants clothing and activity level. The ASHRAE comfort tool software was used to calculate PMV and PPD (ASHRAE 2013).

3.1.2 Ventilation rate

Occupant generated CO$_2$ was used to estimate the ventilation rates by applying a single-zone mass balance (Bekő et al. 2010). The CO$_2$ concentration was measured during a period of one week (January 25th 2013 to February 1st 2013) by a Vaisala CO$_2$ transmitter connected to a HOBO data logger with a built in air temperature and relative humidity sensor. The placements of the HOBO data loggers were in representative locations in rooms R1-R11 (see FIG 1). The data acquisition interval was set to five minutes. In order to smooth the data and reduce extreme values, a 20-minute running average was used. Individual activity protocols for each room were completed by occupants for each day, in order to obtain behaviour related input to the calculation of the ventilation rates.

3.2 Results

3.2.1 Thermal comfort

Air temperature, mean radiant temperature, relative humidity and air velocity were found for all measuring locations. The average values over three locations in each apartment living room are illustrated in FIG 2 together with their standard deviations. The measured air temperature was close to the mean radiant temperature which also coincides with the high surface temperatures measured at the floor and ceilings. This indicates uniform thermal conditions in the measured rooms caused by well insulated building envelope and inner walls creating individual thermal zones.

*FIG 2. Parameters obtained in the 2nd floor apartments (Ap.9-12)*

Based on the four obtained parameters and the assumed clothing insulation and metabolic rate, the PMV and PPD indices were calculated for the living room in each apartment shown in TABLE 1.

*TABLE 1. PMV and PPD indices calculated for Ap. 9, 12, 10 and 11*

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PMV [-]</td>
<td>-0.13</td>
<td>-0.13</td>
<td>0.04</td>
<td>-0.10</td>
</tr>
<tr>
<td>PPD [%]</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

*Calculation based on measurement at 0.6m height at three locations in each apartment living room.

According to ISO 7730 (2006), the PMV and PPD values for all apartments were within category A. In FIG 3, no noteworthy air temperature gradient occurred at any of the measurement locations. Also, the air velocity was generally below 0.15 m/s.
FIG 3. Vertical air temperature and air velocity profiles for the 2nd floor apartments

The local thermal discomfort measurements; draught rate (DR %), radiant asymmetry, vertical air temperature difference and floor temperature corresponded to category A for Ap. 12, 10 and 11, whereas Ap. 9 was in category B. The lower category was due to a slightly higher air velocity and lower air temperature, which resulted in 16% draught rate.

3.2.2 Ventilation rate

In TABLE 2 the measured ventilation rates and the design values are shown. It can be seen that the measured ventilation rate, for most rooms, is comparable with the design ventilation rate. However, the ventilation rates for all rooms in Ap. 11 were much lower than the design values. The low ventilation rate in Ap. 11 may be due to the size and geometry of the apartment which created problems with sufficient ventilation or simply the fact that the ventilation system did not work properly for these rooms.

TABLE 2. Measured and design ventilation rates in the different rooms

<table>
<thead>
<tr>
<th>Ventilation rates [-]</th>
<th>Room</th>
<th>Room Volume [m³]</th>
<th>Measured* [l/sm²]</th>
<th>Design [l/sm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap. 9</td>
<td>R1/ R2/ R3</td>
<td>88.5/ 27.8/ 19.1</td>
<td>0.62/ 0.47/ 0.6</td>
<td>0.6/ 0.7/ 0.7</td>
</tr>
<tr>
<td>Ap. 12</td>
<td>R4/ R5/ R6</td>
<td>88.5/ 29.8/ 19.1</td>
<td>0.72/ 0.63/ 0.6</td>
<td>0.6/ 0.6/ 1.0</td>
</tr>
<tr>
<td>Ap. 10</td>
<td>R7/ R8</td>
<td>31.9/ 73.0</td>
<td>0.85/ 0.32</td>
<td>1.0/ 0.8</td>
</tr>
<tr>
<td>Ap. 11</td>
<td>R9/ R10/ R11</td>
<td>18.6/ 18.6/ 98.1</td>
<td>0.47/ 0.30/ 0.14</td>
<td>0.8/ 0.8/ 0.6</td>
</tr>
</tbody>
</table>

*The values are based on averages of the decay- and build-up periods throughout the measurement period.

4. Dynamic building simulation

4.1 Methods

The intended design of the heating and solar shading systems of the apartment building were evaluated by dynamic simulations performed with the simulation program IES- Virtual Environment, IESVE (IESVE 2013). The performance of the air heating and shading design was investigated throughout a one year period based on parameter variations. The parameter variations were compared with reference to the thermal environment categories I-IV given in EN 15251 (2007). The prerequisite for conducting parameter variations was to compare the simulated air temperature with measured data obtained from the HOBO data loggers during 25th of January 2014 to 1st of February 2014. The assumption was that if the simulated air temperatures approximated the measured ones, then the model setup would be sufficient in order to perform the parametric study.

4.1.1 Model setup

An IESVE model of the 2nd floor of the apartment building (see FIG 4) was set up, based on observations made during the field measurements and drawings of the building geometry. The rooms marked with black were included in the simulation while the grey ones were assumed adjacent rooms.
For the western apartment Ap. 9 and Ap. 12 additional heat loss is present compared to the eastern apartment.

FIG 4. South east view of the IESVE model geometry of the apartment building and U-values

The location was set to Copenhagen/Kastrup and the weather data file to ‘CopenhagenDRY.ftw’. The automatic external solar screen system was set to roll down when the incident solar radiation was above 30 klx and to roll up again when it was below 25 klx. The static shading design from balcony overhangs had a shading angle of approximately 50°. According to fieldwork observations, internal curtains and vertical lamellas were included in Ap. 12 and Ap. 10.

Occupant and equipment profiles were created based on information provided from the activity protocols. The heat load emitted by the occupant was 90 W while the heat load from electrical appliances including illumination was approximated to 5 W/m² and 3 W/m² for the living rooms and bedrooms, respectively. The heat generated was assumed as 100 % sensible and 0 % latent. Venting was activated when the room temperature exceeded 26 °C during the occupied periods providing a venting rate of 0.9 l/sm² appropriate for manually operated windows (Aggerholm & Grau 2011). An overall infiltration rate of 0.07 l/sm² was estimated based on a Blower door test as a part of the Passive House certification ($n_{50} \leq 0.6$ h⁻¹).

The apartment building was ventilated and heated by a centralized Constant Air Volume (CAV) system with 85 % heat recovery based on two aggregates supplying the east and west sections. During the heating season, the heat exchanger was set to be active when the outdoor air temperature was below 15 °C and operated with a set point supply temperature of 18 °C. The heat exchanger was by-passed during the summer months when the outside temperature was above 22 °C. The individual heating coils installed before each room were set to regulate the air temperature as a function of the room air temperature. The coil adjusted the air temperature between 23 °C and 18 °C as the room air temperature varied.

4.2 Results

The results used for the evaluation of the model setup can be seen in FIG 5.

The simulated and measured air temperature distributions ranged between 19-24.5 °C for the examined period (see FIG 5). In Ap. 9 the air temperature difference was approximately 2.5 °C where simulated temperatures were below 21 °C and measured ones mainly above 21 °C. In Ap. 10 simulated and measured data differed by 3 °C. In this apartment the simulated temperatures were below 22 °C and measured above 22 °C. The expected extra heat loss in the west apartment Ap. 9 and the air temperature difference between the apartments fit with both the simulated and measured air temperature distributions. The model setup was therefore considered sufficient to perform parameter variations where the intension was to compare the relative effect between different heating and shading designs.

4.2.1 Parameter variation

A parametric sensitivity analysis was conducted in order to evaluate the performance of the heating and shading system based on EN 15251 (2007). The parameter variations (P) are listed below:

- P1 was the reference model based on the intended model setup.
- P2 was similar to P1 but with a reduced supply set point temperature of 21°C, instead of 23 °C.
- P3 was similar to P1 but only with the balcony overhang as shading.
- P4 was similar to P1 but with added automatic external solar screens also on the south windows (controlled as the east and west windows).

To evaluate the air heating system the parameter variations P1-P2 were simulated. The results can be seen in FIG 6, where the annual thermal environment was compared.

![FIG 6. Annual thermal environment in % time in four categories for parameter variation P1 & P2](image)

The reference model (P1) indicated a thermal environment within category III in Ap. 9, Ap. 10 and Ap. 12 whereas in the big south apartment (Ap. 11) 7% of the occupied period was within category IV (see P1 in FIG 6). The reason for this was hours of overheating. When the supply temperature set point was reduced to 21 °C the occupied period within category IV increased 2% (see P2 in Figure 6) and this was found to be caused by recorded hours below 20 °C as well.

To evaluate the influence of solar shading the parameter variations P3 and P4 were simulated and compared with the reference model (P1). According to FIG 6 the effect of the solar shading systems indicated that for P1 significant duration with overheating occurred in the South facing apartments (7%). By removing the automatic external solar screens the duration of temperatures in category IV increased as illustrated in FIG 7.

![FIG 7. Annual thermal environment in % time in four categories for parameter variation P3 & P4](image)
The design with no automatic external solar screens deteriorated the thermal environment in the living rooms with windows facing east and west, which in the actual case were the ones equipped with automatic external solar screens. This indicated that the design of the automatic external solar screens was effective in reducing the number of overheating hours. The apartment mostly affected was the large South oriented apartment (Ap. 11), where 17% of the occupied period was within category IV. This was expected since it has a large glazing area facing south as well as windows oriented towards east and west. For apartments Ap. 9 and Ap. 10 with balconies facing east and west, the balcony overhang did not provide sufficient shading since the shading angle was designed for a high position of sun corresponding to summer midday (see P3 in FIG 7). Adding automatic external solar screens at the south windows of apartment Ap.12 and Ap.11, the number of hours with overheating was reduced significantly (see P4 in FIG 7).

5. Discussion

The results indicated PMV values within comfort ranges (-0.2 < PMV < 0.2) corresponding to the best indoor climate category A according to ISO 7730 (2006). Local thermal discomfort in Ap. 9 was within category B due to slightly increased draught rate. This showed that air heating alone with individual room control could maintain minimum thermal comfort category B in the apartments. The short term measurements also indicated uniform air temperature distribution as well as no air temperature asymmetry in the apartments where local discomfort could have been expected by the combined effect of heating by ventilation air and high measured ventilation rate. Parameter variations illustrated that air heating was less sensible to change in supply temperature in the north apartments than in the south apartments, where a 2 °C lower supply temperature resulted in a 2% increase of room air temperatures within category IV. Moreover parameter variations documented that automatic external solar screens were indispensable in order to achieve comfortable temperature ranges. The results also illustrated that the existing design can reduce overheating hours by 7-10% in the south apartments. The simulations indicated that the design was likely to operate ineffectively during summer months as excessive hours of overheating were obtained in the south apartments even when venting was introduced. The simulation results should be validated in future work by performing field measurements during summer months while occupant observations is recommended to be taken into account by allocating questionnaires. By implementing automatic external solar screens to the south, thermal environment would improve further. However for dwellings this may constitute a problem since the user behaviour interacts with the shading control.

The ventilation rates in the apartment rooms were calculated based on the method of using occupant generated CO₂ to predict ventilation rate. The use of the single zone mass balance for estimating the air change rates does not take into account the distribution of CO₂ between rooms (interzonal air flow) and infiltration (Bekö et. al. 2010). The calculated air change rates could therefore be overestimated. In the current study the ventilation rates were calculated based on average values of decays throughout the measuring period. The consistency in well developed and continuing decays over the period increased the reliability of the estimated ventilation rate and provided a conservative measure for a total ventilation rate. In future work it is recommended to include airflow measurements at the air inlets or tracer gas measurements.

When performing dynamic building simulations uncertainties were involved as the indoor environment performance was estimated according to several assumptions regarding the schedule, occupant behaviour and heat loads. Fine tuning of the simulation model would be necessary in future work in order to comply with measured data. The intention of the dynamic simulation was to compare, based on a parametric study, the relative difference between temperature distributions. The results should therefore not be considered as absolute values since this would require a further validation of the simulation model and the use of specific located weather data.
6. Conclusions

Short term measurements documented that the provided heated air in the apartments could keep a minimum thermal comfort within category B according to ISO 7730 even in an unusual cold winter period. Using air heating with individual room control alone as well as higher ventilation rate can keep uniform operative temperatures without creating draught problems and is a sufficient mean of heating low energy apartment buildings.

Still an important factor to be considered for the design of low energy buildings is the correct implementation of external solar shading systems. This is possible by incorporating dynamic solar loads early in the design phase as static shading alone, caused by the balcony overhangs, cannot shade adequately the large south oriented windows. Building orientation, window distribution and dynamic shading need to be taken into account in order to utilize passive heating and still provide sufficient shading during summer.

References


Integration of energy and indoor environment simulation tools into building design processes

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KEYWORDS: Design, process, method, energy, simulation, building, tool

SUMMARY:
Building simulation tools can help make informed design decisions and improve the final building performance. A gap between building design processes and the implementation of building simulation tools exists because of a lack of knowledge on integrated design on the level of tool implementation. Yet, the gap can be bridged by fitting design processes and simulation methods to each other. This essay suggests a division of four building design processes in order to link these simplified processes to simulation methods. The four design processes range from being based on an architectural concept to being design based on computational input. The essay discusses that conceptual design process should sufficiently rely on (i) diverging and converging, (ii) cross-disciplinary input, and (iii) performance and intuition. The four building design processes relate to building simulation methods that implement certain types of tools for energy and indoor climate simulation. It is discussed how specific building design processes are more suitable for certain specific simulation methods. Energy and indoor climate simulation methods involve the use of simulation tools which may provide design input, optimise and/or evaluate a design prototype. The essay concludes with a table of building design processes related to simulation tool types aiming to stimulate knowledge-based design to achieve designs with better indoor environment quality and energy performance.

1. Introduction

It is buildings where we spend most of our time. They account for about 40% of the total primary energy consumption in Europe (International Energy Agency, 2011). Therefore it is essential to create buildings of high indoor environment performance with low energy consumption. This essay focusses on the conceptual design of a building. During the conceptual design the building geometry is largely defined, the building geometry alone can reduce the final energy consumption of a building up to 40% with no extra cost (Cofaigh et al., 1999). Therefore buildings have a high potential to save energy already in the conceptual design stage.

Building simulation tools can help make informed decisions and help improve the final building performance. Building simulation tools are currently mainly being used for building performance verification rather than design support. This lack of design support can partially be attributed to a lack of knowledge of the integration of energy simulation tools and methods into conceptual design processes. In the Integrated Design Process (IDP), designers are supported by tools that generate simulation-based design support in order to integrate energy performance and indoor environment requirements in their earliest design decisions (Löhnert et al., 2003). Even though the development of tools has mainly focused on building performance verification Petersen (2011) states:

“With minor adjustments to the workflow, building simulation tools could also become an active driver in the development of the building design.”

Typical research on integrated design focusses on a high level of abstraction of design and tends to omit specific design methods and tools when talking about integrated design. As integrated design is mainly understood on an abstract level, little is known on how to apply integrated design on a practical level where building simulation knowledge has design implications. Because of this lack of knowledge designers still struggle to effectively use building simulation tools to support their design decisions. This research attempts
to aid in bridging the universal gap between building design processes and the implementation of simulation tools. The term ‘simulation tools’ refers to both energy and indoor climate simulation tools. The research hypothesises that:

The gap between building design processes and the implementation of simulation tools can be bridged by fitting design processes to simulation methods and vice versa.

The essay consists of an analysis of design focusing on conceptual design and building performance simulation. The research analyses four building design processes into which the integration of energy simulation methods are shown. Energy and indoor climate simulation methods are linked to simulation tools, bridging the gap from design process to implementing simulation tools.

2. Theory on conceptual design processes

Researchers have long been interested in the phenomenon of designing, since it is a complex process suitable for improvement. Moreover, design has an aura of mystery around it from which novel designs may seem to appear as sudden illuminations. This “creative leap” is considered to be essential to the design process (Cross, 1997).

The act of designing involves a workflow – the way you work. Such a workflow (indicated in FIG 1) is defined as a sequence of processes, for example creating a design team, visiting the site or designing the cooling system. Such processes involve methods. Methods involve a systematic way of performing a specific task. The use of tools can be a part of such a method. FIG 1 indicates the hierarchical order of acts of designing where workflow is placed at the top and tools at the lower end.

FIG 1. From workflow to method

It should be mentioned that every designer has adopted his or her own workflow, each involving a unique set of processes and methods. Designers tend to be rather protective of their workflows including their methods, described by Zimmerman (2011) in the following quote:

“Design methods are like toothbrushes. Everyone uses them, but no one likes to use someone else’s.”

The upcoming paragraphs argue a conceptual design process should sufficiently rely on (1) diverging and converging, (2) cross-disciplinary input, and (3) performance and intuition.

2.1 Diverging and Converging

Östman (2005) defines conceptual design as the initial problem-setting and creative phase. The process of conceptual design is seen as a sequence of diverging and converging steps at different levels of abstraction (Turrin et al., 2011). In the divergent phase, the solution space is explored and a number of concepts are generated. In the traditional design process there is a lack of diverging steps; only a narrow solution space with a limited number of alternatives is explored (Turrin et al., 2011). Diverging allows the designers to increase the odds of finding good solutions in the infinite pool of possibilities.

In the convergent and exploiting phase, concepts are evaluated and selected. The concepts retrieved from the exploring phase must be developed and evaluated in order to select design – or ‘the best genomes from the generation’. Design alternatives can be compared to the design criteria to assess to what degree they meet the set requirements in order to select the best design.

2.2 Cross-disciplinary input

Design problems are wicked, ill-defined problems (Cross, 1997). Since the design problem cannot be completely defined, no ultimate, optimal solutions exists (Rittel & Webber, 1984) (Petersen, 2011). As no optimal solution exists, it is important to develop design processes and methods that test the solution space as
effectively as resources allow. Therefore, in order to develop a design that effectively tackles the full spectrum of the design problem, cross-disciplinary input is essential. Cross-disciplinary input also refers to generating solutions (diverging) from different disciplines and evaluating and selecting cross-disciplinarily (converging).

2.3 Performance and Intuition

Efficient and effective design can only be found by narrowing down the solution space, meaning the solution space is limited. For example, the freedom in architectural expression is limited in order to find an efficient and effective structural design. Consequently, the developed design is no longer evident to be a good design – in a holistic sense. Benjamin (2012) therefore warns us not to rely too heavily on performance and optimisation as the driver of design, since they might prevent finding a good, holistic design. Vice versa: dismissing performance and relying mainly on judgement and intuition may, similarly, prevent us from reaching good, holistic design.

3. Simulation Methods and Design Processes

3.1 Design Process

Architectural and building design processes have long been discussed in history as they lead to the creation of our environment. Below a division of four design processes are suggested based on B. Chandrasekaran (1990), Turrin (2011), and Benjamin (2012). The four building design processes are defined as (1) The Primary Generator, (2) Performance Based Design, (3) Synthesising the Parts, and (4) Optimising Creatively. It should be noted that the four listed design processes do not cover all possible design processes but are merely an attempt of listing the most prevalent ones.

3.1.1 The Primary Generator

The Primary Generator design process involves an abstraction of the problem. Based on the simplified problem an initial concept, or primary generator, is created and a crude design is developed which is evolved, through alterations, into the final conceptual design. The complex problem is addressed by some designers by seeking a ‘primary generator’ (Darke, 1979) which suggests the designer to define an important aspect of the problem in order to ‘develop a crude design’. Consequently the designer is to test the solution to see what else can be discovered concerning the problem. In general, the primary generator tends to be an architectural concept in the form of an analogy or configuration (Rittel & Webber, 1984). An example would be Fallingwater by Frank Lloyd Wright, where the analogy of a water fall lead to a design.

Turrin (2011) states “In earlier phases of traditional design, assessing the fulfilment of design requirements relies on the insight of the designer and focuses on a specific range of performances such as functionality and aesthetics.” The primary generator fulfils this definition of traditional design since the primary generator makes the designer focus on a narrow range of performances (such as functionality and aesthetics).

3.1.2 Performance Based Design

In the design process of Performance Based Design, designers use building simulation software to drive the design process. A concept for optimised evacuation, indoor environment or fire safety is promoted to be dominant and lead to the final design. Petersen and Svendsen propose a room-based simulation and design method; this method can be used in the defined process. In contrast to the primary generator, the evaluation takes place in the process of re-prototyping, this may be considered to be an optimisation process. The Energinet Building designed by Henning Larsen Architects is such a design, its façade has been optimised for energy and daylight levels (Henning Larsen Architects, 2014). An extreme example of performance based-design is ‘form follows performance’, where optimisation algorithms generate design form based on an initial set of parameters and requirements.
3.1.3 Synthesising the Parts

In the process of “Synthesising the Parts” the problem is divided into a set of sub-problems. Each sub-problem leads to a set of sub-solutions. In this exploring process all parties propose a number of sub-solutions. For example, the architect proposes a number of architectural sub-solutions and the energy engineer proposes a set of energy strategies. The architect then synthesises the wide range of both qualitative and quantitative sub-solutions into a prototype. The architect or designer coordinates the design team and ensures the timely consulting of experts.

Peter Zumthor appears to have synthesised sub-solutions in his design Werkhaus raum in Austria. The design consists of a roof supported by columns and an interior design containing various volumes creating a composition and routing within the building. The parts seem to tackle different sub-solutions: the roof encloses and is load-carrying, and the interior design of boxes facilitates functional requirements such as storage and reception. The sub-solutions are synthesised afterwards. The synthesis can be a complex task and requires simplification and insight by the architect. The synthesising is a subjective and value-dependant process. In the process of ‘synthesising the parts’ there is a danger of a lack of cohesion and of conflicting interests. In the example of ‘Werkhaus raum’ columns may for example collide with the inner volumes.

3.1.4 Optimising creatively

In the design process of ‘Optimising Creatively’ all design disciplines are stimulated to provide design prototypes based on the set of initial requirements: the sub-problems. A number of prototypes is selected by the design team and developed to the same level of detail for comparative evaluation. The evaluation is an act of multi-criteria decision-making. New alternatives are developed based on the comparison and the problem statement is sharpened. This process is repeated until resources are depleted and/or a satisfactory design is reached.

Masdar Institute Abu Dhabi by Foster + Partners implements a variety of strategies ranging from shading, natural ventilation and electricity production to vernacular architectural expression. Such a large diversity in integrated concepts indicates a creative optimisation process as the design would have to accommodate multiple, possibly conflicting strategies.

3.2 Energy and Indoor Climate Simulation Methods

This chapter describes how the four conceptual building design processes relate to methods of implementing energy and indoor environment simulation tools. Building simulation tools can (1) perform an evaluating role, (2) optimise given designs, or (3) provide design input. Each discussed building simulation process relates to a set of building simulation activities, these activities are executed by building simulation methods.

There are four types of building simulation methods (Citherlet, 2001):

- **Stand-alone:** the energy engineer acts as an external actor using stand-alone tools to perform evaluations with. Models have to be recreated and building information such as insulation values is not shared among disciplines through the building information model (BIM).
- **Interoperable:** the energy engineer uses simulation tools that can perform simulations on an exported BIM but not directly on the BIM. Interoperable tools are able to exchange or share models and information through different formats.
- **Integrated:** the energy engineer uses simulation tools that are an integrated part of the BIM software and performs simulations directly on the BIM as it contains a building energy model (BEM). Models and information are not exchanged across disciplines through exporting.
- **Run-time coupling:** simulation tools are coupled to the BIM software by the energy engineer who can run instant simulations on the BIM as the model is altered. Optionally, parametric design tools can be used to generate design solutions through optimisation algorithms available in for example Grasshopper.
3.2.1 The Primary Generator

The flow diagram FIG 2 depicts the design process known as ‘Primary Generator’. The dashed box involves the building simulation method where the related specialist, i.e. energy engineer, is involved. The energy engineer typically assesses the energy and indoor environment performance, optimises design and/or provides design input.

FIG 2. Methods in the flow diagram of The Primary Generator

In the ‘Primary Generator’ energy engineers are typically only involved in the evaluating of a design proposal. Energy engineers are typically provided with a design that has to be remodelled from scratch in a separate domain (Domain A in FIG 2). This is known as the stand-alone method. A digital building model is developed which is run in an application, providing results ready for evaluation. Depending on the outcome of the evaluation the engineer will suggest improvements and new prototypes may be developed. Alternatively, the conceptual design may include a BIM that can be used in an interoperable manner by the energy engineer meaning some useful information can be exported allowing for faster design evaluation. In the example of the Fallingwater the energy engineer would take no part in the designing of the house, but would merely evaluate its performance leaving little room for improved performance.

3.2.2 Performance Based Design

FIG 3. Methods in the flow diagram of Performance Based Design

In ‘Performance Based Design’ (FIG 3) the energy engineer is involved in the establishing of the performance criteria, as well as developing, evaluating and optimising the prototypes. The prototypes are typically modelled as a BEM, allowing for the implementation of the integrated or run-time coupling methods. The design performance can be assessed without the need of exchanging information or models between software tools. In the case of the office building Energinet by Henning Larsen Architects, the energy engineer suggests improvements to the design, in this case external vertical shading. He dimensions the shading system together with the design team in order to improve the daylight performance of the design.
This is an iterative optimisation process searching the solution space. The simulations were performed in Ecotect in which the shading geometry can be modelled acting as an integrated design tool for daylighting.

3.2.3 Synthesising the Parts

In the process of ‘Synthesising the Parts’ (FIG 4) the energy engineer is involved in developing his own sub-problems and sub-solutions regarding for example indoor climate or energy conservation. When the energy engineer develops the sub-solutions, it is most likely he will do this through a stand-alone or run-time coupling method. In the act of evaluating sub-solutions from other disciplines or prototypes he will typically use a stand-alone or interoperable method. The integration of the sub-solutions is typically done by the architect but may be done by a design team consisting of more specialists than the architect alone. As the sub-solutions are synthesised, a BEM may be created allowing for design evaluation through an integrated or run-time coupling method.

In the example of ‘Werkhaus raum’ the energy engineer may perform analysis on his sub-solutions, such as the building services in order to optimise this sub-solution. This would typically be done in a stand-alone method where the engineer works in a tool that is not interoperable with those of the other disciplines. As the design is synthesised and a design or prototype is created the energy engineer may be involved to perform evaluation on the design. In the design of ‘Werkhaus raum’, sub-solutions appear to be integrated by the architects and no energy engineer was involved in this process.

3.2.4 Optimising Creatively

In the design process of ‘Optimising Creatively’ (FIG 5), the energy engineer is involved in defining the sub-problem(s) from his discipline. He is involved in developing, evaluating and optimising the prototypes. In the developing of the prototype, the design is modelled as an integrated building information and energy model where designs can be evaluated consecutively through integrated method or real-time through run-time coupling method.
In the example of the Masdar institute this would entail that the design team suggested a number of prototypes each tackling the sub-problems through different strategies. Prototypes may have different configurations, building systems, building element properties, shading strategies etc. The prototypes are assessed and evaluated leading to the final design through a number of iterations.

3.3 Energy and Indoor Climate Simulation tools
Energy and indoor climate simulation methods involve the use of simulation tools which may provide design input, optimise and/or evaluate a design prototype. Energy and indoor climate simulation tools may affect the decision making process of the building’s geometry, systems and components, envelope and material properties, and functional layout. The discussed design methods can be connected to simulation tools as shown in TABLE 1.

**TABLE 1. Tool types and examples of energy and indoor climate simulation tools**

<table>
<thead>
<tr>
<th>Method</th>
<th>Simulation tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand-alone</td>
<td>A+E3D, Bsim, BuildingAdvice, Design Advisor, eQuest, Parasol, IDbuild, Crawley, Energy+</td>
</tr>
<tr>
<td>Interoperable</td>
<td>Vasari, DesignBuilder, EcoDesigner, Ecotect, gModeller, IDA ICE, IESve, Velux</td>
</tr>
<tr>
<td>Run-time coupling</td>
<td>DIVA, Geco</td>
</tr>
<tr>
<td>Integrated</td>
<td>Building Design Advisor, OpenStudio, Sefaira, Revit</td>
</tr>
</tbody>
</table>

**TABLE 2. The four design processes linked to simulation methods and tool types.**

<table>
<thead>
<tr>
<th>Design process</th>
<th>Role of energy simulation method</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Primary Generator</td>
<td>Evaluating</td>
<td>Stand-alone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interoperable (exchange only)</td>
</tr>
<tr>
<td>Performance Based Design</td>
<td>Creating, evaluating and optimising</td>
<td>Integrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Run-time coupling</td>
</tr>
<tr>
<td>Synthesising the Parts</td>
<td>Creating, evaluating and optimising</td>
<td>Stand-alone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Run-time coupling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interoperable</td>
</tr>
<tr>
<td>Optimising Creatively</td>
<td>Creating, evaluating and optimising</td>
<td>Integrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Run-time coupling</td>
</tr>
</tbody>
</table>

This essay does not attempt to dictate a specific design process or simulation tool to designers. It merely attempts to help understand the relation between processes and simulation tools in order to help others design more effectively. It should be noted that every design team has a different specific skillset and is therefore more or less likely to be successful with a specific design process. This essay, in particular TABLE 2, should help designers define what design process and accordingly what tool types work best for them.

4. Conclusion and Discussion
This essay attempts to aid in bridging the gap between building design processes and the implementation of energy simulation tools by fitting design processes and simulation methods to each other. Design processes should sufficiently allow for diverging and converging in order to explore the solution space and exploit the design possibilities. Additionally, design processes should facilitate cross-disciplinary input and enable both performance and intuition based input to the decision making process.
By educating designers on the relation between designing and using simulation tools, this essay aims to help designers understand which design process they desire. The team of designers and engineers may adopt one of the four mentioned methods and integrate it into their workflow. Energy engineers can use the description of simulation methods to define their role in the design process. Desired design processes differ from firm to firm as they are dependent on the available knowledge, skills and resources. As simulation methods are successfully integrated into the design process, the performance of designs can be assessed and optimised at an early stage in the design process.

More research on the implementation of simulation tools and their integration into design processes is required and case studies should be performed. Performing case studies on the implementation of simulation methods would contribute to refining the fitting of design processes to simulation methods and vice versa. Moreover, case studies would show the potential as well as possible bottlenecks for the implementation of simulation methods.

5. Acknowledgements

First of all I would like to thank Toke Rammer Nielsen, associate professor at DTU, for being my mentor throughout this project. I would also like to express special thanks to Jakob Strømann-Andersen and Erik Holm Hansen at Henning Larsen for providing guidance and constructive feedback during my research.

6. Works Cited


External shading control principles for low energy office buildings

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KEYWORDS: External shading, low energy buildings, shading control principles, facades, windows

SUMMARY: An optimal control principle for external dynamic venetian blinds facades in a cold climate was determined based on generic office floor simulation. The cases were chosen so that the proportion of cooling in total energy use varied. The numbers of window panes, window-to-wall ratios and external wall U-values ranged from 3 to 5, 25% to 60% and 0.09 to 0.16 W/(m² K) respectively. The results show that controlling shade position according to internal temperature and desktop illuminance is most effective whereas suntracking can be used for slat angle adjustment. The room temperature setpoint for pulling down venetian blinds should be chosen slightly lower than cooling temperature (e.g. +24 °C) and the bandwidth for desktop illuminance should be chosen large enough to assure as good daylighting as possible (e.g. 1000 lx) while preventing unnecessary frequent changes in the position of blinds. Control methods according to external parameters such as vertical irradiance and outdoor temperature did not prove to be effective. The largest savings were obtained for cases with larger windows that had higher initial cooling energy use and the whole floor primary energy was decreased by up to 3.2 kWh/m² by using external venetian blinds. The savings in the primary energy of different orientations ranged from 2.5 to 6.6 kWh/m² in case of large quintuple windows.

1. Introduction

External shading is considered an effective measure to improve a buildings indoor climate and energy performance. Cooling needs and summertime indoor temperatures are decreased by blocking direct sunlight and another benefit is that glare is also avoided. Several studies have pointed out that the position of motorized shading is changed more frequently than of manual blinds, whereas when not controlled automatically a significant proportion of people formulate their decisions about blind position over a period of weeks or months, and not days or hours (Van Den Wymelenberg 2012). In a cold climate it is essential to utilize as much of sun radiation during heating period, however in case of low or nearly zero energy office buildings the heating need remarkably depends on the office use and internal gains (Thalfeldt 2013). Therefore simple control principles of automated blinds depending only on external conditions may not be optimal and might even increase energy consumption (Thalfeldt 2013). The possible energy penalty caused by external shading in the climate of Scotland was also pointed in a study by Littlefair (2010) and the importance of control strategy especially in case of balanced heating and cooling has been also stressed by da Silva (2012). One of the crucial aspects of automated dynamic solar shading is choosing the control parameters. In a study by Daum and Morel (2010) it was pointed out that at least two parameters should be used and the importance of internal temperature stood out. Controlling shades based on solar radiation is often used, however illuminance threshold might be a more appropriate solution (Tzempelikos and Shen 2013).

The purpose of this study was to determine an optimal control principle for external shading on different facades in a cold climate. An effective control principle of external venetian blinds was analyzed and the effect of algorith simplifications on the energy use was studied. A generic office
floor was analyzed and the cases were chosen so that the proportion of cooling in total energy use varied. The numbers of window panes, window-to-wall ratios and external wall U-values ranged from 3 to 5, 25% to 60% and 0.09 to 0.16 W/(m² K) respectively.

2. Methods

The study was conducted by simulating 3 different generic office floors with varying façade properties. External or internal automatically controlled dynamic venetian blinds were used. Initially an effective control method was used and then it was simplified to see the effect on energy use.

2.1 Office floor simulation model

Energy simulations were conducted on the basis of a generic open-plan office single floor model that was divided into 5 zones - 4 orientated to south, west, east and north respectively and in addition one in the middle of the building (figure 1). The longer zones consisted of 12 room modules of 2.4 m and shorter ones of 5 room modules, resulting in inner dimensions of the floor 33.6 x 16.8 m. In all cases the heating was district heating with radiators (ideal heaters in the model), and air conditioning with room conditioning units (ideal coolers in the model) and mechanical supply and exhaust ventilation with heat recovery was used. The working hours were from 7:00 to 18:00 on weekdays and the usage factor of heat gains during working hours was 55%. Ventilation worked from 6:00 to 19:00 on weekdays. The lighting was with dimmable lamps and daylight control with setpoint of 500 lx in workplaces. The position of workplaces used for the control is shown in figure 2. The initial data of simulation model is shown in table 1.

![Figure 1: Description of simulation models' geometry. Office floor models with triple, quadruple and quintuple windows (from bottom to top in the 3D figure left) were simulated in separate models.](image)

**TABLE 1** Input data of office rooms and HVAC systems for energy calculations.

<table>
<thead>
<tr>
<th>Occupants, W/m²</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment, W/m²</td>
<td>12</td>
</tr>
<tr>
<td>Lighting, W/m²</td>
<td>5</td>
</tr>
<tr>
<td>Temperature set point for heating and cooling</td>
<td>+21 and +25 °C</td>
</tr>
<tr>
<td>Air flow rate</td>
<td>1.5 l/(s·m²)</td>
</tr>
<tr>
<td>Illumination setpoint at locations (x,y,z)=(2.2, 4.0, 0.9), lux</td>
<td>500</td>
</tr>
<tr>
<td>Frame ratio of windows, %</td>
<td>15</td>
</tr>
<tr>
<td>Heating system (radiators) efficiency, -</td>
<td>0.97</td>
</tr>
<tr>
<td>Heat source (district heating) efficiency, -</td>
<td>1.0</td>
</tr>
<tr>
<td>Cooling system losses, % of cooling energy need</td>
<td>10</td>
</tr>
<tr>
<td>Mechanical cooling SEER, -</td>
<td>3.5</td>
</tr>
<tr>
<td>Temperature ratio of heat recovery, %</td>
<td>80</td>
</tr>
</tbody>
</table>
2.2 Simulation cases

The office floor façade solutions were chosen so that the balance of heating and cooling energy need would vary, which is achieved with differing thermal properties of windows and external walls and also window-to-wall ratios (see table 2 and figure 1). The case names are derived from the number of window panes used in the specific case. Detailed window models were used, which means that the thermal resistance depended on the temperature difference between internal and external conditions.

<p>| Table 2 Description of simulation cases. |</p>
<table>
<thead>
<tr>
<th>Glazing</th>
<th>No of panes*, U-value**, g-value, -</th>
<th>Visible transmittance $\tau_{\text{vis}}$, -</th>
<th>Gas filling</th>
<th>Gap width between panes, mm</th>
<th>Window-to-wall ratio, %</th>
<th>U-value of external walls, W/(m$^2$K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 3</td>
<td>3</td>
<td>0.55</td>
<td>0.45</td>
<td>0.71</td>
<td>Argon</td>
<td>18</td>
</tr>
<tr>
<td>Case 4</td>
<td>4</td>
<td>0.32</td>
<td>0.34</td>
<td>0.63</td>
<td>Krypton</td>
<td>12</td>
</tr>
<tr>
<td>Case 5</td>
<td>5</td>
<td>0.21</td>
<td>0.25</td>
<td>0.56</td>
<td>Krypton</td>
<td>12</td>
</tr>
</tbody>
</table>

* - One is a simple highly transparent pane, the other panes have low emissivity coating ($\epsilon=0.03$)
** - Given according to calculations of ISO 15099:2003/E at internal and external temperature difference of 20 °C

2.3 Control principles

The initial control principle for external venetian blinds chosen as the base for optimization is described in figure 2 and has the following principles:

- The external shade position and slat angle was controlled according to room temperature (always) and illuminance on desktop (only during occupancy)
- The shade position had on/off control with room temperature setpoint slightly below cooling setpoint and the bandwidth was 1.0 °, desktop illuminance setpoint was chosen so that the blinds would be drawn at 1900 lx and the bandwidth varied between 600 and 1400 lx
- The slat angle was adjusted with PI-controllers to keep the room temperature at setpoint and the desktop illuminance at 2000 lx.

![FIG 2. Description of the effective external shading control principle. The abbreviations set and band have been used for setpoint and bandwidth respectively.](image-url)
The simplification/optimization of the control principle was done in the following order (see table 3):

- Cases with internal venetian blinds was simulated for reference (Internal)
- The room control setpoints of initial principle were optimized (Ideal)
- Slat angle was controlled according to sun altitude instead of PI-controllers (Suntracking)
- Vertical irradiance on the façade was used for shade position control (Ver. Irr.)
- External temperature was used for shade position control (Ext. temp.)

A control macro was created in the simulation program IDA ICE 4.5 for each control principle.

### TABLE 3. Shading position and slat angle control principles of studied cases

<table>
<thead>
<tr>
<th>Control principle</th>
<th>Shade position</th>
<th>Slat angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal</td>
<td>Room temperature</td>
<td>Internal 200 W/m²</td>
</tr>
<tr>
<td></td>
<td>Internal blinds, internal vertical irradiance</td>
<td>Sun altitude</td>
</tr>
<tr>
<td>Ideal</td>
<td>24.5 ± 0.5 °C</td>
<td>1400 ± 500 lx</td>
</tr>
<tr>
<td></td>
<td>24.0 ± 0.5 °C</td>
<td>1400 ± 500 lx</td>
</tr>
<tr>
<td></td>
<td>23.5 ± 0.5 °C</td>
<td>1400 ± 500 lx</td>
</tr>
<tr>
<td></td>
<td>23.0 ± 0.5 °C</td>
<td>1400 ± 500 lx</td>
</tr>
<tr>
<td></td>
<td>24.0 ± 0.5 °C</td>
<td>1600 ± 300 lx</td>
</tr>
<tr>
<td></td>
<td>24.0 ± 0.5 °C</td>
<td>1200 ± 700 lx</td>
</tr>
<tr>
<td>Suntracking</td>
<td>24.0 ± 0.5 °C</td>
<td>1600 ± 300 lx</td>
</tr>
<tr>
<td></td>
<td>Irradiance on facade 200 W/m²</td>
<td>Sun altitude</td>
</tr>
<tr>
<td></td>
<td>Irradiance on facade 300 W/m²</td>
<td>Sun altitude</td>
</tr>
<tr>
<td></td>
<td>Irradiance on facade 400 W/m²</td>
<td>Sun altitude</td>
</tr>
<tr>
<td>Ver. Irr.</td>
<td>External temperature 10 ± 1.0 °C</td>
<td>Sun altitude</td>
</tr>
<tr>
<td></td>
<td>External temperature 15 ± 1.0 °C</td>
<td>Sun altitude</td>
</tr>
<tr>
<td></td>
<td>External temperature 20 ± 1.0 °C</td>
<td>Sun altitude</td>
</tr>
</tbody>
</table>

3. Results

3.1 Optimizing setpoints

The results of the simulations of the effective control principle with different room temperature and desktop illuminance setpoints show that the most reasonable setpoint values are 24 ± 0.5 °C and 1400 ± 500 lx (table 4). However other setpoint values in the vicinity of the most optimal ones did not alter the energy performance significantly. Generally internal temperature setpoint value should be chosen slightly lower than the temperature for cooling and the bandwidth for desktop illuminance should be large enough to assure as good daylighting as possible while preventing unnecessary changes frequent changes in the position of venetian blinds. It has to be also stated that the setpoints for vertical irradiance and external temperature resulting in best energy efficiency were 400 W/m² and +20 °C respectively.

3.2 Simplifying control principles

The comparison of control principles showed that dynamic external venetian blinds offer energy savings in all cases compared to internal blinds however choosing the most effective control method is essential for reaching the decrease in energy use. The initial effective control method proved to be most effective for all cases but one, however the primary energy use did not increase significantly if
suntracking i.e. slat angle control according to sun altitude was used. The energy needs and primary energy uses for triple window cases are shown in figures 3 and 4, for quadruple window cases in figures 5 and 6 and for quintuple window cases in figures 7 and 8 respectively. When external shading was controlled according to vertical irradiance or external temperature then the energy use increased for almost all cases compared to effective principles. In most cases the cooling needs of offices with standardized use were fulfilled by supplying cooled air into the rooms, however less effective methods of blind control caused unnecessary additional heating and lighting energy use. The only façade where control according to external temperature seemed to work energy wise was the south, however glare was probably not avoided due to low sun angles in the winter time.

*TABLE 4. The effect of shading control setpoints of room temperature and desktop illuminance on the energy use of studied cases, the whole office floor results have been given and it has been marked if the optimal setpoint value of a façade zone differed from 24.0 ± 0.5 °C or 1400 ± 500 lx*

<table>
<thead>
<tr>
<th>Energy use, kWh/m²</th>
<th>Room temperature setpoint, °C</th>
<th>Desktop illuminance setpoint, lx</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case</td>
<td>24.5 ± 0.5</td>
</tr>
<tr>
<td>Heating</td>
<td>3</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.4</td>
</tr>
<tr>
<td>Lighting</td>
<td>3</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>Primary energy</td>
<td>3</td>
<td>30.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>29.7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>30.0</td>
</tr>
</tbody>
</table>

S – lowest primary energy for south façade
E – lowest primary energy for east façade
W – lowest primary energy for west façade
FIG 3. Energy need of cases with triple windows

FIG 4. Primary energy of cases with triple windows

FIG 5. Energy need of cases with quadruple windows
FIG 5. Primary energy of cases with quadruple window

FIG 6. Energy need of cases with quintuple windows

FIG 7. Primary energy of cases with quintuple windows
4. Conclusions

An optimal control principle for external dynamic venetian blinds facades in a cold climate was determined based on generic office floor simulations. Energy calculations of zones with different orientations were conducted and the results show that controlling shade position according to internal temperature and desktop illuminance is most effective whereas suntracking can be used for slat angle adjustment. The room temperature setpoint for pulling down venetian blinds should be chosen slightly lower than cooling temperature (e.g. +24 °C) and the bandwidth for desktop illuminance should be chosen large enough to assure as good daylighting as possible (e.g. 1000 lx) while preventing unnecessary frequent changes in the position of blinds. Control methods according to external parameters such as vertical irradiance and outdoor temperature did not prove to be effective. The largest savings were obtained for cases with larger windows that had higher initial cooling energy use and the whole floor primary energy was decreased by up to 3.2 kWh/m² by using external venetian blinds. The savings in the primary energy of different orientations ranged from 2.5 to 6.6 kWh/m² in case of large quintuple windows.

5. Acknowledgements

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References

Vertical temperature increase in multi-storey buildings

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KEYWORDS: Thermal indoor climate, indoor temperature, vertical temperature increase, case study, mathematical model, disturbance model

SUMMARY:
Indoor temperature is by measurements stated to rise 0.1 – 0.2°C per storey upwards in multi-storey buildings, despite occupants’ possibility to control the temperature. Due to upward air temperature gradient in rooms there will be a heat transfer through slabs upwards. The size of this depends on insulation degree of building envelope and slabs and air flow through the building.

With a linear mathematical model, considering 1 m² floor area, it is shown how some parameters affect the heat transfer. Starting position for the model is a building in the thermal balance from which deviations are calculated. The model gives, for a basic case, results that agree well with the measured values.

The vertical temperature increase, results in lower temperature in lower storeys and higher temperature in upper storeys. Total temperature rise for 4 – 28 storeys are in the range 0.5 – 0.7°C, which give vertical heat transfer of 0.6 – 1.1 W/m². A better insulated building envelope will increase the vertical temperature deviations. Better insulated slabs between the storeys will decrease the deviations. A building with well insulated envelope should also have well insulated slabs between storeys to limit the vertical heat transfer and temperature differences between storeys.

1. Introduction

For different reasons inhabitants desire different indoor temperature. In a building with individual measuring and billing (IMB) of space heating costs, it is desirable for each tenant to be able to control the temperature in their apartments, e.g. to keep a low indoor temperature to lower the heating cost.

However, this can be difficult to reach, as an apartment, through the slabs, is vertically thermally coupled with the apartment above and the apartment below and horizontally connected with adjacent apartments through the walls (Jensen 1999) and (Danilevskii 2011). The latter connection is normally weaker due to a smaller connection area. An apartment is also coupled to the surroundings via the external walls, bottom and top slabs and via the total air flow through the apartment.

The inner coupling, i.e. between adjacent storeys, depends on the slab construction. With in situ casted concrete slabs, without insulation, we will a U-value of about 2.7 W/m²K.

The thermal coupling for storeys in the middle of the building to surroundings depends on the U-values for facade walls and windows and the ventilation flow. For buildings erected in southern Sweden during 1960’s typical facade U-value, $U_f$, are 0.6 – 1.3 W/m²K and for windows, $U_w$, 3.0 W/m²K (BABS 1960). Typical facade/floor area ratio is 0.4 – 0.5 m²/m² and window/floor area ratio 0.1 – 0.15 m²/m². With these measures the building, calculated per m² floor area, will have a thermal coupling through the facade in the range of 0.6 – 0.9 W/K.

The minimum fresh air flow is 0.35 l/s per m² floor area, which give a thermal coupling of 0.42 W/K per m² floor area.
Temperature measurements in one nine storey apartment building situated in Lund, in southern Sweden, has been done in a system for individual measuring and billing of space heating costs. Measurements from a period of 21 months have been analyzed and temperature differences between vertically adjacent apartments are noticed. Despite the occupants possibility to control their temperature a vertical increase in temperature was registered.

2. Aims and objectives

The overall aim of this study is to, with a theoretical model, show why and how vertically adjacent apartments thermally influence each other.

3. Methods and approach

Based on a case study of an apartment block, the temperature measurements are analyzed, mainly with help of Matlab. A mathematical model to simulate the heat transport upwards in the building is programmed and analyzed in Matlab.

3.1 Case study

3.1.1 Description of the building and its building services

The building with nine storeys and a basement was erected in Lund, in southern Sweden, 1965. It comprises 75 apartments, with 198 rooms, on totally 5150 m² heated area. See Figure 1.

*FIG 1. Location of the 75 apartments. Apartments directly above each other, e.g., 711, 721, ..., 791 are addressed as a column; numbered 1 – 9 from left to right. The entrances face close to south.*

The construction is typical for the period, reinforced concrete frame with lightweight curtain walls and triple glazed windows, the slabs between storeys are of concrete with a plastic mat. The U-values are assumed to comply with Swedish building codes for the building year, see Table 1. The building is one of ten objects in a study with totally 1177 residential apartments (Dahlblom & Jensen 2011). The building is equipped with a two-pipe hydronic heating systems with radiators connected via a heat exchanger to the district heating system. The building is ventilated by a mechanical exhaust
ventilation system with constant air volume at a rate of 0.615 ac/h, which in this case means 0.41 l/(s·m²) floor area. The used principle for individual metering and billing (IMB) of space heating costs are based on achieved indoor temperature. The rent includes a “comfort temperature” of 21°C, for temperatures down to 18°C, tenants will be refunded and, vice versa, for temperatures up to 24°C tenants will be extra charged (Lunds Kommuns Fastighets AB 2011).

**TABLE 1. Assumed properties for the basic case.**

<table>
<thead>
<tr>
<th>Building element</th>
<th>U-value</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facade walls</td>
<td>0.6</td>
<td>320</td>
</tr>
<tr>
<td>Windows and balcony doors</td>
<td>2.5</td>
<td>90</td>
</tr>
<tr>
<td>Ceiling above top floor</td>
<td>0.6</td>
<td>690</td>
</tr>
<tr>
<td>Slab above ground floor</td>
<td>0.6</td>
<td>690</td>
</tr>
</tbody>
</table>

3.1.2 **Data collection and processing**

A housing company has a system for individual measuring and billing of space heating costs (IMB) in about 3000 apartments, in size varying from one to six rooms. The method used for IMB is based on measurements of indoor temperature.

For the IMB-system the building is equipped with one temperature sensor in each room. For this purpose the temperature is measured every 15 minutes in all bedrooms and living rooms and it should, during the 21 months this study covers, at maximum been 12·10^6 readings, but due to shorter and longer interruptions there are 7.5·10^6 readings, i.e. a mean coverage of 62%. Though this data loss, it provides a unique opportunity to investigate indoor temperatures, absolute levels as well as temperature differences between apartments, in this study concentrated to differences between apartments above each other.

3.2 **Vertical temperature differences between storeys for 21 months**

Monthly mean temperature for each apartment was calculated for the covered period January 2010 until September 2011. Differences between seven vertical neighbours in the nine columns (Figure 1) were calculated and are presented in Figure 2.

**FIG 2. Monthly vertical mean temperature difference per storey for January 2010 to September 2011.**
Only seven storeys are included due to floor plan nr 1 and nr 9 differ too much. This means 54 values on temperature differences per month. The temperature rise per storey is between 0.09°C and 0.24°C, in average over all 21 months 0.15°C, average during heating periods is 0.16°C and during non heating periods 0.13°C.

4. Temperature model

The model, illustrated in Figure 3, is normalized to calculate on one square meter floor area. The thermal coupling to the surroundings on each storey is related to one square meter floor area. The coupling depends on U-values for the façade and windows and on the ventilation air flow. The model comprises four temperatures on each storey, the air temperatures at floor level, $T_{\text{air floor}}$, and ceiling level, $T_{\text{air ceiling}}$, the floor surface temperature, $T_{\text{floor}}$, and the ceiling surface temperature, $T_{\text{ceiling}}$.

A temperature difference, $\Delta T$, between air temperatures at ceiling and floor is set to a fixed value, 2°C. This temperature difference is actually created by up going air plumes from radiators, appliances and occupants and down going plumes at cold façades and window surfaces. Figures can be found in (Rietschel 1960). The model is, storey by storey, set up for the whole building.

The convective heat transfer, $P_c$, upwards in the room, is partly balanced by the radiant heat transfer, $P_r$, downwards, from ceiling to floor, described by the parameter $h_r$. The difference between the convective heat transfer, $P_c$, and radiant heat transfer, $P_r$, is equal to the slab heat transfer, $P_s$, if there are no heat losses, in the model $h_n = 0$. This means also that $T_{\text{ceiling}}$ is higher than the floor surface temperature on the next storey, $T_{\text{floor above}}$. The heat transfer through the slab is described with the parameter $h_s$.

The outdoor temperature set to zero as the model describes disturbances from steady state conditions. The model is described as a linear equation system, which means all temperatures are proportional to the assumed temperature difference, $\Delta T$.

$$T_{\text{floor above}}$$

$$T_{\text{air ceiling}}$$

$$T_{\text{floor}}$$

$$T_{\text{ceiling below}}$$

FIG 3. Model for heat transport for one storey

Total thermal coupling, except the vertical, to the surroundings through external walls and windows and air flow through the storey, per square meter floor area, is calculated by equation (1). The air flow is sum of ventilation air flow and infiltration, independent ventilation system type, i.e. it is valid both for exhaust ventilation and balanced ventilation.

$$h_n = U_w \cdot a_w + U_e \cdot a_e + \rho \cdot c_p \cdot q_e$$

(1)
Where:
- \( h_t \): total thermal coupling except the vertical versus floor area (W/(K·m²))
- \( U_w \): U-value windows (W/(m²·K))
- \( a_w \): window area versus floor area (m²/m²)
- \( U_e \): U-value external walls (W/(m²·K))
- \( a_e \): external wall area versus floor area (m²/m²)
- \( \rho \): air density, 1.2 kg/m³
- \( c_p \): specific heat capacity air, 1000 J/(kg·K)
- \( q_e \): exhaust air flow versus floor area (m³/(s·m²))

This thermal coupling for one storey is in the model divided on four nodes, two connected via heat transport due to differences in surface floor and ceiling temperatures and two due to difference in air temperature, in the model described with \( h_t \) and \( h_a \), see Figure 3.

\[
h_n = 2 \cdot h_f + 2 \cdot h_a
\]

(2)

How these couplings are distributed between those 4 nodes are not further investigated and therefore simplified set to be equal, i.e.

\[
h_a = h_f = h_n / 4
\]

(3)

Losses through the top ceiling slab and the bottom floor slab are included in the model, named \( h_{se} \).

### 4.1 Parametric study

To see the influence from different parameters a study, where some parameters are varied, has been carried out. The parameters for the basic case are, as close as possible, chosen to agree with the building in the case study above. Though, as only seven of the nine storeys have the same floor plan, this building height was chosen for the basic case. Note that the building has mechanical exhaust ventilation without heat recovery.

Following cases are studied, for details on parameters, see Table 2.

1. building with 4 storeys
2. building with 14 storeys
3. building with 28 storeys
4. better insulated slab between storeys (lower \( h_t \))
5. better insulated bottom slab and top slab (lower \( h_{se} \))
6. better insulated facades, windows, bottom slab and top slab
7. better insulated facades, windows, bottom slab, top slab and slab between storeys

### 5. Results

Results from the parametric study are presented in Table 2 and Figure 4 and Figure 5. \( AT_{storey} \) in Table 2 was calculated as the total temperature difference between bottom and top storey divided by number of storeys. \( AT_{storey} \) for the basic case is 0.110°C, to be compared to the temperature rise per storey in the case study above, which was in the range 0.1 – 0.2°C. Corresponding heat transport upwards in the building according to the model is in average per storey 0.811 W/m².

For a building with only 4 storeys the temperature rise per storey seems to be linear; when studying buildings with 14 and 28 storeys respectively it is obvious that it is not, the disturbance in the middle storeys is close to zero. The mean temperature difference between bottom and top is approximately 0.7°C for 7, 14 and 28 storeys compared to 0.5°C for 4 storeys.
An insulated slab between the storeys, case 4, will decrease the mean temperature difference from 0.110°C to 0.079°C per storey, i.e. to 72% compared to the basic case, but the vertical heat transport $P_s = h_s \cdot \Delta T_s$ so this will decrease to 28% compared to basic case.

Better insulated bottom and top slabs, case 5, will increase temperature disturbances to 0.137°C per storey, compared to 0.110°C per storey for the basic case.

Case 6 have better insulated building envelope, close to what is required to meet present building codes. We can see a weaker coupling to surroundings and stronger coupling within the building; more heat is transported upwards in the building, the mean per storey, $P_{sm}$, is 0.583 W/m², compared to originally 0.811 W/m² for the basic case.

The last case, nr 7, is like nr 6 but with insulated slabs between the storeys. As can be expected, the temperature difference and hence the heat transport will decrease. The vertical heat transport is halved compared to the basic case, Table 2 and Figure 5.

**TABLE 2. Input parameters for parametric study and results.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Storeys</th>
<th>$U_f$</th>
<th>$U_w$</th>
<th>$h_n$</th>
<th>$h_s$</th>
<th>$h_{se}$</th>
<th>$\Delta T_{build}$</th>
<th>$\Delta T_{storey}$</th>
<th>$P_{sm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>basic</td>
<td>7</td>
<td>0.6</td>
<td>2.5</td>
<td>4.40</td>
<td>10</td>
<td>0.6</td>
<td>0.660</td>
<td>0.110</td>
<td>0.811</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.6</td>
<td>2.5</td>
<td>4.40</td>
<td>10</td>
<td>0.6</td>
<td>0.522</td>
<td>0.174</td>
<td>0.563</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>0.6</td>
<td>2.5</td>
<td>4.40</td>
<td>10</td>
<td>0.6</td>
<td>0.702</td>
<td>0.054</td>
<td>1.031</td>
</tr>
<tr>
<td>3</td>
<td>28</td>
<td>0.6</td>
<td>2.5</td>
<td>4.40</td>
<td>10</td>
<td>0.6</td>
<td>0.702</td>
<td>0.026</td>
<td>1.139</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>0.6</td>
<td>2.5</td>
<td>4.40</td>
<td>4</td>
<td>0.6</td>
<td>0.474</td>
<td>0.079</td>
<td>0.594</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>0.6</td>
<td>2.5</td>
<td>4.40</td>
<td>10</td>
<td>0.1</td>
<td>0.822</td>
<td>0.137</td>
<td>0.709</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>0.1</td>
<td>1.0</td>
<td>2.67</td>
<td>10</td>
<td>0.1</td>
<td>1.038</td>
<td>0.173</td>
<td>0.583</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>0.1</td>
<td>1.0</td>
<td>2.67</td>
<td>4</td>
<td>0.1</td>
<td>0.822</td>
<td>0.137</td>
<td>0.458</td>
</tr>
</tbody>
</table>

**FIG 4.** Mean temperature for the 4 nodes in each storey, i.e. deviation relative to a building in thermal balance, basic case and case 1 - 3.
5.1 Stationary model

Case 3, floor 10-20, show constant temperature conditions. Constant conditions mean that the temperature difference between floor and ceiling surfaces and across a slab is equal, i.e. there is no temperature increase for any level with constant conditions.

Therefore, if external losses are neglected, i.e. $h_n = 0$, the heat power through a slab can be written as $P_s = h_s \cdot \Delta T_s$, where $\Delta T_s$ is the temperature difference across a slab, or as $P_s = P_c - P_r$, i.e. the difference between the convective heat power upward and radiation heat power downward, which can be written as

$$P_c = h_c \cdot \left( \Delta T - \Delta T_s \right)/2$$  \hspace{1cm} (4)

$$P_r = h_r \cdot \Delta T_s$$  \hspace{1cm} (5)

$\Delta T$ is assumed to be $2^\circ C$, while $\Delta T_s$ is unknown.

Inserting $P_c$ and $P_r$ make it possible to decide $\Delta T_s$

$$\Delta T_s = \frac{h_c \cdot \Delta T / 2}{h_s + h_c + h_r / 2} = \frac{1}{2 \cdot h_s / h_c + 2 \cdot h_c / h_r + 1} \cdot \Delta T$$  \hspace{1cm} (6)

Equation (6) shows that $\Delta T_s$ always is less than $\Delta T$, as $h_s$, $h_c$ and $h_r$ always are positive.

The heat, $P_s$, upwards in the building can be expressed as

$$P_s = h_s \cdot \Delta T_s = \frac{h_s \cdot h_c \cdot \Delta T}{2 \cdot h_s + 2 \cdot h_c + h_c}$$  \hspace{1cm} (7)

With values from the basic case, i.e. $h_s = 10$, $h_c = 2$ and $h_r = 5$, we get $P_s = 1.25 \text{ W/m}^2$, compared to $P_{sm} = 1.139 \text{ W/m}^2$ for case 3.
6. Conclusions

The results in the model are close to the measured temperature differences for the building in the case study, which indicates that the model gives reasonable values.

It can be concluded that there is an internal vertical heat transport upwards in multi-storey buildings. The temperature difference between floor and ceiling causes a temperature difference over the slabs between storeys which drive the heat upwards. This results in lower temperature in lower storeys and higher temperature in upper storeys and hardly noticeable deviations in between, shown for buildings with a large number of storeys.

Better insulated slabs between storeys will decrease the temperature deviations.
Better insulated top ceiling and bottom floor will increase the temperature deviations.
Better insulated building envelope will increase the temperature deviations.

A building with these three cases of insulation can result in either decreased, increased or no temperature deviations at all versus the basic case.

A building with a well insulated building envelope should also be well insulated between storeys to limit the vertical heat transport upwards the building and the temperature differences between storeys.

7. Acknowledgements

This study was possible to complete thanks to the large data set provided by LKF.

References


Optimized damper control of pressure and airflow in ventilation systems

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KEYWORDS: ventilation system, HVAC control strategy, variable air volume, static pressure reset, modelling, Simulink, energy savings.

SUMMARY:
Conventional control strategies in variable air volume (VAV) ventilation systems do not take fully into advantage the potential energy savings since the system operation is based on maintaining a constant static pressure (CSP) set point in the main duct irrespective of the actual pressure demand. The static pressure reset (SPR) control strategy can optimize the operation of the supply air fans by adjusting the pressure set point to be just enough to deliver the required airflow to the most critical zone.

This study investigated the operation and energy savings potential of an SPR control algorithm by using the Simulink programming tool which is add-on software to MATLAB mathematical programming language. A model of a VAV ventilation system was created in Simulink based on the International Building Physics Toolbox (IBPT); the IBPT thermal zone was remodelled in order to calculate dynamically the airflow demand according to the zone air temperature. The performance of the Simulink model was evaluated based on the experimental setup of the ventilation system. The SPR control method established stable system operation and was proven efficient to maintain comfortable space conditions while reducing by 14 % the fan energy used in a typical working day.

1. Introduction
In traditional control of variable air volume (VAV) systems the terminal boxes and the air handling unit (AHU) are operated independently without integration. The common practice is to control the AHU to a constant static pressure (CSP) set point corresponding to the pressure rise required under the design full load condition (Wei et al 2004). However in this way the AHU is regulated irrespective of the actual pressure demand. This is because under part load condition the fan is providing excessive static pressure (Wei et al 2004; Federspiel et al 2005; Liu et al 1997) which is dissipated by increasing the airflow resistance of the air distribution network via throttling at the terminal boxes. As a result significant fan power is wasted in mechanical energy losses. By integrating the control of terminal boxes into the building management system (BMS) it is possible to implement the static pressure reset (SPR) control strategy. This method regulates the AHU in real time according to feedback from several individual zones. In this case the fan generates the pressure required in order to satisfy the space conditions in the most critical zone while maintaining the airflow resistance of the distribution network at a minimum (Wang et al 1998). Consequently the fan pressure rise and thus the fan power is reduced. The control method of trim and respond based on zone pressure request alarms is the most efficient SPR strategy since it is more stable, flexible and it minimizes the impact of rogue zones (Taylor 2007). The objective of this paper is to investigate the operation and the potential energy savings of the trim and respond SPR control strategy. A mathematical model of a conventional VAV ventilation system is developed in Simulink (Simulink 2013) and the model is expanded by implementing the optimized SPR control algorithm. The Simulink model operation is validated by experiments performed on the full-scale test system.
2. The Simulink model

The model of the VAV ventilation system was created in the graphical environment of Simulink in Matlab (Matlab 2013) and it was built based on the blocks of the international building physics toolbox (IBPT). The IBPT toolbox (IBPT 2012) is a library of blocks added on Simulink, specially constructed for the thermal analysis in building physics. The construction blocks (external and internal surfaces, windows) provide detailed calculations of the thermal state of every subcomponent in the structure according to the surrounding conditions to which it is exposed. The thermal condition of the zone is calculated according to the heat gained through the building envelope, the systems used for heating, ventilation and air conditioning, the internal gains occurring in the zone and the weather data corresponding to a certain location. The default IBPT blocks for the internal gains and the ventilation system were rebuilt in order to fit the operation needs of the VAV ventilation system. FIG 1 illustrates the Simulink model which consists of three IBPT thermal zones.

FIG 1. The Simulink model of the VAV ventilation system.

2.1 The internal gains

The IBPT internal gains block was configured to include an hourly load schedule of the ventilated zone. The modified block calculates the heat gains based on user defined profiles considering occupants, equipment and lighting use in the zone.

2.2 The ventilation system

The IBPT ventilation system block was remodelled to calculate dynamically the airflow demand ($q_{dem}$) according to the zone air temperature ($T_a$); the strategy is implemented with the ramp functions shown in FIG 2. The user defined data are the minimum ($q_{set,\min}$) and maximum ($q_{set,\max}$) airflow set point required in order to maintain a comfortable temperature range ($T_{set,\min}, T_{set,\max}$) in the zone.
2.3 The fan

The fan operation is regulated according to the tracking error determined as difference between the CSP set point and the duct pressure at the sensor position; the block diagram is shown in FIG 3.

\[ F(s) = \frac{k_f}{T s + 1} \]  

Where  
- \( s \): representation of Laplace transformation (\(-\))  
- \( k_f \): the process gain correlating the plant input with the plant output (Pa/rpm)  
- \( T \): the time constant is the time required to reach the system a steady state condition (sec)

The controller operation complies with equation 2; the tuning of the proportional integral (PI) controller is performed by using the simple analytic rules proposed by S. Skogestad (2002).

\[ n(t) = K_{p,f} e_f(t) + K_{i,f} \int e_f(t) dt \]  

Where  
- \( e_f \): the tracking error between the CSP set point and the pressure sensor reading (Pa)  
- \( K_{p,f} \): the proportional controller gain, 7.14  
- \( K_{i,f} \): the integral controller gain, 17.85

2.4 The damper

The damper operates as shown in FIG 4; the damper position is adjusted based on the tracking error determined as difference between the zone airflow demand (see FIG 2) and the airflow provided to the zone. In the control process in FIG 4 the plant block is representing the damper system that receives the controller signal which corresponds to the damper position. The plant output, the resistance coefficient, is calculated accordingly. The second-order LTI system (Franklin et al 1993) presented in equation 3 approximates the operation of a typical damper (D).
FIG 4. The damper operation principle.

\[ D(s) = \frac{k_d \omega_n}{s^2 + 2 \zeta \omega_n s + \omega_n^2} \]  

(3)

Where 
- \( k_d \) the process gain correlating the plant input with the plant output (m³/s/Pa%)
- \( \omega_n \) the natural frequency relevant to the speed response of the system, assumed 10 rad/s
- \( \zeta \) the damping ratio relevant to the oscillation mode of the system, assumed 1

The controller operation is applied according to equation 4; the tuning gains of the PI controller are set based on typical product values.

\[ dp(t) = K_{p,d} e_d(t) + K_{i,d} \int e_d(t) \, dt \]  

(4)

Where 
- \( e_d \) the tracking error between the demanded and the delivered airflow in the zone (m³/s)
- \( K_{p,f} \) the proportional controller gain, 1
- \( K_{i,f} \) the integral controller gain, 10

2.5 The pressure and airflow solver

The friction and single pressure losses blocks illustrated in FIG 1 implement the hydraulic calculation of the VAV ventilation system according to the duct design shown in FIG 5. The unknown pressure and airflow conditions are determined by setting up a system of equations expressing the pressure losses occurring in every component of the system. The hydraulic calculation determines the pressure demand (P) at the beginning and end of every component as well as the airflows (q) delivered to the different zones (see FIG 5). The system of equations cannot be solved analytically; therefore the Newton-Raphson numerical method is used instead.

FIG 5. The duct design in the pressure and airflow solver block.

In a piece of duct the pressure losses due to friction are calculated according to the Darcy-Weisbach equation (White 1998) given in equation 5. The Darcy friction factor is obtained by the Swamme-Jain equation (Swamme et al 1976), which is an approximation of the implicit Colebrook-White equation (see equation 6).
\[ \Delta P_{fr} = f_D \frac{L \rho}{d^2} u_{air}^2 \]  \hspace{1cm} (5)

Where  
\( f_D \)  the Darcy factor (-)  
\( L \)  the length of the duct (m)  
\( d \)  the diameter of the duct (m)

\[ f_D = \frac{0.25}{\left( \log_{10} \left( \frac{5.74 \cdot Re^{\frac{1}{3}} + \varepsilon}{3.7d} \right) \right)^2} \]  \hspace{1cm} (6)

Where  
\( Re \)  the Reynolds number (-)  
\( \varepsilon \)  the roughness height, for thin plate ducts is equal to \( 0.15 \times 10^{-3} \) m

The pressure losses due to connections and fittings are calculated according to equation 7.

\[ \Delta P_{sing} = \frac{\zeta_r u_{air} \rho}{2} \]  \hspace{1cm} (7)

Where  
\( \zeta_r \)  the resistance coefficient (-)  
\( u_{air} \)  the mean velocity of airflow (m/s)  
\( \rho \)  the density of air, 1.204 kg/m\(^3\)

The pressure losses introduced by the damper component are approximated based on equation 8.

\[ \Delta P_{sing} = \left( \frac{q_{del}}{k_{value}} \right)^2 \]  \hspace{1cm} (8)

Where  
\( q_{del} \)  the airflow delivered to the zone (m\(^3\)/s)  
\( k_{value} \)  the damper resistance coefficient (m\(^3\)/sPa)

### 2.6 The static pressure reset algorithm

In order to implement the SPR control method of trim and respond based on zone pressure request alarms, one more block was added to the Simulink model presented in FIG 1. The operation principle of the applied control logic can be seen in FIG 6.

**FIG 6. The control logic of the trim and respond static pressure reset method.**

Every damper of the VAV system transmits an alarm signal when its position exceeds 85 % opening; the zone keeps generating a pressure request until the damper closes to a position of 80 % opening. The pressure requests from all zones are summed and when at least two zones give an alarm the fan pressure set point is reset 10 % upwards of the pressure demand at the sensor position. In the opposite case it is reset 5 % downward. The SPR is performed within a specific pressure range; the upper limit is set equal to the CSP set point while the lower SPR limit is determined according to the pressure demand ensuring precise damper operation. The SPR loop resets the pressure set point every 90 sec...
and the fan adjusts to the new pressure set point.

3. The experimental setup

The performance of the Simulink model was validated on a full scale experimental setup; the experimental setup arrangement was identical to the duct design given in FIG 5 where the distribution duct had a diameter of 315 mm and the connection ducts a diameter of 160 mm. The setup consisted of three LeanVent DropDamper LERX and a box fan (Exhausto BESF1804-1EC). The VAV system was evaluated both with the CSP and the SPR control strategy; the two methods were modelled in LabVIEW (LabVIEW 2013). The validation was performed by providing the Simulink model and the experimental setup with the same airflow demand data; two different airflow demand profiles were used for testing the model performance with each control strategy (see FIG 7). Ventilation zone 3 behaved like a rogue zone with the SPR method because the lower limit of the pressure range, within which the fan operation set point reset, was insufficient for delivering the required pressure.

FIG 7. Airflow demand profiles with the CSP and the SPR control method, respectively.

4. Results

4.1 Simulink model validation

The graphs in FIG 8 compare the performance of the Simulink model and the experimental setup of the VAV ventilation system when the fan was controlled with the CSP and the SPR control method, respectively.

FIG 8. Response curves of the dampers with the CSP and the SPR control method, respectively.
According to the obtained results the Simulink model with both control strategies approximated satisfactorily the actual operation conditions since the dampers followed a similar response trend. The largest deviation between the Simulink model and the experimental setup was obtained from damper 2 when the VAV system was regulated with the SPR control method. As presented in the second graph in FIG 8 the deviation was below 10 %, however in the last minutes it increased to 22 %. This occurred because the damper modelling represented insufficiently the actual speed response of the Dropdamper. The mathematical model of the damper should be tuned to coincide with the experimental data. The speed of the damper model is relative to the natural frequency parameter involved in the mathematical expression describing its response (see equation 3). In this case the speed of the damper was assumed; in order to accelerate the response, trial and error simulations have to be performed increasing the natural frequency.

4.2 Energy savings from optimized damper control

The energy savings potential of the SPR control strategy is determined based on the fan power used when controlling the ventilation system with the CSP and the SPR method, respectively. Considering that the fan efficiency varies according to the different pressure and airflow conditions that the fan is operating with, the fan efficiency was approximated from producer table values by using average hourly values of airflow and pressure rise delivered by the fan. The average hourly values were derived based on 24 hour simulation data obtained from the Simulink model of the VAV ventilation system when operated with both control strategies. The fan power was calculated according to equation 9.

\[
Power = \frac{\Delta P_{\text{fan}} q_{\text{tot}}}{n_e}
\]

(9)

Where $\Delta P_{\text{fan}}$ the fan pressure rise (Pa)

$q_{\text{tot}}$ the fan airflow (m$^3$/s)

$n_e$ the fan efficiency (-)

The fan energy used in a typical working day in winter when the occupancy period was set from 8 am to 17 pm with the CSP and the SPR was determined to 151 Wh and 130 Wh, respectively; the energy consumption was reduced approximately by 14 %. The highest energy savings potential of the SPR control method occurred under part airflow conditions as the fan operated with decreased static pressure. Due to the fact that the fan was correctly sized the combination of lower pressure set point and airflow improved fan efficiency and thus the energy savings were further increased. With the CSP control method the same airflow conditions combined with increased static pressure lowered the fan efficiency and as a result the fan operated inefficiently.

5. Conclusions

The results presented in this paper draw the following conclusions:

- The first and the second-order LTI systems were proven representative for the response of the fan and the damper, respectively. For the current study we assumed the parameters of the mathematical model of the damper ($\zeta$, $\omega_n$). The value of the natural frequency parameter turned to be inaccurate for representing the speed response of the Dropdamper as it introduced high deviation to the Simulink model when it was controlled with the SPR control. The damper mathematical model should be tuned to fit the experimental data.

- The SPR control method documented higher energy savings under part airflow conditions where the fan operated with decreased pressure set point.

In practical applications of the SPR control strategy caution should be given when determining the lower limit of the pressure range within which the variable fan operation set point is established. This
parameter is critical because in case that the minimum fan pressure rise is insufficient to satisfy the system pressure demand, the far located zones will act as rogue zones. Therefore it is advisable to perform airflow measurements in order to ensure that the set point selected is appropriate for the precise operation of the dampers. In order to maximize the energy savings potential of the SPR control method, the fan should be correctly sized; in this case the fan efficiency improves when the fan operates with decreased static pressure.

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References


Variations in indoor temperature in residential apartments of different size and building category

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KEYWORDS: Indoor temperature variations, residential apartments, thermal indoor climate, case study, individual metering and billing.

SUMMARY:
In a case study, comprising 1177 residential apartments with 3248 rooms, temperature registrations every 15th minute in all living-rooms and bedrooms, during one year, in the system for individual metering and billing of space heating costs, were analyzed. The apartments were divided into two categories, apartment blocks from 1960th and row houses from about 1990. Apartments mean temperatures and standard deviations as a function of apartment size and category was compared. Corresponding was done on room level divided on apartment size for the two building categories. Finally, temperatures in bedrooms were compared to those in living-rooms for two objects from each category; presented in duration charts based on all single 15th minute values. The same pattern between different apartment sizes is kept for all month, though with a seasonal variation. The living-rooms are in mean warmer than bedrooms. The larger the apartments are the larger are the differences. The results provide a more nuanced picture of the temperature conditions in homes beneficial for better input data for building energy simulations.

1. Introduction
Knowledge of real indoor temperatures is important both in terms of thermal comfort and as the temperature affects the building's energy need for space heating. When performing simulations of the energy need in the design stage assumptions of what indoor temperatures the building will have must be done. To get reliable results it is necessary to use realistic indoor temperatures, an underestimation of 1°C give at least 5% error in the space heating need in Nordic climate. Both the absolute level and statistical measures of the variation of the indoor temperature are important to know.

Indoor temperatures in residential buildings have recently been studied by Pavlovas (2006), Bøkenes et al (2009), Yohanis et al (2010), Bagge et al (2011) and Kavgic et al (2012). Today's detailed knowledge of indoor temperature and its variations in different aspects, as dependency of apartment size, building age, time of the day, etc., in residential buildings is however limited. Bøkenes (2009) and Yohanis et al (2010) present detailed data for temperature variations between different rooms within apartments on Ireland. However, the habits in Northern Ireland do not agree with Scandinavian; the temperatures there are clear below what we can see in studies from Scandinavia. When looking at the residential building stock, it is of interest to know whether there are differences for example between rooms. People sometimes express a preference to have lower temperature in the bedroom. The type of homes and accordingly type of building technique may also be significant. Will the indoor temperature be different in older apartment blocks compared to newer row houses? Differences in plan, exterior surfaces and insulation level of the building envelope may imply different temperature and distribution. These are some objectives which this study strives to examine and gain increased detailed knowledge about.
In southern Sweden a housing company has implemented a system for individual measuring and billing of space heating costs (IMB) in about 3000 apartments, in size varying from one to six rooms. The method used for IMB is based on measurements of indoor temperature. The temperature is measured every 15th minute in all bedrooms and living-rooms. This provides a unique opportunity to investigate indoor temperatures, absolute levels as well as temperature distribution between rooms in different apartments.

2. Aims and objectives

The overall aim of this study is to investigate and present how indoor temperature varies between rooms in apartments of different size in multi-family buildings of mainly two types, apartment blocks and row houses, to give a more differentiated picture of the thermal climate in these types of buildings. A second aim is to contribute to more refined temperature data for energy simulations in apartment buildings.

3. Method and approach

In a case study of ten residential properties (here known as objects) with totally 1177 apartments and 85715 m² heated area, the temperature measurements, primarily used for individual metering and billing (IMB) of space heating costs, are analyzed from different aspects, mainly with help of Matlab.

3.1 Description of objects

Basic data for the ten objects this study covers are presented in Table 1. Nine of them are situated in the city of Lund in southern Sweden (55°42′N, 13°12′E) and one just outside. The climate in Lund (55°42′N, 13°12′E) is oceanic with relatively mild winters despite the northern location. Temperatures during winter are mainly around 0°C and summer 14-22°C; yearly precipitation approximately 600 mm, sparsely as snow; prevailing wind direction W-SW.

The objects can, based on house type, be divided into two categories; apartment blocks (object 1-6) vs. row and semidetached houses (object 7-10). These two categories also represent two groups of age, the block houses are built 1963-1973, i.e. before the oil crisis, and houses in the other group are built during 1986-1995. Hence they are built according different building codes; the energy efficiency requirements got stricter step by step from 1973. Detailed information of building envelope construction was however not available. The apartment sizes in the first group are 1-4 rooms and kitchen with a total mean area of 69.3 m² and average room size of 26.2 m². The apartment sizes in the second group are 2-5 rooms and kitchen with a total mean area of 78.0 m² and average room size 26.6 m². More data about the studied building stock can be found in Dahlblom et al (2011).

The buildings are equipped with two-pipe hydronic heating systems with radiators. Nine objects are connected to district heating and the tenth has a natural gas fired boiler. Object 1-3 close to each other, share one substation, the other have one each and underground distribution pipes connecting the buildings in the object. The major part has exhaust ventilation systems with fans placed on the roof, two have balanced ventilation with heat recovery, see Table 1. The heating system was balanced and new thermostatic radiator valves were installed in all buildings before this study was performed. All buildings are subject to IMB of space heating. The set point indoor temperature is 21°C and the tenants can vary their indoor temperatures between 18 and 24°C with help of a thermostatic valve on each radiator.
TABLE 1. Basic data for the 10 objects.

<table>
<thead>
<tr>
<th>Object number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of buildings</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>4</td>
<td>10</td>
<td>11</td>
<td>14</td>
<td>14</td>
<td>53</td>
<td>116</td>
</tr>
<tr>
<td>No of floors</td>
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<td>9</td>
<td>9</td>
<td>2</td>
<td>3</td>
<td>3 - 4</td>
<td>1 - 2</td>
<td>2</td>
<td>1 - 2</td>
<td>1 - 2</td>
<td>1 - 9</td>
</tr>
<tr>
<td>No of apts</td>
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<td>75</td>
<td>130</td>
<td>118</td>
<td>72</td>
<td>276</td>
<td>85</td>
<td>133</td>
<td>93</td>
<td>172</td>
<td>1177</td>
</tr>
</tbody>
</table>
| DH = district heating, H = heat pump, NG = natural gas, S = solar collector, EAH = exhaust air heat pump, EVS = exhaust ventilation system, BHR = balanced ventilation with heat recovery.

3.2 Individual metering and billing of heating costs in the studied objects

The used principle for individual metering and billing (IMB) of space heating costs are based on achieved indoor temperature. The rent includes a “comfort temperature” of 21°C, for temperatures down to 18°C, tenants will be refunded and, vice versa, for temperatures up to 24°C tenants will be extra charged (LKF 2011). For the apartments in this study it will mean maximum of ±1200 SEK a year (135 € a year), to be compared with the mean rent 77000 SEK a year (8700 € a year) for the average apartment size.

3.3 Data collection and processing

The system for individual metering and billing of space heating registers indoor temperatures in all living-rooms and all bedrooms in the buildings. Thus, the number of sensors in each object is equal to the number of rooms in the object, see Table 1. The temperature sensor was calibrated during production to show a temperature reading with accuracy better than ± 0.15 °C (Sygel 2008). The temperature sensors are placed on internal walls, 3 – 4 m from the façade wall. They mainly measure the air temperature, but due to their position the difference between air temperature and operative temperature can be assumed to be small. Data from January until December 2010 was processed.

The system is supposed to register temperatures every 15th minute, which could have meant nearly 114 million readings for the studied period of 12 months. Unfortunately there have been data losses, partly due to interruptions in communication with the data server, partly due to scheduled interruptions during the summer. When communication is broken, the system inserts 21.0 °C, which leads to an overrepresentation of the temperature 21.0 °C. The retrieved data is processed by Matlab, excessive numbers of 21.0 °C readings are filtered and for shorter interruptions interpolated temperatures are inserted, longer are ignored. After this the available amount of data is 82 million temperature readings, i.e. 72 % average coverage over the year, and covering 79% of heating periods during 2010.

The living-rooms are generally about twice as large as the mean bedroom area, thus, when calculating apartment mean temperatures, living-rooms maybe should have been given double weight, which is not done here.
4. Results

4.1 Temperatures due to apartment size and building category

Figure 1 presents monthly mean indoor temperature and standard deviations for January-April and October-December 2010, i.e. months during heating periods, for varying apartment size divided on the two categories apartment blocks and row houses. Small variations in monthly mean temperature between apartments of different size can be observed, the same pattern is obtained for all months, e.g. apartment size 2 R&K in apartment blocks are always little colder than the others. The standard deviations do not differ much, but is somewhat larger for 5 R&K in the category row houses. There is also a seasonal variation, i.e. the indoor temperatures are not independent of outdoor temperature, and there are no cooling possibilities except free cooling by window airing.

![Graph showing monthly mean values and standard deviations for heating months on apartment level. Apartment size for category block houses are 1 R&K, 2 R&K, 3 R&K and 4 R&K respectively and for category row houses are 2 R&K, 3 R&K, 4 R&K and 5 R&K respectively.]

4.2 Temperatures due to room type and building category

In Figure 2 and 3 the temperatures are further divided and, for the two categories, mean temperatures for living-rooms and bedrooms are separated. Broken down to room level, generally the living-rooms are warmer than bedrooms, the larger the apartment, the larger is maximal difference between living-rooms and bedrooms. About the same pattern can be observed in both categories and the pattern is kept for all month.

More detailed, on object level for apartment blocks, the mean values for the heating periods are between 21.3°C and 21.7°C with standard deviations in the range 1.11-1.34°C. Corresponding values on object level for row houses are mean temperatures between 21.5°C and 21.8°C with standard deviations in the range 1.22-1.40°C, i.e. objects in category row houses are warmer with larger standard deviations.
FIG 2. Monthly mean values and standard deviations for heating months on room level, divided on apartment size, for the category block houses. Solid lines are living-rooms, dashed lines bedrooms.

FIG 3. Monthly mean values and standard deviations for heating months on room level, divided on apartment size, for the category row houses. Solid lines are living-rooms, dashed lines bedrooms.
4.3 Temperature due to room type on object level

An even better overview of the differences between different rooms in apartments can be obtained from duration charts. Figure 4 – Figure 5 show, for two objects from each category, temperature differences between bedrooms and living-rooms, divided on apartment size. The scale on the x-axis is relative duration, i.e. compared to the total length of heating periods. The zero-line represents the mean temperature in the living-rooms in the object, the thick line represent the difference between mean temperature in living-rooms and bedrooms nr 1, the thin line d:o for the bedrooms nr 2, etc for broken and chain lines. The vertical lines show the breaking point when bedrooms mean temperature shift from colder to warmer than the living-rooms.

It can generally be noted that the temperature are lower in bedrooms, different bedrooms follow each other fairly well, with some exceptions, especially for larger apartments. Object 2 and object 8 are the two objects where the differences are largest, object 4 and 10 represent well the pattern in the other objects. Generally the differences are larger the larger the apartments are. From Figure 4 and Table 2 can for example be seen for object nr 2, apartment size 2 R&K that bedrooms nr 1 are colder than the living-rooms during approximately 35% of the heating periods (thick line). Accordingly, for apartment size 4 R&K, bedrooms nr 1 are colder during 94% of the heating periods, bedrooms nr 2 during 55% and bedrooms nr 3 during 27% of the heating periods (see Table 2). Remaining time the opposite situation is prevailing, i.e. bedrooms are warmer than living-rooms.

It is also possible to read out the largest differences in mean temperature, e.g. for bedrooms nr 1 in 4 R&K it is maximum 3°C colder, but only for a few hours. Temperature differences at 10<sup>th</sup> and 90<sup>th</sup> percentiles for the different bedrooms divided on apartment size and object are presented in Table 2, where also the relative duration for breakeven of bedroom and living-rooms temperature is reported. The temperature range between 10<sup>th</sup> and 90<sup>th</sup> percentile varies from 1.2°C to 3.1°C.

**FIG 4. Duration for temperature difference between living-room and bedrooms; thick = bedroom 1, thin = bedroom 2 and broken = bedroom 3. Object 2 and 4, category apartment blocks.**
FIG 5. Duration for temperature difference between living-room and bedrooms; thick = bedroom 1, thin = bedroom 2, broken = bedroom 3 and chain = bedroom 4. Object 8 and 10, category row houses.

TABLE 2. Relative duration of equal temperature (dur_{0\%}) and temperature differences at 10th and 90th percentiles (\Delta T_{p10} and \Delta T_{p90}) for bedrooms and living-room for different apartment size and object.

<table>
<thead>
<tr>
<th>size</th>
<th>2 R&amp;K</th>
<th>3 R&amp;K</th>
<th>4 R&amp;K</th>
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<tbody>
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<td>0.35</td>
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5. Conclusions and discussion

Based on the large data set it can be concluded that the indoor temperature for the category row houses are slightly higher than for category apartment blocks, though they have the same set point temperature, 21°C. The standard deviations are also slightly higher. In both categories apartment size 2 R&K has the lowest mean temperatures, all over the heating periods (Fig 2). Differences in mean temperatures between living-rooms and bedrooms, within apartments for all apartments in each category, are in the range 0.1°C – 0.5°C, larger for larger apartments (Fig 3).

The temperatures in bedrooms are generally below the temperature in living-rooms, but with large individual variations. The 10th percentile temperature difference is in the range -2.0°C to -0.6°C, with extremes on -3.4°C. Though the bedrooms are not always colder, the 90th percentile temperature difference is in the range 0.0°C to +1.9°C, with extremes on +2.3°C.

Only measuring one temperature in each apartment, as is done in some systems for IMB, may not give representative values. This study shows that deviations for single apartments in the dignity of 0.5°C, up to 0.75°C, can occur, if living-room temperature is used instead of apartment mean temperature.

The results can be beneficial as more refined temperature data for energy and moisture simulations in apartment buildings.

The floor plans and household size and composition are unknown and how these parameters affect the indoor temperatures have not been investigated. The fact that apartments of size 2 R&K have the lowest temperature may be explained by the number of person living in the apartment. Generally apartment of 1 R&K and 2 R&K are occupied only by one person, which means lower occupation density for 2 R&K, followed by lower heat gains from lighting, appliances etc.

6. Acknowledgements

This study was possible to complete thanks to the large data set provided by LKF.

References


SIMULATION STUDY OF SOLAR CHIMNEY ASSISTED SOLARIUM

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KEYWORDS: Natural ventilation; Solarium; Solar chimney; Simulations

SUMMARY:
The objective of this study is to develop a modelling method for optimizing the design of a Solar Chimney Assisted Solarium (SCAS) to maximize the ventilation rate in the solarium. A thermal model is developed and implemented in SIMULINK to simulate the thermal response of the solarium combined with a solar chimney based on the first principle of thermal engineering. Thermal simulations are performed for critical summer days. The greenhouse air temperature and its ventilation rate with various geometrical configurations are calculated on the basis of solar irradiance intensity and ambient temperature. The preliminary numerical simulation results show that a solar chimney, combined with an appropriately inclined roof of a solarium, would be a better option for ventilation improvement in the solarium. The cross sectional air movement produced by a SCAS in an adjacent building maintains the interior condition within the adaptive and predictive comfort standard limits in about 85% of the month of July resulting in a potential cooling energy saving.

1. Introduction
The potential of a solarium system to reduce the temperature swing and heating demand of the house and achieve big savings in the operating costs of the building has been explored in several studies and was found to be satisfactory (Bastien and Athienitis, 2010; Mihalakakou 2000). Most of these studies, however, ignored the ventilation requirements of the solarium, despite the fact that Bryn and Schiefloe (1996) found that an improper design may cause overheating, resulting in an increase in the energy consumption of the building. Moreover, the solar chimneys can contribute to the production of the natural ventilation when they are applied to buildings (Marti-Herrero and Heras-Celemin, 2006). A solar chimney consists of one or more walls of a vertical chimney that are made transparent by providing glazed walls. The solar chimney contributes to building conditioning by using solar radiation to produce convective air flow. A study by Ekechukwu and Norton (1997) showed that the buoyancy force is proportional to the air density variation between the inside chimney air and outside air. Several studies on the ventilation of crop dryers and atriums have also been carried out. These studies demonstrate that using a solar chimney in conjunction with a highly glazed space can ensure stable natural ventilation performance even without encouragement of wind force (Afriyie et al., 2009 and Reuss et al. 1997). However, most of these studies were based on steady state conditions (Ong and Chow, 2003; Bashiouny and Koura, 2008). Studies subjected to dynamic climate conditions were mostly performed for typical buildings for hot and arid climates.

Research to date does not appear to consider the application of a solar chimney as the means of solar-driven natural ventilation in a solarium. To provide a more realistic assessment of the feasibility, benefits and potential improvement of this application, thermal and airflow simulations under dynamic conditions should be performed for solarium ventilated with solar chimney.

This paper develops a numerical model to investigate the dynamic performance of an inclined solarium combined with a solar chimney under transient conditions.
2. Physical model

In this study, a simple two-story residential building has been simulated with various solariums and solar chimney configurations. The simulated solarium is assumed to be located on the south side of a building in the region of Toronto, Canada with the glass wall facing south. A vertical solar chimney has been used in conjunction with inclined roof of the solarium to enhance the ventilation through the solarium. The schematic side section of the SCAS is presented in FIG. 1. As shown in this figure, air from the adjacent room in the house enters the solarium through a bottom inlet. This air is then heated up in the solarium and flows upwards and heated up further in the solar chimney. The air finally exits into the ambient, producing flow from living space to the outdoor. Uniform cross sections are assumed throughout the solar chimney in this application.

FIG. 1. Schematic side section of the SCAS: Ws and Ls are the width and height of the solarium (m); Wsc and Lsc are width and height of the chimney (m) and Ai and A0 are inlet and outlet areas of the openings (m²)

The back walls in both chimney and solarium and the solarium floor are made of concrete, acting as thermal mass. Thermal inertia of these components converts them to a heat source for the air inside the SCAS when solar radiation is not available. These concrete elements are well insulated.

3. Mathematical model

3.1 Heating model

The energy balance method is employed to determine different temperatures inside the solarium and the solar chimney. FIG. 2 illustrates the physical heat exchange process in this model. Since the heat transfer in highly glazed spaces such as a solarium is a very complicated process, the following assumptions have been made to simplify the model.

- The air temperatures inside the solarium and the solar chimney are assumed to be well mixed and have values of Tfs and Tfsc at every time n respectively.
- The glass surfaces in the solarium and the chimney, concrete walls and floor in the chimney are also assumed to have constant temperature values of Tgs, Tgsc, Tw, Twsc and Tb respectively.
- Thermal inertia of the glass and the air inside the SCAS are negligible.
- Heat flow in the model is steady and one dimensional.
- The glass walls and roof are opaque to the long-wave radiation from thermal masses.
FIG. 2. Heat transfer process in the dynamic model of SCAC

In FIG. 2, $S_g$, $S_w$ and $S_b$ are solar radiation incident on the glass wall, concrete back wall and floor of the solarium respectively, $h_{wrb}$, $h_{rwg}$ and $h_{rbg}$ are radiative heat transfer coefficient between wall and floor, wall and glass cover, concrete floor and glass cover and glazing and the sky, $h_w$, $h_b$ and $h_g$ is the convective heat transfer coefficients of wall, concrete floor and glass cover and air inside the solarium, $h_{c,int}$ and $h_{r,int}$ are convective and radiative heat transfer coefficients between wall and adjacent room, $h_{wind}$ and $h_{rgs}$ are convective and radiative heat transfer coefficients between glass cover and ambient due to the wind and sky respectively, $U_w$ and $U_b$ are the U values of the back wall and concrete floor, $T_{wi}$ and $T_{bi}$ are the temperatures of concrete wall and floor in each inside node, $T_{w0}$, $T_{w1}$, $T_{b0}$ and $T_{b1}$ are the surface temperatures of concrete wall and floor and $T_i$ and $T_r$ which have the same values are the temperature of adjacent living space which enters the SCAS.

3.1.1 Solarium and solar chimney concrete walls and solarium concrete floor heating models

The energy balance on the concrete wall of the solarium can be expressed as:

$$S_w + h_{wrb}(T^n_w - T^n_b) = h_{rwg}(T^n_w - T^n_g) + h_w(T^n_w - T^n_f) + U_w(T^n_w - T^n_r) + \rho C_p \frac{dT}{dt}$$

(1)

The energy balance on the concrete wall of the solar chimney is as follows:

$$S_w + h_{wrb}(T^n_w - T^n_b) = h_{rwg}(T^n_w - T^n_g) + h_w(T^n_w - T^n_f) + h_{wfs}(T^n_w - T^n_{sky}) + h_{wind}(T^n_w - T^n_f) + \rho C_p \frac{dT}{dt}$$

(2)

Where $T_{sky}$ sky temperature which is given by (Swinbank, 1963):

$$T_{sky} = 0.0552T^{1.5}$$

(3)

Where $T$ represents ambient temperature

The energy balance on the solarium concrete floor as follows:

$$S_b + h_{rbg}(T^n_b - T^n_w) = h_{rbw}(T^n_b - T^n_w) + h_b(T^n_b - T^n_f) + U_b(T^n_b - T^n_e) + \rho C_p \frac{dT}{dt}$$

(4)

The temperatures of each heat absorbing walls and the floor are characterized by 14 interior temperatures of $T_{w0}$, $T_{w1}$, $T_{b0}$ and $T_{b1}$. These are calculated employing conductive heat transfer equation in a solid.

3.1.2 Solarium and solar chimney fluid (inside air) heating models

The energy balance of the air inside the solarium and the solar chimney, considering the air being well mixed and having one unique temperature ($T_i$), has the following time dependant expressions:
Solarium:

\[ h_L (T_f^n - T_g^n) + M (T^n - T_r^n) = h_w (T_0^n - T_f^n) + h_b (T_0^n - T_r^n) \]  \[(5)\]

Solar chimney:

\[ h_g (T_0^n - T_g^n) = h_g (T^n - T_s^n) + M (T^n - T_p^n) \]  \[(6)\]

Where \( M \) is heat that leaves the solarium, can be expressed as:

\[ M = \frac{mc_f}{\gamma WL} \]  \[(7)\]

\( \dot{m} \) is the air volume that cross the solarium (kg/s) and has the following form ((Bansal et al., 1993 and Andersen, 1995)):

\[ \dot{m} = C_d \frac{\rho v_o A_o}{1 + \left(\frac{A_o}{A_f}\right)^2} \sqrt{\frac{2gL(T_{fsc} - T_r)}{T_r}} \]  \[(8)\]

\( c_f \) the heat capacity of the air

\( \rho \) density of the air (kg/m³)

\( v_o \) air velocity when leaving the chimney (m/s)

\( C_d \) coefficient of discharge of air channel, 0.57 (Flourentzou et al. 1997)

\( T_f \) mean fluid temperature (°C)

\( \gamma \) Coefficient of heat transfer to the air stream which flows out, Afriyie et al. (2011)

found the value of 0.756 for the \( \gamma_{sc} \) and explored that for various configurations of the solarium \( \gamma_g \) is dependent on the tilt angle (°Rad) and has the following form:

\[ \gamma_g = -0.3856\theta^2 + 1.084\theta - 0.0844 \]  \[(9)\]

The heat transferred to the air stream inside the solarium can be rewritten as follows:

### 3.1.3 Solarium and solar chimney glass cover heating models

With assumptions stated in 3.1, the energy balances on the glass walls of the solarium and the solar chimney can be expressed as:

\[ S_b + h_g (T_f^n - T_g^n) + h_{rwg} (T_0^n - T_g^n) + h_{rbg} (T_0^n - T_r^n) = h_{bwind} (T_g^n - T_a^n) + h_{rgs} (T_g^n - T_{sky}^n) \]  \[(10)\]

\[ S_b + h_g (T_f^n - T_g^n) + h_{rwg} (T_0^n - T_g^n) + h_{rbg} (T_0^n - T_r^n) = h_{bwind} (T_g^n - T_a^n) + h_{rgs} (T_g^n - T_{sky}^n) \]  \[(11)\]

### 3.1.4 Heat transfer coefficients

Convective heat transfer coefficient due to the wind can be calculated using the following correlation (Palyvos, 2008):

\[ h_{b\text{wind}} = 7.4 + 0.4V \]  \[(12)\]

Where \( V \) the wind velocity (m/s)

According to Duffie and Beckman (1980) and Incropera et al. (2007), the convective heat transfer coefficients between air and wall, glass and solarium floor can be calculated using the following equations:
\[ h_i = \frac{Nu \cdot k_f}{L_i} \]  

(13)

Where  

- \( i \) represents glass, wall and floor  
- \( k_f \) thermal conductivity of air (W/m K)  
- \( Nu \) Nusselt number, has the following mathematical forms (Incropera and DeWitt, 1996):

Laminar flow, \( Ra<10^9 \)

\[ Nu = 0.68 + \frac{0.67Ra^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{4/9}} \]  

(14)

In case of turbulent flow when \( Ra>10^9 \)

\[ Nu = \left[ 0.825 + \frac{0.387Ra^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}} \right]^2 \]  

(15)

\( Ra \) Rayleigh number  
\( Pr \) Prandtl number  
\( \alpha \) thermal diffusivity of air  
\( \beta \) coefficient of expansion of air (1/K)  
\( \mu_f \) dynamic viscosity (kg/m s)  
\( g \) gravitational constant (m/s)

Physical properties of the air that were introduced by Ong and Chow (2003) have been used in the study. The convective heat transfer coefficient between collecting wall and the living space, \( h_{c,int} \), can be calculated as:

\[ h_{c,int} = 1.3 |T_w - T_i|^{1/3} \]  

(16)

The radiative heat transfer coefficient between back wall and the glazing and the living space in both the solar chimney and the solarium can be calculated (Marti- Herrero and Heras-Celemin, 2006):

\[ h_{r,reg} = \frac{\sigma(T_{w} + T_i)(T_{w}^2 + T_i^2)}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1} \]  

(17)

\[ h_{r,int} = \frac{\sigma(T_{w} + T_i)(T_{w}^2 + T_i^2)}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_r} - 1} \]  

(18)

Where \( \sigma \) is the Stefan–Boltzmann constant, \( \sigma = 5.67 \times 10^{-8} \)

The radiative heat transfer coefficients between solarium concrete floor with the glass cover and concrete, based on Afriyie et al. (2011) are expressed as follows:

\[ h_{f,shi} = \frac{\sigma}{A_b} \frac{(T_b + T_i)(T_b^2 + T_i^2)}{1 - \varepsilon_b + \frac{1 - \varepsilon_i}{\varepsilon_i A_b} + \frac{1}{A_b}} \]  

(19)

The following equation represents the coefficient of radiative heat transfer between glass cover in the solarium and the solar chimney and also chimney back wall and the sky (Marti- Herrero and Heras-Celemin, 2006):

\[ h_{ris} = \sigma(T_i + T_{sky})(T_i^2 + T_{sky}^2) \]  

(20)
4. Results and discussion

A thermal simulation using MATLAB/SIMULINK was performed for the critical summer days (15-18 July) to predict the thermal performance of the greenhouse and the solar chimney using the actual weather data for Toronto (FIGs. 3-4). The results are shown in FIGs 5-8.

As shown in FIG. 5 the fluid (inside air) temperature of the chimney is notably higher than that of the solarium and fluctuates more than the solarium air temperature. The solarium fluid temperature stays at around the maximum ambient temperature over the period.

FIGs. 6-8 show that the inertial temperature shift is around 2-5 hours for the internal and external surfaces respectively. This number rises up to 8 hours delay for the exterior wall surface to reach its maximum temperature compared to the highest ambient temperature. The solarium floor has the highest interior temperature difference with the ambient temperature. This temperature variation follows almost the same pattern as the chimney air temperature.

FIG. 9 shows that the flow rate was higher than 0.07 kg/s during the whole simulation period. The flow rate was the lowest around the sunrise (5 am). The air flow rate reaches its maximum around 1 pm. As the FIGs 6-8 clearly show the temperature difference between the inner surfaces of chimney concrete wall and the solarium concrete wall and floor compared to ambient temperature reaches around 5, 5 and 15k at the midnight of July 15 producing a mass flow rate of around 0.1 kg/s or 1.2 ACH for the 300 m$^3$ adjacent residential building. Ventilation standards require a minimum of 3 ACH for residential buildings (ASHRAE, 2003). Therefore, it can be concluded that the investigated SCAS shall be able to provide more than one third of the desired ventilation in the attached building even with the lowest ventilation it produces.

FIG. 3. Toronto weather data (ambient temperature) for July 15-18.

FIG. 4. Toronto weather data (solar radiation on south faced vertical surface) for July 15-18.

FIG. 5. The SCAS inside air temperature profile

FIG. 6. The Solarium concrete floor nodes temperature profiles
Moreover, Brager and de Dear (2002) compared naturally ventilated buildings with HVAC buildings. The study showed that occupants of naturally ventilated buildings become adapted to a vast range of air conditions close to outdoor air conditions. The researchers proposed the adaptive comfort standard (ACS) as an alternative to the predicted mean vote (PMV) method in ASHRAE standard 55 (2010). The study showed that higher air speed in occupied zone can lead to enhancing air quality by offsetting the enthalpy effect.

As can be seen in FIG. 10 the outdoor temperature for the month of July in Toronto is within the range of both adaptive (ACS) and predictive (PMV) mean comfort temperatures 85.7% of the time. Hence the proposed residential building interior condition is able to be maintained within ACS limits around 85% of the time during the warmest month of the year by natural means.

5. Conclusions

This study investigated the performance of a solar assisted ventilation system in a solarium attached to a residential building in Toronto at the initial design stage. Unlike the existing simulation process in the previous studies on ventilation of crop dryers and atriums, the actual weather data of Toronto was used in the simulation model. Simulation results showed that the 24cm concrete walls and floor provide up to 5-hour delay to reach up its peak temperature resulting in a temperature variation up to 15K and producing natural ventilation when solar radiation no longer exists. With the cross sectional air movement produced by a SCAS in an adjacent building, interior condition is able to be maintained within the ACS limits for about 85% of the time in month of July resulting in a potential cooling energy saving of 85% that would otherwise be used by an air-conditioner. The dynamic model proposed for the SCAS establishes a reliable and effective methodology for evaluating the performance of the SCAS, which can be a reliable reference for future experimental investigations and designing process.
References


Perceived and measured indoor climate in new-family buildings
including identifying technical deficiencies

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KEYWORDS: indoor climate, apartments, questionnaire, measurements, occupants, window opening, technical deficiencies

SUMMARY:
When new buildings are constructed the indoor climate for the first period may differ from the one after some years due to various factors, for example may the emissions from the building materials be higher, possibly affecting the air quality, and the balancing of the technical systems; the mechanical supply and exhaust system and heating may not be completely finished. The perceived indoor climate in new-family buildings, with the aim of low-energy use and good indoor climate, has been examined by questionnaires when the buildings were new. In this follow-up study the same questionnaire has been performed after some years. Measurements of the indoor climate and the performance of the technical systems have also been made in some apartments. The objectives are to compare the resident’s experience of indoor climate after some years of occupancy with when the buildings were new and to examine indoor climate and aspects influencing this after some years of occupancy. One objective being studied is the window opening in the apartments and factors related to this. No large difference in experience is seen after some years. A majority of the respondents open their windows during the heating season for rather long time periods and daily or almost every day. It was found that the resulting indoor climate is a complex interaction between the technical systems, the design of the building envelope and the behavior of the occupant. Several deficiencies in all this three areas have been identified and suggestions on possible improvements are included.

1. Introduction

When new buildings are constructed the indoor climate for the first period may differ from the one after some years due to various factors, for example may the emissions from the building materials be higher, possibly affecting the air quality, and the balancing of the mechanical supply and exhaust system respectively heating system may not be completely finished. The perceived indoor climate in new-family buildings in Malmö, built with the aim of low-energy use and good indoor climate, has been examined by questionnaires in a study some years ago (Hansson, Nordquist, 2010).

The main findings were that the measured energy demand was higher than the calculated one and that the indoor climate overall was experienced as satisfying. Some questions were however identified to be worth looking into and were also shown representative for new-built apartment buildings in general according to the nationwide study BETSI (Boverket, 2009). A follow-up study was therefore decided due to the possibility of gaining more knowledge on new-built apartment buildings both in respect of the outcome of energy use and experience of indoor climate.

One of the questions that were identified was the astonishing large amount of window opening reported by the residents. 59% reported that they aired all day/night or for some hours. The amount was in the same order of magnitude as in BETSI; 69%. 57% reported that they air daily or almost
every day during heating season, the corresponding amount in BETSI was 61%. Frequent airing has also been reported in other studies (Sandberg & Engvall, 2009). In the follow-up study the window opening was therefore one factor that was focused on as this influence both the indoor climate and the energy use. The frequent airing is made in these new-built buildings in which a vast majority is ventilated with modern mechanical supply and exhaust ventilation. In the first study it was also seen that several experienced a hot indoor climate especially in summer-time which also is experienced in general according to the BETSI study.

By both asking for the experience of the residents and also performing measurements of the real indoor climate and performance of the ventilation system it is possible to connect the experience of the residents to the real indoor climate in the apartments and aspects influencing this including the behaviour of the occupants. Other studies concerning window opening and occupant behavior have been made by for example Berge et al (2013).

The objectives of the present study are to compare the occupants experience of indoor climate after some years of occupancy with when the buildings were new and to examine indoor climate after some years of occupancy.

The results of the questionnaire concerning the window opening behaviour are more thoroughly presented in another paper (Fransson et al, 2014). This includes reasons for opening the windows respectively closing them. It could be mentioned that the reasons for opening the windows includes both reasons for a need of improving the thermal climate respectively the air quality. This paper focuses on the interaction and studying the conditions in individual apartments.

2. Method

The experience of the occupants has been studied by standardized and validated questionnaires, called the “Stockholms-questionnaire” and used by the city of Malmö (Miljöbyggprogram Syd, 2009). To be able to compare the overall experience with the nationwide study BETSI (Boverket, 2009) two additional questions have also been added. In this follow-up study the same questionnaire has been performed after some years. Questions focusing on the specific issues have been added. The questionnaires were distributed to individual postboxes to each apartment in the staircases in the beginning of March 2012. Twelve different building owners and 32 staircases are included in the study. The residents should put their answered questionnaires in a paper box next to the postboxes in the staircases at the latest on the end of March 2012. All paper boxes were then gathered.

Based on the answers from the questionnaires a selection of nine apartments were chosen in which window opening for long time; window open for some hours to all day/night was reported. The residents were contacted and almost everyone who was asked on the phone agreed to participate. The selection included both rental apartment and condominiums and all existing combinations of mechanical ventilation systems; fans located central respectively fans and ventilation units located inside the apartments. A majority was ventilated with mechanical supply system but also one system which supplied the outdoor air directly to the rooms was included.

Measurements of the indoor climate for winter conditions and the performance of the technical systems have then been made in these apartments in 2013. The indoor climate and the factors influencing it have been studied both quantitative respectively qualitative. Measurements includes for example air flows, operative temperature (no airing, 0,1, 0,6, 1,1, 1,7m), throw, air velocity and focuses in the thermal, the hygienically climate and the ventilation system. Measurement equipment included SWEMA300 with SwemaFlow 125, SWEMAs ISO7730 for operative temperature and for long-term Onset HOBO loggers.
3. Results

3.1 Answers to questionnaire

The overall experience of the indoor climate during heating season is shown in Figure 1. The answers from the 256 people respondents are divided in two groups; one (2012) with the same buildings as in 2010 and one (new 2012) for the two buildings that were not included in the first study.

![Figure 1: Proportion of the people; in percentage, who has answered “Yes, often (every week)” on the question “Have you during the latest 3 months felt bothered by one or some of the following factors in your home?”](image)

Six of the factors are experienced of a somewhat higher percentage after some years; draft 10% (8% before), too high room temperature 7% (5%), variable room temperature 7% (3%), too low temperature 9% (4%), stale bad air 8% (4%) and static electricity 5% (3%), the difference is however rather small. One factor dust and dirt has increased somewhat more; 16% compared to 11% before. Three factors are reduced, dry air is reduced to 9% from 11%, tobacco smoke from others to 4% from 6%; and noise to 6% from 8%; also a small difference. The amount is in the same order of magnitude as the percentage in the nationwide study BETSI. Another measure that can be valid to compare with is the portion of people which are dissatisfied. If maximum 10% are dissatisfied then the indoor climate can be seen as very good (EMTF, 2013). For all factors but dust and dirt this is fulfilled.

The indoor climate is experienced somewhat less satisfying in the two new buildings. Four of the factors exceed the 10% guideline; variable room temperature (12%), too low room temperature (16%), dry air (16%) and dust and dirt (12%).

<table>
<thead>
<tr>
<th>TABLE 1. Answers for two questions regarding window opening behaviour</th>
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<td><strong>Reported percentage</strong></td>
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The amount of the respondents including also the newcomers which report that they apply window opening are shown in Table 1. The opening of windows have decreased somewhat.

### 3.2 Apartments

The results presented in this paper focuses, due to limited space, on some of the findings in the individual apartments and factors that stands out and deviates from the expected values as deficiencies and combines quantitative and qualitative data. In all apartments presented, window opening are reported to take place for long time periods except in building 4 in which airing are made for fully one hour each day. More extensive and complete results are presented in (Fransson, Lindberg, 2013) and (Karlsson, Nordquist, 2014).

**Building 1. Mechanical supply and exhaust ventilation, central fan**

**Apartment 1**

The resident reported that it will become too hot in the bedroom when going to sleep if the window in the bedroom isn’t opens all day. The residents assess a need of having relatively cool in the bedroom. The bedroom has large windows facing west, no solar shading, the whole apartment only facing one west facade. The radiator is working in the bedroom and is set on medium heat emittance by the thermostatic valve on the radiator in the hydronic system. Operative temp: 24.3-25.1°C in living room and 23.4-24.1 in bedroom. The Public Health Agency of Sweden recommends 20-23°C in homes. Measured air flow 18.0 l/s (Building code requirement: 21.3 l/s).

Comment: Both the plan of the apartment, the lack of solar shading and the behaviour of the resident; not reducing the heat from the radiator, contributes to the relatively high temperature during winter.

**Building 2 Mechanical supply and exhaust ventilation, apartment unit, plate-heat exchanger (one of the added buildings)**

**Apartment 2**

The residents report that it will become too hot in the living room and in the bedroom if the windows aren’t open. The apartment has an open plan with kitchen and living room as one large room. The living room has very large windows facing south, no exterior solar shading, the whole apartment only facing south. The solar shading consists of blinds positioned inside the room which means that the heat enters the room. Measured supply air flow 19.3 l/s. Supply air flow requirement according to building regulation 19.6 l/s. The ventilation unit is situated above the stove in the kitchen. The air flow can be varied by a control handle outside the unit. The handle is put on the mode intended for when no people are present (reduced air flow to save energy). When asking the resident why this mode is chosen the explanation is noise. The ventilation unit located inside the apartment creates too high noise level when the mode for being at home is used, so this mode is not possible to have when at home. The residents are bothered both in the living room but mostly in the bedroom in which the experienced noise level is far too high when going to sleep. The mode being at home fulfilled the building code in terms of air flows, however not being in operation. Operative temp: 23.7-24.8°C in living room.

Comment: The design of the building envelope, the location to the south and only one façade may contribute to create high temperatures. The air flow via the ventilation system is not really fulfilling the building code. This is explained by that the setting is wrong. The combination of the several identified deficiencies can contribute to an insufficient indoor climate both in terms of thermal and hygienically conditions.

**Apartment 3**

The resident reports insufficient air flows and a need of window opening in the bedroom. The measured supply air flow in the bedroom is 7.5 l/s. The air flow should be 4 l/s person according to the Public Health Agency of Sweden who are responsible for regulations for homes. Almost all nights...
the bedroom is occupied by two adults and one 6-year old child. The requirement is accordingly 12 l/s in this room when three people are present. If two adults are present, which is the probable intended number of people, the requirement is 8 l/s.

Comment: The air flow in the bedroom via the ventilation system is not fulfilling the regulation for the number of people present. The air flow requirement for day time in an office or in a school would for the same number of occupants be 26,6 l/s in this size of room; almost 4 times more than the measured one.

Apartment 4

The residents report a need of having the window open in the bedroom during the whole night. They assess a need of having cool in the bedroom. They have closed the thermostatic valve at the radiator in the bedroom, which is situated to the west and keeps the door closed all the time. The whole apartment is situated to the south and west and they experience a too hot indoor climate especially in summer time. No exterior solar shading is installed. Operative temp: 24,7-24,8°C in living room. The ventilation unit is located above the stove. The control for the supply air heater after the heat exchanger is controlled by a very small circle located inside the equipment. This control cannot be found in the instructions which the residents have looked into several times. For all the three apartments the plate-heat exchanger should be replaced by a component for summer conditions, a sort of by-pass. All these components are reported by another resident to be in the cellar and not in use during summer time.

Comment: It is not clear how the heater and the plate-exchanger works and there could be a possibility of having the heat exchanger and the heater working all the year including the summer if this control is not adjusted.

Building 3 Mechanical supply and exhaust ventilation, apartment unit, rotary heat exchanger

Apartment 5

The residents report that they feel a need to have the windows open in the bedroom. They assess a need of having cool in the bedroom. Operative temp: 23,5-25,0°C in living room. The ventilation unit is located inside the apartment in the bathroom between the bedrooms. The air flow can be varied by a control panel outside the unit. The operating mode is the one intended for when no people are present – away-mode. The residents report that the reason for having this mode in operation is noise. The ventilation unit located inside the apartment creates too high noise level when the mode for being at home is used, that this mode is not possible to have when at home. The measured supply air flow was 23,8 l/s (Building code: 37,5 l/s). The throw in the bedroom (0,2 m/s) is 0,9 m, covering about 0,5 of the distance of the room intended to be covered.

Comment: The air flow via the ventilation system is not fulfilling the building code. This is explained by that the setting is wrong. The measured throw is too short, a general guideline value is that is should cover 0,75-1 of the room distance if assuring sufficient mixing conditions in the room. The fact that the throw is too short can contribute to an insufficient air movement and there by worse air quality in the room.

Apartment 6

The residents report that they feel a need to have the balcony door open. In the 110 m² apartment the air flow according to building regulation should be 38,5 l/s. Measured supply air flow were 25,2 l/s. The air flow of the ventilation unit located inside the apartment in the washing room/bathroom is controlled by a control panel located outside the unit. The mode in operation is the “away-mode”, by which the air flow should be reduced when people are not at home. The resident answers when asking why this mode is in operation that “oh I don’t know anything about the ventilation system, I never change the setting.”
Comment: The air flow via the ventilation system is not fulfilling the building code due to the wrong setting. The air flows has been significantly below the building code in this apartment who residents includes two adult and two small children.

**Building 4 Mechanical supply and exhaust ventilation, apartment unit, rotary heat exchanger**

**Apartment 7**
The residents report that they experience that it is too hot in the apartment. All thermostatic valves are closed on the radiators but it will become too still too hot. The bedroom directed to the north is aired before going to sleep and closed during night and the bedroom door is kept closed all time. They report a desire to open windows in the other rooms which are directed to the south but don’t, due to dirt which enters the apartment because of building activity in the area. No exterior solar shading to the south is applied. Operative temp: 23,4-24,1°C in living room. The apartment is 99 m²; air flow according to building regulation: 34,7 l/s. Measured supply air flow is 14,4 l/s. The supply air flow requirement to the bedroom is 8 l/s and the measured one is 3,7 l/s. The ventilation unit is situated above the stove in the kitchen. The air flow can be varied by a control handle outside the unit. The display has no clear explanation for the different modes. The handle is put on the lowest mode which is found to be intended for when no people are present (reduced air flow to save energy). The resident have chosen this mode due to noise, they have no knowledge that this mode is intended for non-present situation. The moisture supply was measured to be in average 3,4 g/m³ in the living room and 3,2 g/m³ in the bedroom during two weeks which exceeds the recommended maximum value 3 g/m³ by the Public Health Agency of Sweden.

Comment: The air flow via the ventilation system is not fulfilling the building code for the apartment and not fulfilling the requirement in the bedroom. This is explained by that the setting is wrong. The moisture supply is too high in the apartment which has a local rotary heat exchanger.

**Building 5 Mechanical exhaust ventilation, apartment unit**

**Apartment 8**
The resident report a need for having open the windows in both bedroom and living room and that it will become too hot in living room and bedroom if the windows aren’t open. The resident assesses a need of having cool in the bedroom. The apartment has an open plan with kitchen and living room as one large room. The living room has very large windows facing south, no exterior solar shading, the whole apartment only facing south. The solar shading consists of blinds positioned inside the room which means that the heat enters the room as in other apartments without exterior shading. The radiators are always closed also during winter. The operative temp: 21,7-23,5°C in living room how-ever the windows have been opened for a long time before the measurement.

Comment: Both the plan of the apartment and the lack of exterior solar shading con contribute to a thermal climate perceived by the resident to be too hot.

**Apartment 9**
The resident report a need for having open the windows in both bedroom and living room and a need of fresh air. The operative temperature is measured to 23,4-24,8°C in living room. The radiators are fully open in the living room and reduced in the bedroom. The resident smokes at home.

Comment: Both the relatively high operative temperature and the smoke may lead to a need of opening the windows.

### 4. Conclusions

The overall experience of the indoor climate during heating season reported by the respondents can be concluded to be satisfying. The amount which experience inconvenience have been somewhat increased for most of the indoor climate factors after some years of operation, however no large difference
can be concluded and the levels are satisfying for all factors but dust and dirt. The residents in the two new buildings report however a somewhat less satisfying indoor climate. There is still ongoing building project in the area which can contribute to the reported experience of dust and dirt. The suspected decrease in people experiencing inconvenience after some years is not met for most factors for the present buildings. One relevant parameter to this dry air is however reduced, but in a small amount. The conclusion is drawn that there is no significant difference in experience after some years.

The amount of airing has been somewhat reduced but no large difference can be seen. It is concluded that a majority of the respondents still open their windows frequently during heating season after some years of operation.

The measured operative temperature is rather high during winter conditions and the air flows are not fulfilling the codes in six of nine apartments, several of them significantly.

5. Discussion

There are several interesting results that can be discussed. It is interesting and a challenging matter that a majority of the people feel a need to apply window opening in the apartments which are ventilated with modern mechanical supply and exhaust systems.

Several deficiencies, some technical, have been identified in the limited number of studied apartments for example; too low air flows, no or not sufficient solar shading and perceived noise level. Some of the deficiencies emerge in the interaction of the users; reducing the air flows due to experienced noise, design of interface which leads to not understanding how to control the system. All of these can contribute to create an unsatisfying indoor climate in different ways and contribute to a need for increasing the air flow to the apartment; both for thermal and/or air quality reasons, which is done by window opening. The factors cover several areas; the building envelope, the building services systems and the interaction with the residents. The resulting indoor climate is a complex interaction between all these three areas. As several parameters can contribute to the total resulting indoor climate; all these factors must be observed and functioning. This implies that the area should be studied in a larger context in which several areas also are included; behaviour, design of inter-face and instructions to residents. The findings in the measured apartments in other words supports that research must be performed in a general inter-disciplinary way including both the performance of the building service systems, the interaction of the residents and the behavioural aspect of the people if an satisfying indoor climate is to be achieved.

The number of apartments studied is relatively few and no extensive conclusions can be made. The apartments are however situated in a nice area; nothing speaks for that these apartments should differ from other new-built apartments thus indicating that the apartments and the reported experience could be viewed upon as representative for newly-built well insulated apartment’s buildings. This could be interpreted as that the identified short comings could be worth observing by other building owners and engineers both when building new apartments and also when upgrading and renovating existing one to modern technical equipment and components. Factors which could be worth observing and addressing in the planning process with the aim of creating an good indoor climate includes for example; solar shading, plan of the apartment, the design of building services systems and its interface; ventilation and heating in terms of noise, design of the control of the ventilation system, careful instruction to the occupants of the building services systems, especially if systems are to be controlled solely by the residents as the ventilation units placed inside the apartments.

The results also indicate several research questions to be addressed in the future; one of them is whether a ventilation system solely should be controlled by non-professionals as residents and if this will guarantee a good indoor climate.
In the hunt for saving energy; the ventilation air flows may be reduced. If the ventilation system supplies too low air flows; both in comparison with the Building code and possibly also perceived as too low by the occupants, this may lead to that the windows are opened. The air flow through an open window during heating season could be several times larger than via the ventilation system in a home, and this heat which leaves through the window is not recovered. An alternative could be to design for somewhat higher air flows via the ventilation system; which can both recover heat and also filter the outdoor air. This could be beneficial as the outdoor air pollution is recently classified by the WHO as a leading environmental cause of cancer deaths (WHO, 2013). This way could then be more efficient both in terms of energy use and air quality.

6. Acknowledgements

BEBO is acknowledged for financing the study. The energy part, not presented here, has been done by WSP. All the residents who answered the questionnaire are acknowledged for contributing to the knowledge on how the indoor climate is experienced in new-built apartment buildings. A special thank is directed to the residents who agreed to participate in the measurement study and so generously opened their homes and also gave valuable input on their experience of the indoor climate and the interaction with the building services systems.

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HVAC Models coupled with hygrothermal building simulation software

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KEYWORDS: Hygrothermal building simulation; detailed plant equipment simulation; HVAC; coupling simulation models; FMI for co-simulation

SUMMARY:
This paper describes the integration of HVAC simulation models, developed with the multi-domain modeling language Modelica, into the hygrothermal building simulation software WUFI® Plus. With the existing software a hygrothermal building simulation, considering heating, cooling and air conditioning as ideal systems, can be performed in a user friendly way. Without detailed HVAC models, the software calculates the heating, cooling, humidification, dehumidification and ventilation demand which is necessary to keep the indoor climate in user defined design conditions. This output can be used for further investigation and sizing the plant equipment. However, a direct interaction between the detailed building model and the building equipment was not possible. This is improved with the newly developed Modelica HVAC models. They were exported via the common Functional Mock-up Interface (FMI), which was analyzed to assess the most effective coupling strategy. The FMI is the definition of an open interface between different software systems. The realization of a non-iterative coupling algorithm is illustrated by means of a simulation example. Furthermore, the implementation of the HVAC models into the hygrothermal building simulation program is validated using the results from a Modelica simulation environment as reference.

1. Introduction

1.1 Building model
Traditionally, many building simulation programs were written in high level languages like FORTRAN, or C/C++ with specialized solvers and algorithms for established and approved simulations. There is and always will be the aim to improve such simulation software. One of those traditionally software is the existing hygrothermal building simulation software, called WUFI® Plus (Holm, et.al. 2004; Lengsfeld & Holm, 2007). The holistic model is based on the hygrothermal envelope calculation model developed by Künzel (1994). This detailed model calculates the coupled heat and moisture transfer in building components and is written in FORTRAN and C++. The conductive heat and enthalpy flow by vapor diffusion with phase changes in the energy equation dependent on the moisture fields. The vapor flow is simultaneously governed by the temperature and moisture field due to the exponential changes of the saturation vapor pressure with temperature. The resulting differential equations are discretized by means of an implicit finite volume method. A stable and efficient numerical solver had been designed for the solution of the coupled and highly nonlinear equations.
The building envelope can consist of many and different components, such as exterior- and interior-walls, ceilings, and floors. A multi-zone model, written in C++, links them to the whole building model. Moisture sources or sinks inside the rooms or inside the components, exchange with the envelope due to capillary action, diffusion and vapor ab- and desorption as a response to the exterior and interior climate conditions as well as the thermal parameters are taken into account. The hygrothermal behaviour of the components affects the overall performance of the building and vice versa. The multi-zone model manages the simulation and interaction, even with further models, for windows, the solar radiation in different sun incidence angles, or the building air flow. The graphical user interface and the data management of the existing software WUFI® Plus is developed in C#. The model was validated by comparing simulation results with measured data of extensive field experiments or verification with standards (Antretter et al., 2011).

To simulate the indoor climate, the multi-zone model calculates heat and moisture balances for each zone, regarding all the sources, sinks and exchanges. As long as those balances are not satisfied during a time step, the interior temperature and humidity is adapted iteratively. For example, if the heat loss through the building envelope and ventilation is more than the solar and internal heat gain, the interior temperature is decreased as long as the loss and the gain are not equal.

The user can define design conditions for the indoor climate by setting minimal and maximal values, e.g. for the indoor temperature. Without the detailed HVAC models, ideal systems are regarded, calculating the heating, cooling, de- and humidification demand with the described heat and moisture balances. The systems are defined only per maximal capabilities. If the indoor climate would exceed the design conditions, the solution algorithm tries to get the necessary deficit to equal the balances from the defined systems capabilities. Back to the example before, if a user has set a space heating capacity, the interior temperature is kept by the minimal design condition as long as the space heating capacity is enough to fulfil the heat balance. The resulting actual heating demand is the difference in the heat balance.

However, in reality, the HVAC system may not deliver the demand instantly. It may have to load the water storage and heat up the radiator before energy is provided to the space. After that, the radiator may still heat up the room even the temperature has reached the set point temperature. This inertia of a heating system, regarding the warm-up time or the overheating of a room was not simulated with the ideal system. By coupling the detailed hygrothermal building simulation with the detailed HVAC systems, described later in this paper, the indoor climate may fluctuate more and is not kept exactly at the design conditions. Furthermore, many results regarding the dimensioning and planning of the HVAC system, in direct interaction with the building envelope, can be obtained. The multi-zone model also has to manage this simulation and interaction by setting boundary conditions, such as the radiator surrounding temperature and getting output, such as the heating power of the radiator calculated with the detailed HVAC system.

1.2 Modelica HVAC models

The aim was to create simple but realistic HVAC models, which can be used by practitioners. Following this, only necessary and obtainable plant information is required for the simulation. Also the computation time to simulate a building should not increase to times which are no longer acceptable for practitioners. The different HVAC devices to be simulated, plant equipment for heat generation, distribution, storage and controlling include, so far:

- Condensing gas boiler – simulating the heating power output in different operation modes
• Solar thermal collector – simulating the heating power output regarding the collector orientation, inclination and shading, depending on the position of the sun and surrounding temperature
• Combined heat and power plant – simulating heating and energy power
• Heat pump
• Bore hole heat exchanger
• Thermally activated building systems (TABS) – can be added as inner source directly in the building components
• Radiators – simulate the heat flow to a room regarding mass and nominal heat power
• Storage tanks – simulation of the temperature distribution within the tank
• Control equipment – controlling e.g. the mass flow rates, depending on set point temperatures and actual room temperatures
• PV system – simulate the power output, depending on orientation, inclination and sun irradiation

During the last years, the building simulation community discovered the advantages of using Cross-industry multi-domain modeling languages (CMML) such as Modelica (Elmqvist, 1997) for the development and verification of complex simulation models. Following this the model development of the detailed HVAC systems was done with the software Dymola 2012 (Dassault Systèmes AB, 2011). It was desirable to extend the existing program with the newly developed models to be able to use both, the existing tool as well as the CMML models.

To deliver realistic and validated plant equipment models, the above mentioned sub-models are merged to complete HVAC systems, an example is shown in FIG 1. This was done to increase the usability and avoid the risk of non-feasible system configurations. Finally, the user chooses one HVAC system configuration and has to set only a few necessary parameters or import them from a database.

![FIG 1: Exemplary HVAC configuration designed in Modelica and coupled with WUFI®Plus](image)

2. Coupling

2.1 Preparing the HVAC models

As described above, all the different HVAC components, such as boiler, storage and solar collector are merged to whole plant equipment systems in order to increase the usability and to get feasible, proven and validated systems coupled with the building model. Each configuration can include different components, for example some include the condensing gas boiler, some others include heat pumps and some others include combined heat and power plants. The multi-zone model has to handle each of those configurations, just by changing the configuration type.
One necessary step to develop such models is to define the input, output and the parameters. Parameters are set at the beginning, respectively at the initialisation of a model. They can be computed with some other parameters, but regarded constant for the whole simulation. For example, the maximal gas-boiler output, or the maximal storage tank volume are such parameters. During the simulation the plant equipment has to interact with the building envelope, respectively the multi-zone building model. The multi-zone model has to send input, for each calculated time step. For example the actual interior building temperature and the set-point temperature is needed for the plant equipment, especially for the radiator sub-model to compute the heat flow to the room. Such time varying and simulation depending values must be sent to the plant model as input and delivered for the multi-zone model as output. Especially the model input has to be defined clearly as input in the model variable declaration; otherwise it is often not possible to set those values during the simulation in the exported model. Also the parameters have to be declared as parameters within the model. If not they might get the variability of a constant with the model export and constants cannot be changed.

One overall HVAC model exchange frame with all possible inputs, outputs and parameters for all the different kinds of included HVAC systems was defined. Each system is build up in this frame and using the inputs, outputs and parameters defined in the framework. If one configuration doesn’t inherit the condensing boiler, for example, the parameters are just left empty.

A first coupling approach was to use Dymola specific export possibilities, the so called Source Code Generation or the Binary File Export. More details on this can be found in (Burhenne et.al. 2011). Finally the coupling with the Functional Mock-up Interface (FMI) for Co-Simulation was chosen because of its unified convention and possibilities to perform the co-simulation. Following this, all HVAC systems are exported using FMI for Co-Simulation. Those models include beside the simulation equations also a solver executing the co-simulation. The exported model is called Functional Mock-up Unit (FMU). It is a packed file (zip-file) containing the model binary file, a dynamic link library (.dll), with all the callable functions specified with the FMI application interface. Beside this model, the modeldescription.xml is included, containing all the necessary model information, especially the variables and parameter information.

Each input, parameter, or intern variable gets a model-unique identification number, a so called value reference number, during the export process. This number is documented in the model description file. The whole information exchange is handled via those value reference numbers. For example, the maximal boiler power with the model-variable name qMaxBoiler, gets the value reference number 16777216. With this number, and the transfer function fmiSetReal(..), defined in the FMI specification, it is possible to set the value of the parameter, respectively the maximal boiler power. Even with the stiff configuration frame, the value reference numbers for the parameters and inputs change for different configurations or after a configuration is updated. It was decided not to hard-code the value reference numbers, but to develop a tool to setup the HVAC systems for the coupled simulation and merge the inputs, outputs and parameters.

2.2 Coupling the HVAC models

After a system is designed, validated and exported it can be loaded in the developed system configuration tool, shown in FIG 2 in the left bottom corner. The tool lists all the variables declared in the FMU, respectively the HVAC system. Besides the FMU variables, it also lists all the parameters, inputs and outputs provided within the graphical user interface of WUFI® Plus for the detailed HVAC Systems. They are partitioned per HVAC device, so each device type gets an identification number and the specified variables. For example, the gas condensing boiler has the ID 2 and the maximal heating power has the parameter index 1. Now the only thing to do, during the coupling process, is to find the variable name of maximal boiler power in the FMU (ordinary defined within the HVAC exchange framework before) and copy it behind the listed WUFI® Plus parameter. The tool merges the
Value Reference Number and checks the variability (input, output or parameter) and unit. It is visualised, if a connection is valid or not. The tool stores those links, and also some additional model information's, like model GUID (a unique number each exported model gets for exact identification) and the model binary file name in a HVAC configuration file.

The user of the software has not to do this. Only the model binary files, the HVAC configuration file and a FMU adapter is delivered with the software. The user only has to choose the desired HVAC system and set the values of the parameters within the graphical user interface.

The FMU adapter manages the simulation, also shown in FIG 2, without any user interaction. It gets all the parameter and input values from the building envelope model, connects them with the corresponding value reference number and sends this information to the HVAC model via the FMI-specification. It also manages the instantiation, initialisation and time step execution. Certainly it gets the outputs via the value reference numbers and sends it back to WUFI® Plus.

![Diagram](image)

**FIG 2**: Coupling different HVAC Systems as FMU’s with WUFI® Plus via the Coupling Tool

### 2.3 Simulation with the detailed HVAC models

As described before, the detailed HVAC models replace the ideal systems. Therefore, the implicit solution algorithm of the multi-zone model is replaced by an explicit method (Pazold et.al. 2012). This is required due to the unsupported rejection and repeating of time steps by co-simulation and particularly, because of the fast response of the indoor climate of the HVAC controlling devices and systems. The implicit method iterates each time step as long as the heat- and moisture in a zone is not balanced. With the explicit method, the indoor climate is adjusted for the next time step, regarding the heat- and moisture balances of an actual time step. The building model interacts with the HVAC system via a kind of ping-pong method. With an usual simulation time step size of one hour, to simulate one or more years, this alternative co-simulation would lead to unrealistic simulation results. Therefore, the explicit solution technique requires a decreased time step size, e.g. about five seconds. The computation of the indoor climate, and the heat and moisture field in the components has to be
done 720 times each time step. The implicit method requires only 15 to 40 iterations, respectively. Computations. This and of course the detailed HVAC models increase the computation time. However, the results of the small sub time steps must not be stored, the time steps don’t iterate, and the hygrothermal component simulation module computes a bit faster for such small time steps, which saves some computation time. First simulations, without any further computation improvements, increase the simulation duration about 3 to 5 times. Benefits from the coupled simulation

Some improvements, regarding the hygrothermal building simulation coupled with detailed HVAC systems are mentioned in the text before. Remember the indoor climate; it will be simulated quite more realistic because of HVAC reaction times or over powering. It may not stay exact at the defined design conditions if the plant equipment is active. This will also affect the exchanges across the building components. Furthermore, the interaction between building envelope and HVAC system can be investigated in more detail. For example, the operation mode of a condensing gas boiler or a pellet boiler is simulated. In combination with the dynamic interaction between the thermal storage mass of the building, the mass of the heating distribution system and the water storage tank, the estimated efficiency of the boiler can be investigated. Additionally the power output of a solar thermal collector is simulated regarding the collector orientation, inclination and of course shading - depending on the position of the sun and surrounding components.

Besides the efficiency and heating demand investigations, the comfort assessment within different rooms or zones benefits from the detailed HVAC systems simulation. For example, the operative temperature can be assessed. By choosing a system including the thermally activated building system the dynamically simulated heating power is regarded as inner source within a building component affecting directly the heat and moisture distribution within it, the surface temperature and the heat flow into the room. This simulation can check if the area of the TABS is enough to heat up the room, with a still comfortable surface temperature.

3. Application example

![FIG 3: Application example test building](image)

The effect of a coupled simulation is shown in this chapter. One exemplary case is chosen to show some of the results of a HVAC model and the interaction with the building envelope and the indoor climate. Therefore one small house, with one full storey and a developed attic is investigated as shown in FIG 3. The treated floor area of the building is 118 m² and the net volume 281 m³. It should be located in Lund, Sweden, with the respective climate. The heat transfer coefficient (U-value) of the timber constructed and insulated exterior wall is 0,15 W/m²K, of the roof 0,17 W/m²K and of the windows 1,76 W/m²K. The overall window area is 18,6 m², including window frames. Furthermore, standard internal loads for two residents are regarded. The air change rate is set constant to 0,4 per hour. The reference case is simulated with an ideal heating system with over dimensioned heating power. In a next step, the ideal system is exchanged with the detailed exemplary HVAC system shown in FIG 1. It includes a condensing gas boiler and a solar collector for heat generation, a storage tank and a radiator for heat distribution. The main parameters for the system are listed in TABLE 1.
As described before, the building is simulated twice. Once with the ideal heating system and in the next step with a coupled detailed heating system, described in this paper. The results of both simulations are compared and some additional results, only obtainable with the detailed system are shown.

The graphs in FIG 4 show the indoor air temperature and FIG 5 show the heating power, which was required to keep the indoor air temperature within the design conditions. The reference simulation with the ideal system calculates a quite constant minimum indoor temperature, because of the design condition at 20°C. The simulation with the coupled heating system gives a more fluctuating indoor temperature, because of the detailed simulation of the heating system. The system includes a thermostat, with a hysteresis, setting the heating circuit mass flow rate following the indoor temperature and set point temperature. The behaviour of the whole system, including supply and return temperature of the radiator is simulated. Exemplary, in FIG 6 the water temperature within the water storage at the bottom, the middle and the top of the storage volume is shown. Such new results, only available with the detailed system, may be used to adjust the storage capacity and properties to the whole building.

### TABLE 1. Parameter list for application example HVAC devices

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>condensing gas boiler</strong></td>
<td>Maximal boiler power</td>
<td>5 [kW]</td>
</tr>
<tr>
<td></td>
<td>Boiler and circuit mass</td>
<td>50 [kg]</td>
</tr>
<tr>
<td></td>
<td>Temperature of tank which requires loading by boiler</td>
<td>60 [°C]</td>
</tr>
<tr>
<td></td>
<td>Maximal mass flow of boiler supply</td>
<td>0.1 [kg/s]</td>
</tr>
<tr>
<td></td>
<td>Top border temperature of tank</td>
<td>70 [°C]</td>
</tr>
<tr>
<td><strong>Solar collector</strong></td>
<td>Intercept (maximum) of the collector efficiency</td>
<td>0.8 [-]</td>
</tr>
<tr>
<td></td>
<td>First-order coefficient in collector efficiency equation</td>
<td>3.5 [W/m²K]</td>
</tr>
<tr>
<td></td>
<td>Second-order coefficient in collector efficiency equation</td>
<td>0.015 [W/m²K]</td>
</tr>
<tr>
<td></td>
<td>Area of solar thermal array</td>
<td>6 [m²]</td>
</tr>
<tr>
<td></td>
<td>Length of collector</td>
<td>3 [m]</td>
</tr>
<tr>
<td></td>
<td>Orientation of array (positive east from north)</td>
<td>180 [°]</td>
</tr>
<tr>
<td></td>
<td>Inclination angle of array</td>
<td>35 [°]</td>
</tr>
<tr>
<td></td>
<td>Required temperature diff. between collector and tank</td>
<td>10 [°C]</td>
</tr>
<tr>
<td></td>
<td>Maximal temperature of tank</td>
<td>90 [°C]</td>
</tr>
<tr>
<td></td>
<td>Maximal mass flow of collector circuit</td>
<td>0.05 [kg/s]</td>
</tr>
<tr>
<td><strong>Water storage tank</strong></td>
<td>Thermal storage capacity</td>
<td>400 [Liter]</td>
</tr>
<tr>
<td></td>
<td>Diameter tank</td>
<td>0.5 [m]</td>
</tr>
<tr>
<td></td>
<td>Heat transfer coefficient tank fluid to ambient</td>
<td>0.25 [W/m²K]</td>
</tr>
<tr>
<td></td>
<td>(relative heights of inlets, outlets and sensors)</td>
<td>0.1 [-]</td>
</tr>
<tr>
<td></td>
<td>Thermal conductance of heat exchanger 1</td>
<td>500 [W/K]</td>
</tr>
<tr>
<td></td>
<td>Thermal conductance of heat exchanger 2</td>
<td>500 [W/K]</td>
</tr>
<tr>
<td><strong>Radiator</strong></td>
<td>Nominal heat power of the used radiators</td>
<td>2 [kW]</td>
</tr>
<tr>
<td></td>
<td>Mass of radiator including water</td>
<td>100 [kg]</td>
</tr>
<tr>
<td></td>
<td>Radiator exponent</td>
<td>1,281 [-]</td>
</tr>
<tr>
<td></td>
<td>Maximal radiator mass flow</td>
<td>0.1 [kg/s]</td>
</tr>
<tr>
<td><strong>DHW</strong></td>
<td>Domestic hot water profile (time scheduled)</td>
<td>variable [kg/s]</td>
</tr>
</tbody>
</table>

The graphs in FIG 4 show the indoor air temperature and FIG 5 show the heating power, which was required to keep the indoor air temperature within the design conditions. The reference simulation with the ideal system calculates a quite constant minimum indoor temperature, because of the design condition at 20°C. The simulation with the coupled heating system gives a more fluctuating indoor temperature, because of the detailed simulation of the heating system. The system includes a thermostat, with a hysteresis, setting the heating circuit mass flow rate following the indoor temperature and set point temperature. The behaviour of the whole system, including supply and return temperature of the radiator is simulated. Exemplary, in FIG 6 the water temperature within the water storage at the bottom, the middle and the top of the storage volume is shown. Such new results, only available with the detailed system, may be used to adjust the storage capacity and properties to the whole building.
4. Conclusion

Cross-industry multi-domain modeling languages (CMML) provide a fast way to design and simulate different HVAC devices which are merged to pre-defined whole system configurations. Exporting those models with the standardized Functional Mock-up Interface (FMI) can be used to couple them with existing software, written in high level languages. However, some rearrangements of the existing software are necessary to adopt the models, respectively to implement the FMI functionality. The hygrothermal building model with a specialized solver and the HVAC systems are complex proven models, validated and stable for many kinds of simulations. The described coupling using the co-
simulation approach seems to be a reasonable technique to merge those models. The input and output of the different exported FMUs, acting as sub-models, can be defined using the developed tool. With the tool, it is possible to couple new or updated models without recurrent modifying of the source code of the existing software. A still acceptable computation time and realistic simulation results, e.g. a quite equal heating power to keep the indoor climate at the design conditions, leads to the conclusion, that the described coupling is a suitable and confiding method to improve the hygrothermal building simulation.

5. Acknowledgements

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References


A comparison between a commercial energy calculation tool for buildings with calculations using a response model

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KEYWORDS: Energy calculation tool, thermal mass, building, VIP-Energy, Dynamic Thermal Networks (DTN)

SUMMARY: (Style: Summary Heading)
The modeling of energy balances for buildings is a main task in building physics and a key issue in analyzing and developing new low energy buildings. On the market there exist many different calculation tools. They all have both benefits and drawbacks in different cases. As a user it could be difficult to choose the most suitable tool.

In this paper a commercial energy calculation tool (VIP-Energy) is compared with the relative new methodology called DTN (Dynamic Thermal Networks). DTN is developed by Johan Claesson at Chalmers. The methodology is based on response functions which gives a very illustrative picture of a buildings thermal behavior. VIP-Energy is a commonly used simulation tool by consultants and designers in Sweden. VIP-Energy handle full dynamic energy balances with HVAC-systems (heat-ventilation- cooling systems).

The comparison is made in the following areas:

- Accounting of thermal mass text
- Handling long and short time scales
- Influence from HVAC-systems

The aim of this work is to find the most suitably tool to evaluate benefits of heavy thermal mass buildings and be able to make optimization in the construction in order to reach even more benefits of the mass. The considered benefits are; indoor temperature, low energy consumption and low installed power.

An early study shows that a combination of the two calculation tools is a good choice. The DTN methodology is to prefer to make detailed analyses and optimizations and the VIP-Energy is to prefer when analyze the complete energy balance including HVAC.

1. Introduction
Lowering the energy use has not only been an issue of the consumer for a long time. Nowadays utilization of the building structure in combination with adapted HVAC systems can increase the energy efficiency a lot. Buildings with high thermal inertia decrease the power peaks and moves the power demand in time. This is an important part to imply into smart energy systems. This combination can in the future be optimised by right operation of systems for heating, cooling and energy consumption.
Good energy calculation tools are necessary to individually optimise buildings for sustainable and best possible energy utilization. In order to generate an energy balance for buildings, different simulation models exist which are based on either steady state or dynamic conditions. When using these models it is important that the chosen method is reliable. Kalema et al. (2008) have done a comparison of in total 7 different tools to calculate energy balances in buildings. The focus was on analysing effects of thermal mass on cooling and heating energy. They found that the different results between the methods are mainly caused by different input data instead of differences between various calculation methods.

Within the Cerbof 2 project (Wadsö et al., 2012) different studies were done amongst others on optimising energy efficiency by utilizing heavy thermal mass buildings in combination with different operation conditions of HVAC systems. Two different calculation tools were used during these studies. VIP-Energy and is a dynamic method which is developed as a user-friendly, commercial tool for building industry. The relatively new method, called ‘Dynamic thermic networks’ has been developed by Claesson (2003).

The aim of this study is to evaluate both methods for their ability to optimise buildings by accounting for heavy thermal mass as effective as possible. The influence from HVAC-Systems and modified process energy on heavy thermal mass buildings is studied. The handling of long and short time effects of thermal inertia is compared.

2. Method
The two calculations methods are compared by calculating the indoor and wall temperature and the energy demand for a student apartment in north of Sweden. The student apartment is a heavy thermal mass construction. For evaluating the calculation methods, the influence of heat capacity for inner structures, ventilation systems, zone calculations and accuracy regarding input values were taken into account. A buildings response function was calculated in both VIP-Energy and DTN to illustrate how the buildings thermal inertia is accounted for. For the latter task, a simplified building structure is used. A constructions response function is the heat flow caused by one temperature step as a function of time.

3. Energy calculation programs

3.1 VIP-Energy
VIP energy is a thermal simulation program which covers the complete buildings energy balance. The calculations are based on dynamic equations where all parameters are updated with one hour time interval. Heat transfer coefficients are dynamic values which adapt hourly to the environmental circumstances. Input values are known or measurable values such as weather conditions and demands on indoor temperature or ventilation (VIP -Energy, 2002).

3.2 DTN
Dynamic Thermal Network, the theory means that the relations between boundary heat fluxes and boundary temperatures for any time-dependent heat conduction process in a solid material are represented in the same way as for an ordinary thermal network (for steady-state heat conduction). The calculations are based on step-response functions which mean that the heat fluxes through the surfaces are calculated for a unit step change at one surface while keeping zero temperature at the other surfaces. The relations between surface temperatures and heat flows for any time-dependent process are obtained by superposition of the basic step responses.
4. Indata

4.1 Student apartment

A student apartment consisting of two floors and four apartments at each floor is used as study object. The energy balance in VIP-Energy was calculated for the whole building as one zone. The apartments may have different indoor temperatures. Additional calculations were therefore done with the building divided into ten zones (one zone for each apartment and one zone for the stairwell at each floor). The energy balance is calculated for each zone while the heat flow between zones is taken into consideration. DTN calculates the whole upper floor as one zone. The structure is a heavy concrete structure with a thermal conductivity of 2.3 W/(m,K), the density is 4000 kg/m³ and the heat capacity is 830 Ws/(kg,K). More material parameters are given in table 1. As DTN is only calculating for the upper part of the building, boundary conditions had to be applied which result in zero heat exchange towards the intermediate ceiling.

![Studied building with four student apartment per floor.](image)

**TABLE 1. Input values for the construction used in chapter 4 and 5. U-values of some of the construction elements differ slightly for VIP-Energy and DTN.**

<table>
<thead>
<tr>
<th>Building part</th>
<th>Area (m²)</th>
<th>U-Value (VIP)</th>
<th>U-Value (DTN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>155.5</td>
<td>0.097</td>
<td>0.087</td>
</tr>
<tr>
<td>Exterior wall</td>
<td>234.1</td>
<td>0.202</td>
<td>0.171</td>
</tr>
<tr>
<td>Interior wall</td>
<td>287</td>
<td>3.476</td>
<td>2.648</td>
</tr>
<tr>
<td>Intermediate ceiling</td>
<td>311</td>
<td>0.755</td>
<td>0.679</td>
</tr>
<tr>
<td>Window</td>
<td>50</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ground plate</td>
<td>155.5</td>
<td>0.142</td>
<td>-</td>
</tr>
</tbody>
</table>

Input values for process energy and ventilation are given in table 2.

**TABLE 2. Input values for ventilation and process energy, same in both programs.**

<table>
<thead>
<tr>
<th>Ventilation:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of the upper floor:</td>
<td>373.295 m³</td>
</tr>
<tr>
<td>Air changes per hour:</td>
<td>0.525 if $T_i &lt; 24^\circ$C</td>
</tr>
<tr>
<td></td>
<td>1 if $T_i &gt; 24^\circ$C and $</td>
</tr>
<tr>
<td>Process energy:</td>
<td>5 W/m²</td>
</tr>
</tbody>
</table>
The weather data used is a synthesis of the years 1993 to 2003 for Luleå. Hourly values for air temperatures and solar radiation are used in both VIP-Energy and DTN. In addition to that are wind speed and relative air humidity included in the VIP-Energy calculations.

4.2 Input values for response functions

For calculating the response function in chapter 7 a simple construction as given in table 3 is used. The inside dimension is 12.5 m x 8 m x 2.5 m and no doors, windows, ventilation or infiltration are used.

<table>
<thead>
<tr>
<th>TABLE 3. Input values for the construction used in chapter 7, where R are the inside and outside heat transfer coefficients, λ is the heat conduction, ρ is the density and c the specific heat capacity.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy weight construction</td>
</tr>
<tr>
<td>Inside</td>
</tr>
<tr>
<td>150 mm Concrete</td>
</tr>
<tr>
<td>200 mm EPS</td>
</tr>
<tr>
<td>70 mm Concrete</td>
</tr>
<tr>
<td>Outside</td>
</tr>
</tbody>
</table>

U-Value = 0,171 W/(m²,K)

<table>
<thead>
<tr>
<th>Light weight construction</th>
<th>R ( (m^2 \cdot K)/W) )</th>
<th>λ ( (W/(m \cdot K)) )</th>
<th>ρ ( (kg/m^3) )</th>
<th>c ( (Ws/(kg \cdot K)) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside</td>
<td>0,13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 mm Plasterboard</td>
<td>0.21</td>
<td>700</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>200 mm EPS</td>
<td>0.036</td>
<td>25</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>13 mm Plasterboard</td>
<td>0.21</td>
<td>700</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Outside</td>
<td>0,04</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

U-Value = 0,171 W/(m²,K)

5. Accounting of thermal mass

Both the interior walls and intermediate ceiling have a high thermal mass. When removing the heat capacity of the interior construction elements, the total energy demand for heating is 1.26 % higher for DTN calculations. In VIP-Energy the energy demands increases only with 0.45 %.

<table>
<thead>
<tr>
<th>TABLE 4. Energy demand for heating and average indoor temperatures calculated with and without heat capacity for interior walls and intermediate ceiling.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
</tr>
<tr>
<td>Energy demand</td>
</tr>
<tr>
<td>VIP -Energy (without zones)</td>
</tr>
<tr>
<td>DTN</td>
</tr>
</tbody>
</table>

Heat capacity for interior walls has more influence instead on the indoor climate, as shown in figure 2. Without considering thermal mass of interior construction elements, the indoor temperature increases faster during spring and decreases faster during autumn, this is also reflected in the demand of heating energy. In case of less thermal mass, higher daily variations of indoor temperatures are observed. Further the maximum effect needed for heating is slightly higher. The indoor temperatures calculated in VIP-Energy are constantly much lower than those resulting from DTN. Also daily
temperature oscillations are less extensive for VIP-Energy. Figure 3 shows the average wall temperature distribution with VIP-Energy. Both highest and lowest values for wall temperatures can be found for lower thermal mass. In VIP-Energy the wall temperature illustrates an average temperature value for those building materials that mainly are in contact with compartment air (VIP-Energy, 2002). It is not clearly formulated whether VIP-Energy takes a value in the middle of the wall or at the surface; anyhow it is a mean value for the whole building.

**FIG 2.** Indoor temperature during one year accounting for thermal mass of interior walls and neglecting thermal mass of interior walls calculated with VIP-Energy and DTN. Differences between the cases are scaled up for a period in late September.
6. Constructive and functional impact on energy balance

Functional impact on the energy balance is studied with respect to varying operation of ventilation system and by taking into account different process energy distributions. Table 5 summarizes the mean room temperatures and demand of heating energy for 0% and 80% ventilation heat recovery.

**TABLE 5. Energy demand for heating and average indoor temperatures calculated with and without ventilation heat recovery.**

<table>
<thead>
<tr>
<th></th>
<th>With 80% heat recovery</th>
<th>Without heat recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>Energy demand (MWh/a)</td>
<td>T\textsubscript{indoor}</td>
</tr>
<tr>
<td>VIP -Energy (without zones)</td>
<td>8,82</td>
<td>22,03</td>
</tr>
<tr>
<td>VIP -Energy (with zones)</td>
<td>7,23</td>
<td>22,45</td>
</tr>
<tr>
<td>DTN</td>
<td>4,47</td>
<td>22,90</td>
</tr>
</tbody>
</table>

DTN calculates the lowest energy demand in both cases. Several factors can influence the lower values. In DTN the building is calculated for optimised conditions, where no air leakage or unwanted ventilation is assumed. VIP-Energy calculates with air leakage of 0.8 l/(m\textsuperscript{2}s), which equates to 3 MWh/a in zone calculations and 4.5 MWh/a when calculating without zones. Wind is taken care off in VIP-Energy so that the outer transient resistance is reduced and thus the U-values increases. In DTN no heat flow from ground is assumed whereas VIP-Energy calculates with heat exchange from the ground. When the whole building is regarded as on zone, then the energy for the upper floor is assumed to be 50% of that for the whole building. This leads to an even higher heating demand for the upper floor. Heat losses through the ground have an even higher impact on the result.

With heat recovery DTN calculates 38.2% lower heating demand, whereas without heat recovery DTN has only 24.7% less heating demand. In DTN the ventilation is simply reduced to 20% whereas in VIP the efficiency for heat recovery in the ventilation system is set to 80%. From the energy balance we get that only in total 69% of the energy losses due to ventilation are recovered. This is due to a function in the program that will reduce the heat recovery during warm periods in order to reduce high inner temperatures.

Further calculations in VIP – Energy were done considering different cases for ventilation, adapted process energy and sun protection. It turned out that through adapted ventilation system, the energy...
demand can be decreased rapidly. From constant ventilation to different ventilation for day and night time already significant lower demands on both heating and cooling energy could be found. Even more effective use of ventilation could be achieved by temperature regulated ventilation. Different distributions of adapted process energy over the day may also make a significant influence of the inner temperature and the need for cooling. The possibility to divide the building in different zones and to be able to study the temperature variations and energy consumption in the coldest or warmest room is also a useful tool in VIP-Energy.

7. Long and short time effects

Thermal inertia of constructions is indicated by its response function. A constructions response function equates to the temporal gradient of heat flow caused by a single temperature step. For homogeneous material layers the response function can be calculated analytically in DTN and can therefore be considered as accurate. Thus the response function can be used as measure about how VIP-Energy takes into account thermal inertia. The in data used for heavy and light weight constructions are summarised in table 4.

Figure 4 shows the response functions for the heavy and light weight construction. Considering the heavy weight construction, the response function for VIP-Energy reacts directly whereas the analytical solution calculated by DTN shows a time lag of approximately three hours. After 15 hours the response functions overlap and fade to a reverse offset between the functions. Stationary values, where no difference between heat losses should occur anymore, are reached after 48 hours. The inner and outer surface thermal resistances in DTN are fixed. VIP-Energy does not use steady state values for the surface resistance they are a function of radiation and convection in the actual case and will vary during the calculation. It is not possible to know which values are used. Therefore the stationary value which should correlate to the thermal transmittance, U, of the construction will differ between VIP-Energy and DTN.

![Figure 4. Response functions for the heavyweight construction (right) and for the lightweight construction (left).](image)

The response functions show the same behaviour for the light weight construction, but the time lag is only approximately 0.5 hours. The functions overlap after 3 hours and no differences between heat losses are expected after 9 to 10 hours. Anyhow the stationary value for VIP-Energy is again lower than the constructions U-value.
8. Conclusions

The two energy calculation programs VIP-Energy and DTN have been compared. Focus has been on the ability to model the influence of thermal inertia in buildings. The studied parameters are energy consumption, variation of indoor temperature and variation and phase shift of transmission heat losses.

A student apartment in Luleå, Sweden, was used as study object. The calculations with the program VIP-Energy showed higher energy consumption then the DTN calculations. The differences can however be explained by different assumptions of air leakage and boundary conditions for the calculations and the two programs seem to predict similar energy consumptions.

Thermal inertia of constructions is indicated by its response to a single temperature step. The response function was tested on a simplified building model. The response function in VIP-Energy reacts much faster than the analytical calculated solution in DTN. The influence of thermal inertia may therefore be a little underestimated in VIP-Energy. After some time the response functions will overlap and change to a reverse offset between the functions so that the total heat loss will be the same for the two models. The response of a daily varying outdoor temperature and thermal load was also tested. The amplitude of the transmission heat losses is larger in the VIP-Energy model and the indoor temperature will therefore show a larger variation in that model. The total heat losses after 24 hours will however be the same for the two models.

A combination of the two calculation tools will be a good choice. The DTN methodology is to prefer to make detailed analyses and optimizations, especially for temperature cycles with a shorter period. VIP-Energy is to prefer when to analyse the complete energy balance including different HVAC systems with many options. The model can also be divided in different temperature zones to be able to reflect the real behaviour of a building.

9. Acknowledgements

We acknowledge the support from CERBOF – the Swedish Centre for Energy and Resource Efficiency in the Built Environment.

References


Mathematical modeling of airflow velocity and temperature fields for experimental test houses

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KEYWORDS: CFD, energy efficiency

SUMMARY:
Five equal size test houses of different constructional solutions have been built in Riga for building energy performance monitoring. Monitoring is done both during the heating and cooling seasons and necessary temperature is provided by an air-air type heat pump. An important issue regarding the heat pump is the coefficient of performance that changes for different outside temperatures. Therefore, even knowing the total power used by the heat pump, it is impossible to find out how much heat is taken into the room exactly. In this paper previously tested mathematical model is used to calculate coefficient of performance of the heat pump by exploiting the physical measurements of the inflow speed, temperature and air exchange in the room. A transient simulation is done results are compared to those of a stationary simulation and experiment. The integral model is also used to calculate coefficient of performance and compare it with numerical simulation.

1. Introduction

Energy efficiency of buildings and building materials is highly topical subject nowadays. To compare different building materials and constructions energy performance, five test houses with different constructional solutions have been built in Riga. The heating and cooling is done by air – air type heat pump (HP) that has velocity of 2 m·s⁻¹. To try out different constructional options, a mathematical model is necessary as it is impossible to experimentally build a test house for every possible option. This experiment gives excellent verification options for the mathematical model.

The problem itself is transient both because the HP’s cycle is time-dependent and because of fluctuating outside temperature. Period of time has been found form experimental data where temperature is constant and thermal radiation is negligibly small. These problems are studied in chapter 2 – experimental setup. Both - transient and stationary simulations have been made. The assumptions made, turbulence model used, meshing and other considerations regarding experimental implication in mathematical model are discussed in chapter 3 –modelling approach. The results acquired with mathematical model are compared with experimental data in chapter 4 – numerical results and discussion. Precision of numerical results are also discussed there.

2. Experimental setup

2.1 Test houses

As the detailed experimental setup is given in previous publication, the reader is referred to see the work of (Dimdina 2013) as only basic ideas are given here. The test houses (fig.1) are built of equal inner dimensions and cover the main locally produced building materials such as wood logs, ceramic bricks, aerated concrete and rock wool. The inner dimensions are 3x3x3 m that gives the total volume of 27 m³. The calculated U-value is 0.16 W·m⁻²·K⁻¹ for each construction therefore the expected heat
consumption is equal for every building type. The façade of all the houses are made ventilated to ensure equal conditions for every house. The data are gathered every minute for both the meteo station and sensors inside the building (fig. 1).

2.2 Heating cycles

Heating and cooling in test hoses are done with air–air type HPs that are located above doors (fig. 1) and ventilation opening is above the window. The air exchange (Gendelis 2013) in the test buildings have been measured to be \( n = 0.45 \text{ h}^{-1} \). This means that part of the air that is taken into the room by HP is forwarded to ventilation and some are taken back by the HP. The air–air type heat pump make a rectangular cycle every 51 second by changing the inflow angles form \(-45^\circ\) to \(45^\circ\) on the horizontal plane and from \(-30^\circ\) to \(-70^\circ\)on vertical plane with respect to line that is made by cross section of both planes according to (Daikin Ltd. 2012). This makes the problem time dependent, as the transient simulations are computer resource demanding, it was decided to see if the stationary solution is a good approximation. For the latter the inflow angle was set constant for horizontal plane – \(50^\circ\) and for vertical plane \(0^\circ\).

As the mathematical model is developed also for stationary case it is necessary to find a period of time when temperature is constant or at least changes a little around some fixed value. Such situation does not often appear in nature however, a period of time was selected from monitored data for outside temperature \(5.1 \text{ °C}\) that lasted for 2 h 52 min. The corresponding inside temperature should go asymptotically to a stationary temperature if the heating is done continuously with equal power. In experiment however temperature experiences a cyclic behaviour (fig. 2). This means that the HP is making some heating cycles with higher power then the rest. From temperature values it can be seen that last two cycles are approximately the same. Unfortunately no minute by minute power data are present during this particular cycle, only the heat consumption that cannot resolve the time when power was increased.

**FIG 1. A) Test house geometry and B) monitoring sensor positions.**
For the simplicity of the model and the lack of specific experimental data regarding inflow temperature and velocity the average data from experiment were taken into account for model verification. As it is not possible to find out how much mass is taken into the room, additional airflow velocity and temperature measurements were carried out.

![Graph: Inside temperature for various sensors]

**FIG 2.** Inside temperature at monitoring points during the period of stationary temperature outside.

### 3. Modelling approach

#### 3.1 Mathematical model

##### 3.1.1 Governing equations and boundary conditions

For numerical realization the ANSYS/CFX program packet were used. The fluid flow is governed by Navier – Stokes (NS) equations that cannot be solved for this problem so the Reynolds averaged NS equations were used. These equations are derived multiple times in various standard texts on fluid dynamics like (Batchelor 1967) and (Versteeg 1995). The equation implementation in Ansys/CFX environment is described in user guide (Ansys Inc. 2011). Wall functions were used on solid – fluid interfaces that correspond to no slip conditions. Air inlet was defined as a constant mass flux and temperature with time-dependent or stationary direction depending on case. For air feedback to HP constant mass flux boundary conditions were used because the free total flux would produce a negative outflow at some part of the boundary. For ventilation boundary there was an “opening” type boundary conditions where the relative pressure and outside temperature are defined. This was done to ensure that mass is conserved.

##### 3.1.2 Model assumptions and numerical realisation

The thermal radiation was not taken into account because the radiation from wall to wall is negligibly small and there were negligibly small amount of thermal radiation in the night from the windows. As the air velocities are high – 2 m·s\(^{-1}\) the flow is turbulent and therefore a turbulence model was needed. The k-omega shear stress transport model was chosen, because it is robust and performs well both in the volume and near wall region. For buoyancy the Boussinesq approximation was used.
The initial conditions were taken as average temperature in test house that was \( T = 17.84^\circ C \) and the final result from stationary simulation were given as an initial condition for transient simulation. The transient simulation was run for 6 full cycles with time step of 0.05 s. With the given mesh the time required for simulation was 8 days on 3.2 GHz processor with 7 cores.

3.1.3 Geometry and meshing

As the test houses are built with from many layers that are slim or inhomogeneous, the model was simplified and the effective values of heat transfer coefficient, density and heat capacity were used. The meshes were made different for stationary and transient simulations to reduce computational time (Ozolinsh et.al. 2013). For stationary simulations results for coarser and finer mesh were compared.

3.2 Balance calculation and HP efficiency

The numerical simulation is only an approximation and convergence usually doesn’t ensure that results are physically consistent. Heat balance for the model must show that heat gains are the same as heat loses. The heat gains by inflow and loses by both – the ventilation and feedback are calculated (1) as integral over surface (Ozolinsh et.al. 2013).

\[
P_J = c_p \cdot \rho \cdot \left( \frac{T}{v} \right) \cdot dS
\]

Where
- \( P_J \) – power by mass flux through boundary (W)
- \( c_p \) – heat capacity at constant pressure (J/(kg·K))
- \( \rho \) – density (kg/m\(^3\))
- \( T \) – temperature (K)
- \( v \) – airflow velocity (m/s)

Heat loses through walls are calculated (2) as heat flux through outer surfaces.

\[
P_\Phi = \Phi \cdot d\vec{S}
\]

Where
- \( P_\Phi \) – power due to heat flux through solid material surface (W)
- \( \Phi \) – heat flux (W/m\(^2\))

For the various inflow temperatures the average temperature from the experimental points can be determined and compared to the experimental average. By doing two stationary calculations with the different temperatures interpolation can be done to find the inflow temperature that makes model average equal to experiment average. From these calculations the HP coefficient of performance can be determined by mathematical modelling. This result can be compared to integral model by taking into account experimental values.

4. Numerical results and discussion

To compare numerical experiments mutually a line perpendicular to the floor in the middle of room is considered. This is done because there are experimentally measured temperatures (fig. 1b) along it. The temperatures for stationary case are taken directly from final solution, but for transient case averaged over last HP cycle. For the verification that after six HP cycles the flow is stationary, the results were compared between the last two cycles and the difference was negligibly small.

The approximation that in the given time, when outside temperature is almost constant, heat flux through wall is quasi stationary will be better for constructions with lower heat capacity. Therefore for calculation the lightweight construction (made of plywood and rock wool) were taken and experimental data from this particular house was used for verification.
FIG 3. Temperatures at the middle line for mathematical models and experimental data.

The heat balance were computed (eqs. 1, 2) and the results (table 1) show that the heat balance is off by approximately 3%. This means that although the convergence was set to be $10^{-4}$ for maximum residual, the total error is considerably higher. This is due to third type boundary conditions. The temperature is not fixed at any point and therefore an error can occur.

**TABLE 1. Heat balance for numerical simulation.**

<table>
<thead>
<tr>
<th></th>
<th>Heat gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow</td>
<td>697.0</td>
</tr>
<tr>
<td>Heat loses due to ventilation</td>
<td></td>
</tr>
<tr>
<td>Ventilation</td>
<td>-55.6</td>
</tr>
<tr>
<td>Feedback</td>
<td>-537.0</td>
</tr>
<tr>
<td>Heat loses due conduction</td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>-15.0</td>
</tr>
<tr>
<td>Wall</td>
<td>-71.1</td>
</tr>
<tr>
<td>Floor</td>
<td>-15.8</td>
</tr>
<tr>
<td>Ceiling</td>
<td>-25.0</td>
</tr>
<tr>
<td>Doors</td>
<td>-13.1</td>
</tr>
<tr>
<td><strong>Total loses</strong></td>
<td><strong>-732.5</strong></td>
</tr>
<tr>
<td>Error, %</td>
<td>5</td>
</tr>
</tbody>
</table>
Temperature and velocity field plots (figs 4 and 5) for stationary simulation show that results are physically consistent. The overall velocity profiles are as expected and at the near wall region the flow are downward as expected for cold wall.

**FIG 4.** Temperature and velocity field for stationary study.

**FIG 5.** Temperature and velocity field for stationary study.
5. Conclusions

Mathematical model for airflow in the test houses have been set up and two types of calculations done. The numerical results seem to be qualitatively correct as the airflow directions at near wall regions tend to be physically consistent. Also the temperature gradients in the solid are as expected.

As it can be seen, stationary and transient model give similar volume average temperatures for the room, but the experimental point average is higher than model predictions. This is due to inflow angle that is directed toward the experimental point location. The values for each individual experimental point vary significantly in stationary model for points closer to ceiling and floor. This is due to bad mixing that stationary model offer. The transient model however gives much better results as the changing inflow ensures better mixing. Therefore we can conclude that for precise temperature fields in the room the stationary model is insufficient and transient model should be used. If, for example, only the average temperature of the room is necessary, the stationary model could be sufficient, but more tests for different temperatures must be made to verify this claim.

An important drawback for this model is that the power data weren’t available at the time these measurements were carried out. The data is available now and therefore time averaging will be avoided in future studies and the full heating cycle will be included.

The first experimental results show that there are houses that perform in similar manner and therefore it has been decided to test the COP value for heat pump by letting the heating be done by inefficient heater that have COP value of unity.

6. Acknowledgements

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A new Passive House Design Tool and its Application in Cold Climates

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KEYWORDS: hygrothermal building simulation; energy assessment; low energy buildings; passive houses

SUMMARY:
Due to an increasing demand for sustainable low energy buildings, the application of the passive house design methodology spreads worldwide. The methodology applied to balance monthly heat gains and losses is developed for fast energy demand investigations in moderate climates; issues can occur in other climate zones. Furthermore, the hygrothermal effects within the building and the building components are neglected. The monthly method is not suitable for moisture relevant risk management, nor is it for transient effects that influence the building energy performance. This leads to the requirement of a dynamic simulation.

A new user friendly software tool is available that couples the established passive house design methodology, for quite instant energy demand simulation results, with an sophisticated hygrothermal dynamic simulation. The dynamic whole building simulation is based on a detailed building component model simulating the coupled heat and moisture transfer and a multi-zone building model, calculating hourly indoor climate and energy demand.

An advantage of the new tool is the opportunity to work with only one building model while conducting a monthly balance based energy assessment or a dynamic hygrothermal whole building simulation. The graphical user interface exchanges a small amount of parameters which are required by the respective setting. Additionally some results of the monthly method may be used automatically as approach for the dynamic simulation.

This paper includes the description of the coupling of both methodologies and an application example, explaining the usage of the tool for a building in cold climates. Furthermore the possible additional and in-depth analysis options and results by the application of the new tool are shown as well as some recommendations for the design process in cold climates.

1. Introduction

While designing energy-efficient buildings, a designer often uses different approaches to tweak the building in terms of energy efficiency, comfort and hygrothermal performance of the components. Common approaches for the assessment - and also for the certification - of the energy demand rely on steady state methods, using monthly balances, to compute the values used for the estimation of energy demand and for comparing different building designs under predefined boundary conditions. Those methods exclude all transient effects in buildings like the effects of thermal inertia. A comprehensive analysis of comfort conditions indoors is also not possible.

This causes the designer to switch to a dynamic whole-building model using hourly data to evaluate the dynamic behavior of the building. Often, very new and innovative building component
configurations are employed to meet the stringent energy criteria. Therefore, a third step is critical to performance and quality assurance: assessing the hygrothermal performance of envelope components. This third step evaluates the most critical components by employing a hygrothermal component simulation model.

This paper shows the development of a single tool that integrates all three steps. A steady-state approach for assessing the energy performance is combined with the dynamic modeling features of a whole-building simulation model including a full-scale hygrothermal component analysis.

2. Simulation Methodology

This section describes in short the basic equations for the calculation of the steady-state and dynamic model. Furthermore, it describes how integration into one tool for energy, comfort and hygrothermal component performance was implemented in the new WUFI Passive software.

2.1 Methodology for passive house assessment

The monthly balance based method depends strongly on overall heat transfer coefficients, temperature difference and considered time period. It is in accordance with the DIN EN ISO 13790, in particular the simplified approach. The heat transfer coefficient, the reciprocal of the thermal resistance, is an important input value for opaque components. It is calculated from the thermal conductivity and layer thickness of the building envelope materials. For transparent components, the heat transfer coefficient is input data. The monthly heat losses across the building envelope are calculated by determining the heat transfer coefficients, areas of the components and the appropriate temperature differences according to component location. The external boundary condition of exterior walls can be the ambient air temperature, it can also be the ground temperature in case of a basement wall or an increased or decreased derivative of the ambient air temperature in cases of attached spaces exterior of the thermal envelope, such as garages. With the temperature difference and a considered time period, the heating degree hours are calculated following [Feist 1992, Feist et.al. 2007]. Monthly heating degree hours consider the hour count of a month. The period under consideration for the annual demand depends on the monthly difference between the heat losses and the heat gains. If this difference is greater than 0.1 kWh the month will be considered in the calculation of the total annual heating demand. This means that the period under observation could be varying between the different cases. Ventilation heat losses are calculated considering the effective air change rate, building volume, effective heat recovery efficiency and annual heating degree hours as well.

Climate data contains information on the solar radiation for north, east, south, west and horizontal. Each component is associated with a cardinal or horizontal direction. For transparent components, the solar heat gain is calculated considering heat transmittance, shading reduction factors due to obstructions, overhangs and reveals. The solar heat gain of opaque components is computed considering the exterior absorptivity and emissivity. The required heating demand, over a specified time period, is calculated following [Feist et.al. 2007] and in accordance with [EN ISO 13790].

The monthly utilization factors indicate how much of the available heat gains can be used to counteract the heating demand during the heating period. It is calculated from the heat gain and loss ratio and a so-called time constant, depending on the internal heat capacity and the total heat loss coefficient of the building. For the time constant equation a continuously heated building (more than
12 hours per day) is considered.

The monthly losses are calculated using monthly heating degree hours and the annual losses using annual heating degree hours. The total heating demand, including the transmission heat losses for all components and thermal bridges and the ventilation heat loss is decreased by the total heat gain comprised of the solar and internal heat gain, multiplied by a utilization factor. Monthly heating degree hours are determined multiplying the hour count of the month with a temperature difference.

One of the passive house certification criteria is the total annual primary energy demand. To calculate the primary energy demand of a building the electrical and non-electrical demand of the mechanical system, including auxiliary energy, plug loads, appliances and lighting are summed up. The heating demand of the domestic hot water production and distribution is taken into account and if solar hot water generation is used, it is reduced by an estimated solar fraction. It is assumed that the energy use by any device or service is not necessarily continuous. The uses are either reduced by different usage or utilization factors stemming from predetermined utilization patterns or a certain frequency is assumed for each usage. If such energy use takes place within the thermal envelope it is added to the internal heat gains. Heat gains from people are already included in the heat gains. Then an annual specific internal heat gain is estimated. The total is then multiplied by the treated floor area and hours of the month resulting in the total monthly internal heat gains.

In addition to the heating demand the cooling demand is calculated using a very similar algorithm. One difference is that the heat gains are not weighted by the utilization factor as the heat losses are.

2.2 Hygrothermal whole building simulation

The dynamic hygrothermal simulation combines single building components such as walls, floors, and roofs to be modeled as a whole building. Coupled heat and moisture transport is simulated for each opaque component composed of different layers of materials such as wood, insulation, membranes or even air layers. This model was developed by Künzel [Künzel, 1994]. It considers capillary action, diffusion and vapor ab- and desorption. The conductive heat and enthalpy flow by vapor diffusion with phase changes strongly depends on the moisture field. The vapor flow is simultaneously governed by the temperature and moisture field due to the exponential changes of the saturation vapor pressure with temperature. Resulting differential equations are discretized by means of an implicit finite volume method. The component model was validated by comparing its simulation results with measured data of extensive field experiments [Künzel, 1994]. The temperature and moisture field within the component is simulated as a result of the model.

Coupling all the envelope components leads to the multi-zone building model. A zone constitutes one or more rooms with the same indoor climate. The zone boundaries are the components. There is also an outdoor zone. The outdoor climate is specified by location in the climate files assuming that the building itself does not influence the climate. However, the indoor climate is influenced by the simulation results of the component and vice versa - the component simulation is influenced by the indoor climate. Considering this interaction the indoor climate can be simulated. With every time step the zone temperature and humidity values are generated by solving heat- and moisture balance equations [Lengsfeld, Holm, 2007]. Besides the heat and moisture flow across the building the envelope internal heat and moisture sources and sinks are taken into account. They are caused by
people, lighting, mechanical equipment, infiltration and solar radiation. Such sources or sinks cannot only occur in the zones of the building itself but can also occur in the building envelope component with a direct influence on the heat- and moisture field of the component. Additionally, transparent components, like windows, can be modeled more accurately. The solar transmission that passes through a transparent component is calculated taking into account the sun elevation and azimuth angle and the orientation and inclination of the component. Solar heat gain contributions that pass through the transparent components are apportioned out directly to the indoor air and to the inner-surfaces of opaque components according to a defined percentage (user defined, or estimated according to surface area). Besides the short wave solar irradiation also the long wave balance is considered for the opaque building components. Therefore not only the solar heat gains but also the long wave irradiation losses can be calculated.

The zone model was validated via cross-validation with other tools, experiments and standards like [ASHRAE 140, 2007]. The validation of both - the energetic and the hygric part of the zone model - is described in [Antretter et.al. 2011]. Currently the ideal mechanical system has the capacity to supply all minimized heating, cooling, humidification, dehumidification and mechanical ventilation loads. As long as the system’s capacity is sufficient the indoor temperature and moisture can be maintained between defined design conditions and thus the hourly demand can be calculated. If the capacity is not sufficient then the temperature or moisture will rise above or fall below the specified design conditions. If there is no ideal mechanical equipment defined, a “free floating” indoor climate is simulated.

Every time step depends strongly on the previous steps because of the water content and thermal energy storage within the envelope and the air in the zones. A time step is characterized by these dynamic previous variables. New boundary conditions are created with each time step and varying input data like the outdoor climate. Using these initialization values the coupled heat and moisture transport is calculated and consequently the zone heat and moisture balance equations are created. Should these balances not be within an expected defined accuracy of the simulation then the indoor temperature and relative humidity is iteratively adapted.

2.3 Coupling of both methods

Both models, the monthly passive house calculation and the dynamic whole building simulation, rely on user inputs and assumptions. Some inputs are pre-defined, such as specific building materials, their dimensions, location and orientation. Some have to be estimated by measurements or experience.

The pre-defined input is fundamentally the same for both models, though quite more detailed for the dynamic simulation - not only because of the additional consideration of moisture. However, the building geometry, room and component dimensions, widths and heights, roof inclination are the same. Fenestration parameters like solar heat gain coefficients, frame geometries, shading reduction factors and many other boundary conditions such as the design indoor temperature, the overheating limit temperature and the natural air change rate are the same as well.

More different is the climate data. For the monthly method only monthly mean values for temperatures and solar radiation are necessary. For the dynamic hourly simulation, hourly input data for the outdoor climate must be provided. For the more detailed radiation calculation hourly diffuse and direct global solar radiation data is required. The static calculation method estimates ground
temperatures according to the given location and boundary conditions; those values can be used for the climate of the ground for the simulation by converting the data into a useable ground climate format. Additionally needed is information on wind velocity and the quantity of rainfall to calculate the driving rain on the external surfaces as well as the relative humidity of the outdoor climate to calculate the moisture balance. Aside from pre-defined input data some results of the steady-state method can be used for the dynamic simulation, as for example the mechanical ventilation volume flow rates for summer and winter ventilation, the simplified effective heat recovery efficiency, the space heating and cooling capacities of the mechanical equipment. Internal heat sources due to people, lighting, household and mechanical equipment are the same, but also have to be supplemented with moisture characteristics. For the monthly method it is possible to calculate these sources using a utilization factor depending on the average usage. For the dynamic hourly simulation this is a good first assumption, but it might be more realistic to create specific time schedules.

Basically, the main difference of both models is the level of detail. A much more detailed simulation needs more time to compute. The monthly method is fast. An ordinary PC can compute all results in real-time. The dynamic results may need some minutes up to some hours, depending on the complexity of the building model. Within the dynamic simulation not only the indoor air temperature is simulated. In addition the surface temperature of the surroundings of a room, e.g. to calculate the operative temperature, is computed and, once more, also the humidity. Assessments of comfort conditions become possible once those values have been generated. The predicted mean vote (PMV) or the predicted percentage of dissatisfied (PPD) is calculated hourly. Even if generally accepted boundary conditions are exceeded one can assess how long they will be exceeded.

The combination of both models using many of the same initial inputs, results in numerous positive synergy effects. On one hand it is possible to obtain very fast results using only the monthly method, including heating, cooling, electricity and primary energy demand and on the other, with some more calculation time, it is possible to get detailed information on risk of mould growth, rotting of components and of course detailed information on interior comfort conditions.
2.4 Basic application process

To simulate a building different inputs for the desired results are necessary, as shown Figure 1. Typically a user starts with the passive house calculation. The first thing to do is to input the building geometry including structure, material, location and all essential passive house verification data. Once the geometry is set, thermal bridges and windows can be defined. The next step is to define the usage of the building (residential or non-residential) as the next input for inner loads is different for each type. Last but not least the user has to define the mechanical equipment. Therefore different systems for e.g. heating, domestic hot water production and ventilation can be defined as well as information about the distribution system. The software gives feedback at all times during the entry process to inform the user about still missing inputs and provides reasonable input values as well as explanations regarding the current input parameter. Once all inputs are complete, the heating demand and all other passive house verification results are calculated instantly.

For the dynamic hygrothermal simulation a user can switch to the “WUFI Plus” mode once the main passive house criteria are met to a degree. Some input screens change to the dynamic relevant input data. Certain boundary conditions are not applied automatically because more detailed information may be required (like the indoor set point temperature, which can be defined via time schedule), but there is an option to choose them with one click. If a user has used building materials or assemblies provided within the database, no additional information is needed but some additional parameters such as indoor moisture loads should be defined. The software will check all inputs for completeness and prompt the user for missing information before the simulation can start. During the simulation a user can monitor movies for the heat and moisture profiles of each component or the hourly heating demand. If the simulation is finished, detailed reports and graphs illustrate the
3. Application Example

In this example, a residential building in Göteborg, Sweden, is analyzed using WUFI® Plus simulation and the static passive house calculation approach. Results for heating demand are compared and further investigations of possible moisture risks are conducted.

3.1 Simulation Model and Boundary Conditions

3.1.1 Climate

Hourly values of the outdoor climate are required for the dynamic simulation which are available in the WUFI® Plus database (Figure 2, Figure 3). In contrast, the passive-house calculation method is based on monthly mean values. The climate of Göteborg has an amplitude of 48°C with 29.4°C as maximum and -18.6°C as minimum. There is also a significant amount of driving rain from the south.

![Figure 2: Outdoor climate - temperature and rel. humidity](image)

3.1.2 Building and HVAC System

Within the framework of this paper a typical residential building model (Figure 4) has been used for both – the dynamic simulation as well as the static passive-house calculation method. The type of the residential building is a free-standing, two-story house with average wind exposure. In general, the assemblies of the building represent a typical Swedish construction type and are taken from (http://www.scanhome.ie/passive.php, also see 3.1.3). For detailed analysis, the building is subdivided into ten zones with individual internal loads and boundary conditions.

A heat pump with a capacity to ensure the indoor design conditions are met at any time for most of the zones (e.g. not for storage room) is used. Furthermore, a ventilation system with heat recovery efficiency of 85% is
installed. The use of photovoltaic or solar modules is not included in this case.

3.1.3 Components

The building envelope is specified that it fulfills the passive-house standard requirements of <= 15 kWh/m²a. For simplification, the construction is assumed to be without thermal bridges. For more information regarding the U-Values of the components see Table 1. As an example the exterior wall assembly is displayed in Figure 5.

<table>
<thead>
<tr>
<th>Component</th>
<th>U-Value in [W/m²K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior Wall</td>
<td>0.14</td>
</tr>
<tr>
<td>Interior Wall</td>
<td>* 1.93</td>
</tr>
<tr>
<td>Roof</td>
<td>0.13</td>
</tr>
<tr>
<td>Ceiling</td>
<td>* 1.10</td>
</tr>
<tr>
<td>Floor Slab</td>
<td>0.14</td>
</tr>
<tr>
<td>Exterior Door</td>
<td>0.23</td>
</tr>
<tr>
<td>Interior Door</td>
<td>* 1.76</td>
</tr>
<tr>
<td>Windows</td>
<td>0.80</td>
</tr>
</tbody>
</table>

SHGC = 0.55  

* (only relevant for heat storage)

3.1.4 Inner Loads and Design Conditions

The internal loads are set to the passive-house defaults for residential buildings (=2.1 W/m² treated floor area, in this case a total of 166.2 m²). For better comparison of the results between simulation and static calculation method, the internal loads are kept constant the whole day. The heat distribution to the room is 2/3 convective and 1/3 radiant.

The design minimum indoor temperature is set to 20°C for each zone apart from the stairway and storage room and the maximum temperature for overheating is defined to 25°C. If the set-point of 20°C is not reached, ideal heating is provided to the space up to the maximum heating power. Cooling devices are not available.

3.1.5 Ventilation

The building is constructed in such way, that a blower door test would result to n50 = 0.5 l/h which is below the passive-house requirements of 0.6 l/h. Empirical values suggest that a blower door test of 0.5 l/h corresponds to an infiltration rate of 0.03 l/h for this building. For sufficient fresh air supply a mechanical system is installed which runs at an air change rate of 0.35 l/h. The heat recovery efficiency is set to 85%. Manual window opening is not considered in this study.

3.1.6 Shading

For the simulation, a general shading factor (which is active at all-time) due to trees or neighboring buildings is specified to 0.9 (meaning reduction of incoming solar radiation of 10%). Furthermore, for the windows of the living room, there are overhangs of 50cm attached. To reduce overheating in the summer, a temporary sun protection (of 75% solar reduction) gets triggered whenever the design
temperature of 25°C is about to be exceeded. The shading for the static calculation method is estimated by the general factor, overhangs, reveal depth and shading objects.

3.2 Passive House Results

3.2.1 Passive House criteria

Apart from the heating load, all passive house criteria are met. Figure 5 shows a summary of all relevant values.

![Figure 6: Passive-House criteria](image)

3.2.2 Energy balance

The energy balances for the heating and cooling period are summarized in two graphs (Figure 7). In this case, the heat losses via windows are substantial to the overall heat losses during the winter months. For each section there are more detailed information provided for further analysis.

![Figure 7: Passive-House result - energy balance](image)

In case of windows for example there is an overview available (Figure 8), which can be used to quickly see the weak spots as well as detailed calculation for each window.

![Figure 8: Passive-House result - window overview](image)
A comprehensive output report is created, that shows all energy fluxes on building envelope, zone and systems level. All information required for certification is also included.

### 3.3 Dynamic Building Simulation Results

#### 3.3.1 Main results

After completing the simulation, the main simulation results are listed in WUFI® Plus/Passive in a table displaying heating and cooling demand as well as computed indoor conditions. The total heating demand sums up to 2742.42 kWh which equals 15.5 kWh/m² (166m² treated floor area).

#### 3.3.2 Energy balance

The energy balance for the heating period illustrates that the main fraction of the heat loss can be assigned to windows (for zone 1 = living room and south oriented, see Figure 9). It has to be pointed out, that the direct solar radiation on surfaces of surrounding components and radiant internal heating loads, are not considered in the energy balance graph, as it only regards the zone balance (indoor air). Hence, the bars for heat gains and losses are slightly out of balance. Figure 10 shows the hourly heat fluxes for zone 1.

![Figure 9: Simulation result - energy balance zone 1.](image)

![Figure 10: Simulation result - heat flow](image)
3.3.3 Comfort, Moisture risks

The hourly output values allow assessment of comfort and potential moisture damages. Figure 11 shows a simple comfort diagram, plotting relative humidity over temperature in zone 1 in comparison to comfortable areas. Due to the high building standard and sufficient air supply, there are no moisture damages estimated by the simulation. The analysis of the comfort shows, that in most cases the optimum or at least good conditions are met. However, there is a noticeable risk of overheating in zone 1.

The hygrothermal behavior of the components cannot be assessed by the static calculation approach, but is essential to evaluate potential moisture risks. In this example the water content of the fibreboard of the exterior wall is assessed depending on its orientation and the percentage of driving rain hitting this layer. A safety assessment according to ASHRAE 160 [ASHRAE 160, 2009] shows that with the application of 1% driving rain critical conditions might occur in the south oriented components (Figure 12). If the detail conditions are worse and 2% driving rain arrive at the fibreboard a net accumulation of the total water content is found and the building assembly will fail (Figure 13).

3.4 Comparison and Summary

The static calculations method and the simulation show similar results in several aspects, while the simulation estimates rather higher overheating (see Table 2).

Table 2: Result comparison

<table>
<thead>
<tr>
<th></th>
<th>static calculation</th>
<th>simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Demand</td>
<td>15.1 kWh/m²</td>
<td>16.5 kWh/m²</td>
</tr>
<tr>
<td>Heating Period</td>
<td>212 days</td>
<td>180.5 days *</td>
</tr>
<tr>
<td>Heating Load</td>
<td>11.6 W/m²</td>
<td>10.9 W/m²</td>
</tr>
<tr>
<td>Overheating Frequency (&gt;25°C)</td>
<td>10.6%</td>
<td>18.6 % (critical zone 1)</td>
</tr>
</tbody>
</table>

* Sum of heating hours

Figure 11: Simulation Comfort Assessment

Figure 12: Water Content Fibreboard - Orientations

Figure 13: Total Water Content of the Ext. Wall – Percentage of Driving Rain behind cladding
Figure 14 shows the mean daily heating demand for the whole building and each zone over the whole simulation period computed with the selected climate file. A high heating demand can be found for only a very short period of time. Zone 1, the living room, is the main contributor to the overall building heating demand.

Overall both approaches are viable as they complement each other. The static calculation method provides fast results and additional information regarding e.g. primary energy, electricity demand. WUFI® Plus on the other hand gives further information regarding hygrothermal behavior of the indoor climate and components including comfort assessment and potential moisture risks.

4. Summary, Conclusions and Outlook

The combination of both models – a monthly balanced and a dynamic simulation - into one tool has real potential to transform the passive building design process by making very complex processes accessible to more design professionals. Improvements start from a simple work flow perspective; it organizes the input process along a clearly guided path of the familiar tree structure of the WUFI software family while providing constant feedback on missing data entries. In addition, it supports the user by providing recommended and reasonable input values and explanation of the current parameter. Management help to optimize the design process in passive verification mode by allowing the modeler to store side by side an essentially infinite number of different cases is offered. The static calculation is fast and efficient and outputs include both numerical and illustrative graphical representations of the results, which are very helpful in discussions with clients.

Even more significant are the improvements in regards to the design process. Many designers have been forced to master and use separate hygrothermal tools and secondary dynamic energy models to assess wall component appropriateness by climate and thermal comfort by zone. All additional tools required some form of double entry of material properties, dimensions and mechanical specifications. In the design process many of those pieces of information are still in flux and lead to the need of updating three instead of one model when a design change is made. This is not only labor intensive but also increases the likelihood or error.

In conclusion, the most significant improvements aside from the more efficient and organized workflow is the all-in-one risk management capability. The next generation passive modeling needs to
include dynamic simulation and the ability to predict comfort issues such as overheating and high relative indoor humidity. And to conclude with a gaze into the future: as larger buildings with multiple zones also are being modeled to meet the passive building energy metrics it will become imperative to model and verify comfort in multiple zones in more complex buildings. WUFI Passive will meet those challenges on the horizon.

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Development of a Solid Wood Panel for Heating and Cooling of Floor, Wall and Ceiling Constructions

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KEYWORDS:
Multilayer solid wood panel, radiant heating, heating and cooling systems, tempering function, hygrothermal simulation, hygrothermal properties, performance- and damage analysis

ABSTRACT:
In the last years the usage of multilayer solid wood panels in the construction sector, has become increasingly popular. The ecological and sustainable production of wood is leading to this demand. In the frame of an industry driven project the development of a three layer solid wood panel with a functional pipe element in the middle layer is investigated. This functional element is used for heating and cooling of the wooden panel. Of course heat conduction of wood is adverse. Hence the challenge is to ensure the transfer of heat and cold to the wood and to handle the formation of condensation and moisture. Other aspects are to evaluate the pipe intervals and to reduce the thickness of the element. Therefore various hygrothermal simulations are carried out. Subsequently selected prototypes were produced and investigated in the laboratory at defined climatic conditions, using particular developed test benches with numerous sensors and infrared thermographic camera. Moisture, temperature and also strain are measured. The aim of these investigations is to create an energy efficient and optimal thermal behavior of the wooden panel heating/cooling system. In this context the results of the numeric simulations and the experimental investigations will be presented.

1. Introduction
Radiant heating systems increase the level of thermal comfort through the heating of surrounding surfaces. Those systems could be easily integrated in a buildings structure, especially into components surfaces, while merely low temperature is required. This enables the utilization of modern condensing technology, thermal heat pump systems and solar heat.

The most widely used radiant heating system is the floor heating. Operations are realized as hot water heating or electric heating. In case of water heating the system contents of water-flown pipes, made of plastic or multilayer composite. Also cooling of building components is possible. Here the heat of a component is dissipated through the tempering medium. Supply and removal of heat is enabled by the fluid which is flowing through the pipes.

The Department of Building Climatology of TU Dresden and the Institute of Wood Technology Dresden together with six industrial partners plan to create a new type of radiant heating/cooling system, using water-flown pipes for tempering of wooden panels. The base material is wood in form of a multilayer solid wood panel, which is frequently used for interior fittings with static functions in the construction sector. Thereby the diverse amenities of wood (ecological, sustainable, renewable, low weight, high load-bearing strength, natural moisture regulation etc.) are extended with a tempering function. This radiant system should be able to apply to the floor, wall and ceiling.

The structure of the proposed tempering system is shown in figure 1. The element is made of solid wood and consists of two top layers and a middle layer, twisted to around 90°. The layers are bonded together. The panel has a so called exterior top layer, which is faced to the building construction, and an interior top layer, which is faced to the room. In the middle layer a pipe system is embedded.
2. Method

In a first step conceivable materials are examined for usability. These are solid wood lamellas for the face and middle layer, alternative materials for the middle layer (e.g. wood-based materials), adhesives, adhesive additives and pipe materials. The hygroscopic parameters of the selected layer materials are measured in laboratory and appropriate material functions are generated. These material functions form the basis for the numerical simulation with Delphin. In the second step the thermal and hygric behaviors of the different types of solid wood panels are simulated in Delphin, including the functional pipe element in the middle layer. Defined climatic conditions for the ambient climate and the pipe element are given. Upon completion of the first phase of optimization, a number of solid wood panels is manufactured and examined at pilot plant scale. Subsequently these panels are investigated laboratory in a climate chamber, during operation of the functional pipe element. Additionally the preferably variants are proved in climatic test chambers, to testify the performance of the solid wood panel with respect to a defined space. The data acquired from the laboratory tests enable statements about viability and capability of the prototypes. Based on these results a further optimization by means of the numerical software Delphin takes place. This step includes a performance- and damage analysis of the selected solid wood panels. Subsequently further optimized solid wood panels are manufactured in pilot plant scale and tested laboratory. In a further step the options for the connection of the pipe elements of two adjacent panels are investigated. The final aim of the project is the production of solid wood panels with functional pipe element in the middle layer on an industrial scale, as well as the laboratory examination of these panels in the laboratory.

2.1 Selection and testing of the material

In this initial step, potential materials for the element layers, adhesives and its additives and also the pipe elements are searched for. The solid wood lamellas should enable heat conduction in direction of the interior surface. In order to achieve a higher heat flux in the vertical axis of the middle layer, alternative materials are considered and investigated. For the basis variant spruce wood is selected for all layers, it is readily available and favourable. Two alternative types of wood used for the top layer are beech and oak, which have higher heat conductivity than spruce. The middle layer should also be produced with PB (particle board) and MDF (medium density fireboard), assuming that the tight fit between pipe element and middle layer will be better using wood-based materials than solid wood.

In the manufacture of multilayer solid wood panels the usual practice is to employ melamine-urea-formaldehyde (MUF) resin. This adhesive is selected to bond the layers to each other. The resin has to be moisture permeable to prevent moisture accumulation inside and of the surface of the wood panel. Also it has to enable heat flux to ensure the panels performance. To fulfil the heating and cooling task a multilayer composite pipe is chosen.

In this work package the selected wood materials are tested in laboratory to determine the respected hygrothermal properties. The following properties are measured: matrix density, bulk density, porosity, thermal conductivity and capacity, moisture storage, water vapour diffusion resistance, water conductivity and permeability and water absorption coefficient. Continuous measurement of water uptake and measurement of continuous drying are done. Subsequently material functions are generated and implemented in the software Delphin.
2.2 Calculations with numerical simulation software Delphin

The aim of this work package is to obtain an optimal panel construction relating to the progression of heat and moisture and also condensation that might occur.

The computer-aided examination of the solid wood panel is based on the numerical simulation tool Delphin. This heat-, moisture- and air transport software is based on a theory which is deducted from thermodynamic processes. The transport processes and transitions between the solid, the fluid and the gaseous phase are described in these thermodynamic processes. Delphin enables the simulation of a whole building component with diverse material layers and boundary conditions.

Especially the existing buildings are supposed to represent a potential market for the solid wood panel with functional pipe element in the middle layer. Thus the basis for simulating the solid wood panel is build through a wall construction with a U-value of 0.35 W/m²K. This value refers to the Energy Conservation Regulations (EnEV 2009) for existing buildings with interior insulation. The boundary conditions for heating function distinguish between interior (10°C/65% RH) and exterior climate (-5°C/80% RH). The temperature in the pipe element is set to 35°C. In case of cooling function boundary conditions are defined as follows: 28°C/75% RH interior climate and 32°C/60% RH exterior climate. The tempering fluid is supposed to have an average temperature of 16°C (Glück 1999). The temperatures for heating and cooling of the pipe element are chosen to use the environmental energy for tempering. Table 1 gives an overview of the implemented boundary conditions.

**TABLE 1. Boundary conditions for the calculation with Delphin**

<table>
<thead>
<tr>
<th>Tempering function</th>
<th>Exterior Climate</th>
<th>Interior climate</th>
<th>Temperature</th>
<th>Pipe Element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature</td>
<td>Relative humidity</td>
<td>Temperature</td>
<td>Relative humidity</td>
</tr>
<tr>
<td>Heating</td>
<td>-5°C</td>
<td>80%</td>
<td>10°C</td>
<td>65%</td>
</tr>
<tr>
<td>Cooling</td>
<td>32°C</td>
<td>60%</td>
<td>28°C</td>
<td>75%</td>
</tr>
</tbody>
</table>

Additional to the material parameters, the geometry of the solid wood layers is very important such as thickness of the solid wood layers, pipe diameter and distance, piping route and also wood species. The required minimum thicknesses of the wood layers are essentially bounded by the limiting values of the manufacturing process. Standard thicknesses also vary from manufacturer to manufacturer. The included project partners provide top layers in diameters between 6.9 and 9.3 mm and middle layers between 9 and 20 mm.

The dimension of the middle layer is depending on the pipe diameter. The selection of pipe diameter and distance relate to performance criteria. A large pipe diameter in combination with a small distance would be the most powerful solution. Thus a diameter of 16 mm and a (standard) pipe distance of 10 cm is chosen. For the middle layer this leads to a thickness of 20 mm whereby the pipe element is located off-centre in the layer, directly on the adhesive plane.

A small radiation asymmetry represents a fundamental comfort condition (Glück 1999). Therefore the piping route should be symmetric. Two different balanced systems are usual: meander-shaped and spiral curse, as shown in figure 2. The spiral curse will create a more homogenous heat distribution. Here the warmer pipe of the flow is always next to the colder pipe of the return. For that reason the spiral curse is set as the basis variant for the following laboratory investigations.

**FIG 2. Piping routes: meander shaped (left) and spiral curse (right)**
With these determinations a first design variant of the tempering panel is set, which forms the basis for the following simulations. In this variant the thicknesses of the top layers are set to 9.3 mm and the distances between the pipes is set to 10 cm. Furthermore the whole solid wood panel consists of spruce. A first simulation is performed for the heating mode. Figure 3 shows the basis variant and the corresponding simulation result for the panel in case of heating.

In order to improve the heat flux in vertical and horizontal direction diverse modifications regarding to the structural setup of the panel are done:

- Variation of the thickness of the top layers
- Variation of the pipe distance
- Variation of the wooden materials
- Implementation of a heat-conducting layer

2.2.1 Variation of the top layer thicknesses

It is assumed that the heat flux in interior direction increases with reducing the thickness of the interior top layer to 6.9 mm. This assumption is confirmed by the simulation results, which are shown in figure 4. The calculated output value refers to the surface point between the pipes (see the point “TP” in figure 3). The average temperature difference between the both variants is 0.7 Kelvin. Consequently the reduction of the thickness of the interior top layer achieves higher surface temperatures.

FIG 3. Simulation results in case of heating (left: wall construction, right: temperature field in [°C])

FIG 4. Variation of the top layer thickness – surface temperatures

FIG 5. Variation of the pipe distance – surface temperatures
2.2.2 Variation of the pipe distance

A pipe distance of 10 cm is common and provides the basis variant. However, it is believed that the pipe distance should be as low as possible to increase the surface temperature and thus the amount of radiant heat. Determined by the minimum bending radius the minimal pipe distance is set to 8 cm. The result of this simulation is shown in figure 5. The temperature difference at the surface point “TP” is 2.1 Kelvin. Hence the reduction of the pipe distance leads to higher surface temperatures.

2.2.3 Variation of the wooden materials

A further step to increase the heat flux in the interior direction is to select another wood species. Therefore oak is chosen to substitute spruce, because of its high value of thermal conductivity ($\lambda = 0.16$ W/mK). At first only the interior top layer is refunded and then also the middle layer. The results of the simulations are shown in figure 6. In comparison to the base variant the variant with interior top layer made of oak reaches a higher surface temperature on point “TP” (0.3 Kelvin). If also the middle layer is replaced by oak, the surface temperature difference on point “TP” is 0.6 Kelvin in comparison to the base variant. Thus the aim is reached, to increase the heat flow in direction of the interior.

![FIG 6. Implementation of alternative wood species – surface temperatures](image)

![FIG 7. Implementation of a heat conducting layer – surface temperatures](image)

2.2.4 Implementation of a heat conducting layer

The simulations reveal the significance of heat flux at a high level in the plane of adhesive between middle layer and interior top layer and also from this plane in the interior direction. To enhance the level of the heat flux, two capabilities are elaborated. The first one is a fine metal grid which is installed directly between middle layer and interior top layer and the second one is a thermoplastic material which is inserted in the same plane. In the subsequent simulation the plane between middle layer and interior top layer is added with a heat conducting layer ($\lambda = 0.8$ W/mK), such as for example a thermoplastic material. As figure 7 shows, the surface temperature difference between both variants at the point “TP” is 0.4 Kelvin. Hence the installation of a heat conducting layer conduces the increasing of the heat flux in vertical and horizontal direction.

Finally nine prototypes of solid wood panels with functional middle layer are selected to be produced in pilot plant scale. Table 2 below shows the components of the nine prototypes (i.=faced to interior, e.=faced to exterior, S=spruce, B=beech).
TABLE 2. Prototypes produced in pilot plant scale

<table>
<thead>
<tr>
<th>Variant</th>
<th>Piping route</th>
<th>Pipe distance</th>
<th>Wood species</th>
<th>Exception</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>meander-</td>
<td>8 cm</td>
<td>top layer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>shaped</td>
<td>10 cm</td>
<td>(e.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>spiral</td>
<td></td>
<td>middle layer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>curse</td>
<td></td>
<td>top layer (i.)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>MDF</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>PB</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>7</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>B</td>
</tr>
<tr>
<td>9</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

2.3 Measuring of the prototypes

The measuring setup consists of the solid wood element itself and a 10 cm thick insulation in its reverse field (DIN EN 1264-1). The tempering element is connected to a thermostat which is located outside the climatic chamber. The pipes chaining thermostat and solid wood panel are insulated to keep the temperature difference between flow and return as low as possible. Inside the climatic chamber a thermographic camera is placed (see figure 9). Also the data logger for gathering the measuring data is positioned in the chamber. Wires lead outside from the camera and the logger to a computer on which the external storage and analysis of the data takes place. Figure 8 provides an overview of the measuring setup.

The measurement cycle should be determined from a periodic alternation of heating and cooling function, in order to define the impact of temperature change to the material behavior. The evaluation of the measurement course is done by using the software Delphin. The climatic boundary conditions for the heating function are: 15°C for exterior air temperature and 65% for exterior relative humidity. The temperature of the pipe element is 35°C. The aim of the simulation is to obtain statements about the transient state of the system. Figure 10 shows the result of the simulation. The pink curve shows the interior surface temperature between the pipes. The green curve displays the surface temperature at the point between the exterior top layer and the insulation, also between the pipes. After one day a
transient state is reached, which varies only very slightly in the further course. In case of cooling function a similar simulation is implemented. The boundary conditions are shown in table 3. The Figure 11 exhibits the results of this investigation. The transient state of the system is even after five days not yet reached. The main focus of the laboratory investigation is on the element’s hygrothermal behavior during heating. Since the transient state in case of cooling function is reached only after several days and time for the examination of the prototypes is limited the respective phase for heating and cooling is set to one day. The measuring cycle is now for each plate type as follows: preconditioning (2 days), heating (1 day), cooling (1 day), heating (1 day), cooling (1 day). The climatic boundary conditions are shown in table 3.

![Winter case - flow temperature 35°C](image1)

![Summer case - flow temperature 16°C](image2)

**FIG 10. Transient state – heating mode**  
**FIG 11. Transient state – cooling mode**

**TABLE 3. Measurement in climatic chamber – climatic boundary conditions**

<table>
<thead>
<tr>
<th>Tempering function</th>
<th>Exterior climate</th>
<th>Temperature pipe element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preconditioning</td>
<td>Temperature</td>
<td>Relative humidity</td>
</tr>
<tr>
<td>Heating</td>
<td>15°C</td>
<td>65%</td>
</tr>
<tr>
<td>Cooling</td>
<td>28°C</td>
<td>65%</td>
</tr>
</tbody>
</table>

In order to achieve a qualitative assessment for the hygrothermal behavior of the system measurements are performed during the operation. Here a distinction is made between the measurement plane on the panel’s surface and the measurement plane between face and middle layer. The temperature and the relative humidity are measured at two different distances to the pipe element. On the elements surface the temperature is also measured perpendicular above and also between the pipes. Equally the temperature of flow and return is measured. A strain gauge, also positioned on the surface, provides information about the stretching properties of the wood. A heat flux plate measures the heat flux. By means of an infrared camera the homogeneity of the heat radiated form the solid wood surface is recorded. To verify the climatic boundary conditions (temperature and relative humidity) another sensor is applied in the climatic chamber. In figure 12 the measuring points are shown.
3. Conclusions and outlook

In the frame of an industry driven project the development of a three layer solid wood panel with a functional pipe element in the middle layer is investigated.

In the first step suitable materials were procured for the systems structure such as different kinds of wood, wood-based materials, pipe materials and adhesives. Types of wood and wood-based materials were examined in the laboratory for their hygrothermal properties. Based on these measured properties, material functions were generated and implemented in the numerical simulation software Delphin.

With the aim to obtain an optimized panel a simulation study was done regarding to the hygrothermal behavior of the element. Here parameters such as material selection, geometry of the layers and the pipe elements and pipe distance were varied. As a result, the following optimizations were obtained: The reduction of the thickness of the interior top layer achieves higher surface temperatures. The reduction of the pipe distance also leads to higher surface temperatures. Wood species with a higher thermal conductivity, implemented as interior top layer, increase the heat flow in direction of the interior. The installation of a heat conducting layer in the plane between interior top layer and middle layer conduces the increasing of the heat flux in vertical and horizontal direction.

With these concretions of the panel’s structure, nine different prototypes of multilayer solid wood panels were manufactured with a functional pipe element in the middle layer to be tested in laboratory on their performance. The measurement setup and the measurement cycle were explained.

Currently the nine prototype panels are examined in the laboratory. First measurement results will be shown at the 10th Nordic Symposium on Building Physics in June 2014.

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Wood construction: Energy, Emissions and Experience

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KEYWORDS: Wood, latent heat, thermography, indoor climate, wood, spruce, untreated panel emissions, health.

SUMMARY:
Increased environmental awareness includes more consideration to indoor surface materials. The project Wood – Energy, Emission, Experience (WEEE) focuses on three aspects of interest when using wooden surfaces indoors: (I) The energy interaction of the air and the wooden surface – does the hygrothermal buffer capacity of wood contribute to improved indoor climate and possible reduce the energy need? (II) The emissions from wood panels – how does wood emissions differ and reach critical levels in residential buildings? (III) The experience of wood in our close surroundings – does exposure to wood environment and emissions influence our comfort and health, positively or negatively? This paper provides preliminary results from an ongoing project on untreated, solid wood.

1. Introduction

In the Western Hemisphere, people spend most of our time inside buildings. A substantial share of global energy consumption is used to accommodate desired indoor climate. There is an increased focus on actions to encounter energy-efficient buildings. This has resulted in concerns about possible human health effects from these actions.

The project Wood – Energy, Emission, Experience project (WEEE) (NFR 216404, 2011) examines the possibility to reduce primary energy input due to indoor wood surfaces, the expected emissions and following health effect. This paper sums up current results and presents future work. Each part is presented individually and commented on in the concluding remarks.

2. Do untreated wood surfaces contribute to the energy balance?

Based on the natural behavior of growing trees to provide the best growth environment at any climate, wood counteracts changes in the ambient environment in order to keep the vital moisture supply. Due to its water transport system, water on surface is absorbed in the capillaries (tracheides) and bound physically to the cell walls. Therefore wood can be seen as a natural phase change material (PCM). With varying relative humidity water molecules are bound and released, and this will respectively disengage and require energy. The authors investigate to which extent latent energy may be retracted from damp air with high enthalpy and this effect can be used to reduce the energy peaks.

Wood can be a conditioning component in the indoor environment because its open pore structure interacts with ambient air. This is defined as an active surface. Untreated wood has a surface of 200 m² per gram (Wimmer, 2012). Typical interior wall products in dwellings (often gypsum boards with wall paper or paint) have a much smaller capacity to interact with the indoor air and buffer moisture.
When including the pronounced hygroscopic capacity of wood, the energy gain from latent heat exchange may exceed the total energy gain of other materials with merely high thermal capacity (e.g. stone, concrete or glass). Energy gain from latent heat is studied on small samples in laboratory and with WUFI®plus simulations (Antretter and Winkler, 2014).

With the increasing need for energy efficiency in all buildings more efficient heating and advanced ventilation controls are receiving substantial attention. Research does, however, indicate that in spite of more efficient heating like from heat pumps, energy demand does not decrease like anticipated (Halvorsen and Larsen, 2013).

2.1 Initial simulations and laboratory test

Korsnes (2012) conducted hygrothermal simulations defining a potential energy outlet as a part of the phase change present from damp air to bond to the wood surface. A bathroom was heated, solely with damp air, by two degrees. This gives sufficient heat for comfortable dressing after a shower. The equal amount of energy is needed to dry the panels afterwards, but at this time no extra heat is needed; no one is getting dressed.

A laboratory test in a well controlled climate chamber has been conducted to verify the simulation results. Two wood surface samples (planed softwood, measuring 105 x 205 mm²) are subjected to change of ambient relative humidity from 20% to 90%. The temperature was kept constant and the relative humidity was rapidly changed within minutes. Both samples were from untreated wood, one exposed wood surface and one reference sample covered with low-emitting PE-foil to exclude moisture uptake, cf. FIG 1. The responding moisture uptake and heat release are measured by weight cells and thermography.

**FIG 1.** Samples mounted in housing. View Samples (covered left, uncovered right) and thermocouples mounted in the ceiling of a well controlled climate chamber. In center the air speed meter is placed.

Thermography is used to measure temperature differences on the two samples. Thermography detects the emitted magnetic waves from objects in the infrared spectrum and displays this as thermal images. Planed softwood reflects radiation with an emissivity of 0.86 while aluminium is an appropriate ambient material with a low emissivity of 0.02 at 25°C. Thermography has high sensitivity for temperature differences within areas and enables comparison of several spots at a time. Temperature is also measured with thermocouples in order to control the temperature measured by thermography. Ambient air velocity interacts with moisture uptake and is measured close to the surface. Weighting cells are used to measure the weight change (i.e. uptake of humidity) of the test samples.
The results show a substantial difference between the two wood samples, both in temperature rise and moisture uptake when increasing the relative humidity of the room, cf. FIG 2a and 2b. The covered reference sample is also heated mainly due to moisture condensation, but no moisture is absorbed as shown in no weight gain in FIG 2b. The difference of the reference sample and the exposed wood reach nearly 2 °C. About six grams of water is absorbed in around five minutes.

2.2 Potential energy savings

The material buffer effect has been discussed the last decades. Large investigations have been made on the effect of furniture and room surfaces. However, the potential in latent heat is sparsely treated (Hameury, 2006).

The wooden surface act like a heat battery. The sun dries out the surface during the day and the heat is delivered back to the room as the humid night air is distributed. The wood moisture equilibrium may change up to 10 weight percent in one daily cycle if the surface air relative humidity reach around 30 % at daytime and 75 % at night. A living room with a floor space of 20 m² may have 50 m² active surface, including the ceiling and major part of the walls. The outer millimetre of the wood surface is considered active (Hameury, 2006). This millimetre then accounts for almost 50 litres of wood if the wood has a density of around 470 kg/m³ (Norwegian Spruce). With the change in moisture content, this gives around 2.5 litres of water fluctuating between being bound to the wood surface or part of the humid air. When considering the enthalpy of their compared to the water bound in wood this gives a difference around 4 J/g. The energy ready for cooling at daytime and heating at night-time then reach 10 kJ, which equals 2.8 kWh. This is a quite substantial amount of energy in such a small room. Do you still wonder why it feels good to live in a wooden house?

The next step is full scale testing. There is a need to unveil effects which may interrupt the heating from the hygroscopic capacity of the wood surfaces.
2.3 Field test

Two cross-laminated timber (CLT) test houses were erected and instrumented at the Norwegian University of Life Sciences (NMBU), cf. FIG. 3.

The natural wood surface in walls and ceilings of these modules provide perfect conditions for studying wood surface and indoor air interaction. Documenting these processes in a near to real scale by accurate measurements, will also serve as reference to parallel hygrothermal computer simulations.

The test houses have previously been used for testing impact of sound (Aarstad 2009). The test houses were moved during the autumn of 2012 out to a test field of the university, which also includes a national meteorological station for Ås County. They have high prior moisture content due to the storage and transportation. The modules are heated and monitored for an initial period, until a stable and representative indoor environment is established.

Ventilation flow, heat demand, resulting temperatures and relative humidity of air into and out from the modules are controlled and registered. Extract ventilation is installed and controlled at 0.5 h\(^{-1}\), according to ordinary levels in Norwegian regulations (TEK10). Electric resistant heaters (2 x 2 kW) are easy to control and register power consumption in to keep indoor temperatures at intended level.

In the following phase, moisture will be introduced into the indoor environment, simulating natural use of buildings. The moisture buffering response to this will be studied. Surface materials will be changed during the experiment. Different ventilation strategies may also be studied. One potential will be to document the experience that one “seldom see dew on the mirror a bathroom panelled with untreated wood”. A consequence may be that air exchange levels are reduced, in cases where the reason for these ventilation levels have been to control moisture level in indoor air to below acceptable threshold levels. Reducing air exchange levels is one of the possible steps to achieve ambitious levels of energy use in Scandinavian dwellings.

![FIG 3. Field test at Ås. Two identical test-houses (7.0 m x 3.6 m x 2.2 m internal measurements).](image)

3. Emissions from wood

Generally, standard emission testing and certification schemes require measurements of emissions from building products after 28 days. The international standard ISO 16000-9:2006 also requires measurements after three days, and optionally additional measurements depending on the purpose of the study.

In Norway, a national adaption of the international BREEAM environmental classification of buildings have developed into BREEAM-NOR. This classification scheme has adopted somewhat
stricter criteria, e.g. emission testing after both three and 28 days. Another criterion that differs greatly from the international BREEAM standard is the requirement of low polluting building materials in BREEAM-NOR, this is mandatory for classification levels of very good and higher. The criteria for low polluting are based on the Finnish Emission Classification of Building Materials and its class M1, also included in NS-EN 15251:2007 Appendix C. The emissions that are limited include total volatile organic compounds (TVOC), formaldehyde, ammonia, carcinogenic compounds and odour. For solid spruce and pine wood the TVOC criteria must be taken into consideration, cf. Table 1.

**TABLE 1.** M1 criteria and area specific emission rates of softwood after 28 days (Englund 1999, Englund 2010)

<table>
<thead>
<tr>
<th>Examined qualities</th>
<th>M1 criteria</th>
<th>Spruce</th>
<th>Pine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[µg/m²h]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The emission of total organic compounds (TVOC)</td>
<td>&lt; 200</td>
<td>30-550</td>
<td>125-7000</td>
</tr>
<tr>
<td>The emission of formaldehyde</td>
<td>&lt; 50</td>
<td>4-5</td>
<td>3-6</td>
</tr>
<tr>
<td>The emission of ammonia</td>
<td>&lt; 30</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>The emission of carcinogenic compounds</td>
<td>&lt; 5</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Dissatisfaction with odour</td>
<td>&lt; 15%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For wood products, emission levels often show relatively high values after 28 days, but they are greatly reduced after further exposure to air. Perhaps the most striking observation is the considerable natural variation in emission source strength when testing a larger number of softwood samples with different origins. In the two publications by Englund, cited in Table 1, terpene emissions (and thereby TVOC) span over much more than one order of magnitude for a very limited number of samples. The same observation was made in a Nordic collaborative research effort in the late 1990’s (Nordic Wood, 1998). Englund (1999) concluded that ”The task of reaching a full and generalized picture of the emission characteristics of wood is a tremendous task, which hardly is possible to accomplish with realistic, limited resources… …To try to establish average values that could be used e.g. for all Nordic pine is, however, neither desirable nor meaningful. The only reasonable strategy is to acknowledge the large natural variations and to show their span, when necessary.” The emission source strength is furthermore strongly dependent on kiln drying schemes (Steckel et al. 2011) or thermal modification processes (Hyttinen et al. 2010).

Current understanding is fairly incomplete regarding the contribution of individual compounds on the indoor air quality (IAQ), but also on how emissions vary with the moisture content of the material and the ambient air. Theoretical predictions can be made from distribution coefficients, but this project will attempt to shed further light on this through experiments. Emissions at different relative humidities will be investigated. Bearing in mind the limitations given by the natural variations of solid wood, the data will also serve to expand the bulk of base data to make the overall assessments of expected emission behaviour stand on firmer ground. Predictions of indoor air quality may also be estimated in WUFI®plus.

### 4. Health effect from wood emissions

#### 4.1 State of the art

Research on health effects related to the built environment has mainly concentrated on the health impact of and various physical factors; ventilation, dust particles (Gyntelberg et al. 1994; Hauschildt et al. 1999), electrical fields (Skulberg et al. 2001) and emissions (Bornehag et al. 2010) as well as temperature, humidity and chemical substances (Wolkoff et al. 2003). Many indoor environment studies have measured the total volatile organic compounds (TVOC). No correlation between TVOC and health has been found (Andersson et al. 1997). However, several studies have found correlation between health outcomes and individual chemical substances such as formaldehyde, phthalates
Cross-sectional design has been used most often in indoor environment studies. Questionnaires have been used in several Nordic studies, e.g. the Örebro questionnaire (Andersson et al. 1993), which aims at detecting three different groups of health outcomes: general symptoms (fatigue, headache, dizziness and failure to concentrate), irritation symptoms from mucous membranes (eyes, nose and throat) and skin symptoms (face and hands).

A few studies have specifically addressed health effects of indoor wood use, mainly focusing on subjective experience of wood materials, such as tactile and acoustic properties, thermal effects, odor or visual appearance and psychological effects and well-being. A few studies have also studied health effects as measured by objective physiological parameters (Gminski et al 2011), and all available results indicate that no adverse effects can be found. Nyrud and Bringslimark (2010) provide a review of relevant literature. Issues related to material use, building design and health have also been studied, e.g. Bringslimark, Bysheim and Nyrud (2010).

4.2 Laboratory experiment

A laboratory experiment evaluating occupant health in a controlled indoor environment was conducted in the indoor laboratory at the Oslo and Akershus University College of Applied Sciences (HiOA). The study addresses responses among human participants under two different conditions in a controlled environment, with different concentrations of emissions from wood. The aim was to evaluate the effect of emissions from Scots pine (*Pinus Silvestris*) on test persons in a simulated indoor environment.

Sixteen groups of two participants were scheduled for exposure to each of the two different conditions for two hours per condition. The control condition was without pine in the chamber, and the intervention condition was with fresh sawn pine wood in the chamber. The test subjects could not see whether there was pine in the chamber. Continuous measurement of Volatile Organic Compounds was conducted using a Proton-transfer-reaction mass spectrometer. The temperature and humidity were kept stable and monitored along with the CO2-concentration. The experimental sessions for each group took place over a seven day period. The groups were exposed for one condition (no emissions/emissions) and subsequently for the other condition seven days later. The experiment consisted of 60 minutes of acclimatization, 30 minutes of introductory health tests, 120 minutes of exposure in the chamber and 30 minutes of post exposure health tests.

The order in which participants were exposed to the different conditions was balanced across groups. Participants were not informed about specific conditions in each session.

Before, during and after each exposure condition, participants completed a computer-based test of subjective health outcomes (c.f. Örebro questionnaire, Andersson et al. 1993) where they reported subjective evaluation of health symptoms related to indoor air quality.

The study was approved by the Regional Committee for Medical and Health Research Ethics (REK). Test subjects were mainly recruited among students at the HiOA. All test subjects were at least 20 years old, non-allergic non-smokers.

4.3 Results

Results are not fully analyzed. The concentration of monoterpenes in the control condition was less than 50 ppb, whereas the concentration in the intervention condition with pine wood in the exposure chamber reached levels of 1 000 – 3 000 ppb.

1000 ppb is equivalent to a concentration of 6000 μg/m$^3$ which equals an area-specific emission rate 3000 μg/m$^2$h. This is 15 times higher than the limit to M1 (200 μg/m$^2$h). There were no statistically significant health effects on test subjects from the exposure to emissions from wood. For several
outcomes (eye blinking ratio, neuropsychological test and self subjective health symptoms) there was, however, a statistically significant effect of participating in the experiment. This may be due to a learning or observer effect where test subjects may improve or modify behaviour in response to the fact that they know they are being studied.

5. Concluding remarks

Thermography provides an adequate method for measuring temperature differences due to moistening of wood. The comparison of reference samples and samples provided sorption and heat characteristics in correlation with the climate. This is with suitable accuracy for closer examination.

The latent heat exchange provides energy in indoor areas for hours after moistening. Thus untreated wood has energy saving potential in every kind of interior application.

The use of energy input and indoor climate levelling from untreated wood surfaces may increase the energy efficiency in our modern houses.

The monoterpane levels of the trial experiment showed a emission concentration which will be compared to as 15 times higher than the M1 criteria which must be fulfilled to deliver a BREAM certified building in Norway. There were no statistically significant health effects of the exposure to emissions from wood.

This research project will bring forward documentation of physical and experienced real wood behaviour.

6. Acknowledgements

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References


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Window-opening and indoor climate in new multifamily-dwellings – A questionnaire survey

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KEYWORDS: Window-opening, airing, comfort, questionnaire survey, indoor climate

SUMMARY: The apartment-block of Flagghusen in Malmö in the south of Sweden was built and designed with the intention to achieve a lower energy use compared to the regulations and a good indoor environment. The outcome of this ambition was evaluated in a first report in 2010 that showed that the overall notion of the perceived indoor climate in the apartments were good but that the measured energy use exceeded the estimated values. It was revealed that the residents air their apartments frequently and for extended periods of time, which was in congruence with the previously made nationwide questionnaire survey BETSI. This observation in combination with the exceeded energy use resulted in the wish for a more comprehensive questionnaire study with in-depth questions concerning the window-opening behavior. A second questionnaire study took place in the heating season of 2012. This study aims at showing the magnitude and frequency of the window opening and to delve in the reasons why residents air their apartments with this second study as basis.

1. Introduction

1.1 Background

The apartment-block of Flagghusen in Malmö in the south of Sweden was built and designed with the intention to achieve a lower energy use compared to the regulations and a good indoor environment. This was made by the initiative of Malmö Stad who at that time were a part of Bygga-Bo dialogen, a government financed program to promote sustainable city development. In 2010 a study was presented showing the outcome of the project both by comparing measured energy use with estimates from the design face and an evaluation of questionnaires concerning the indoor climate (Hansson and Nordquist 2010). The report showed that the overall notion of the perceived indoor climate in the apartments were good but that the measured energy use exceeded the estimated values. The evaluation of the questionnaire also revealed that the residents air their apartments frequently and for extended periods of time. More than 50 % indicated that they air daily or almost daily which is in congruence with the nationwide questionnaire survey BETSI (Boverket, 2009). Only the amount of airing could be concluded from this study. The reasons why the residents wanted to air their apartments were however not possible to attain. These reasons are one important part to examine if the behavior and the factors affecting it are to be understood. This observation in combination with the exceeded energy use resulted in the wish for a more comprehensive questionnaire study with in-depth questions concerning the window-opening behavior. This second questionnaire study took place in the heating season of 2012. The answers were then analyzed. Based on the answers from the questionnaire additional measurements were performed in selected apartments where extensive airing took place, the measurements was performed during the heating season of 2013. In connection with the measurements the residents were interviewed regarding their interaction with the heating system and airing. The conclusions from these short interviews and measurements in individual apartments is presented in (Nordquist et al 2014). The complete report for both questionnaire survey and measurements can be
found in Fransson and Lindberg (2013). The results presented in this paper is a compilation of results from the questionnaire survey regarding airing more extensively presented in the above mentioned report. An analysis concerning energy use and window-opening in this apartment block will be published this spring, Karlsson and Nordquist (2014). Other recent studies concerning window opening and occupant behavior in dwellings have been made by for example Berge et al (2013), Frontzak et al (2012) and Vinther Andersen et al (2008).

1.2 Paper Outline

This study aims at showing the magnitude and frequency of the window opening and to delve in the reasons why residents air their apartments. The window opening behavior will also be investigate by evaluating answers from questions mostly regarding thermal sensation. For determination of the impact of this comfort parameter on airing behavior.

2. Questionnaire survey

In the beginning of 2012 a questionnaire-survey was performed in the apartment-block of Flagghusen in Malmö in the south of Sweden. This study was a follow-up of a similar questionnaire-survey made a few years earlier in 2010 but now extended with comprehensive questions including airing behavior.

2.1 Method

The experience of the occupants has been studied by standardized and validated questionnaires, called the “Stockholm’s-questionnaire” (Engvall, 2002) and used by the city of Malmö (Miljöbyggsprogram Syd, 2009). As mentioned above additional questions focusing on airing have been added from the previous study, the questionnaire consisted of a total of 62 questions. This paper will discuss the questions and answers regarding the issue of airing behavior and not the complete survey of 62 questions.

Questionnaires were distributed to 523 apartments in 12 different properties in between 5-7 of March 2012 and gathered during the end of the same month. The questionnaire were distributed to each member of the residence by the age of 18 or older and they were asked to be answered individually. 257 questionnaire were returned and the answers from these are the base for the conclusions in this paper. The response rate can be compared with the Swedish nationwide survey BETSI (Boverket, 2009). There is a slight difference between the Flagghusen study and the BETSI study as the former consisted of two questionnaires, one to be answered for each household concerning the residence and a personal questionnaire that was distributed to all persons in the household. The Flagghusen questionnaire were distributed to each adult of the residence but consisted of questions regarding both residence and the persons themselves so it can be viewed upon as a combination or merger of the BETSI study’s two separate questionnaires. The response rate from the Flagghusen survey viewed upon as per person was 32 % compared to 46 % in the BETSI study, viewed upon as per household the response rate for Flagghusen was 45 % compared to 49 % for the BETSI study.

3. Results

3.1 General answers

This first part of the result chapter aims to give a general overview of how the residents that answered perceive their indoor environment together with the frequency and the cause for airing their apartments.

| TABLE 1. How do you perceive the air quality in your apartment? |
|------------------|---------|-------|-------|-------|-------|
| Very good        | Good    | Acceptable | Bad | Very bad |
| 30 %             | 43 %    | 21 %       | 4 % | 0 % |

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The results from Table 2 show that only 4 % of the inhabitants are dissatisfied with the air quality in their apartments.

**TABLE 2. Do you think it is too cold or too hot in any of the rooms in your apartment during the heating season?**

<table>
<thead>
<tr>
<th></th>
<th>Much too cold</th>
<th>Too cold</th>
<th>Equilibrium</th>
<th>Too hot</th>
<th>Much too hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchen</td>
<td>5 %</td>
<td>8 %</td>
<td>82 %</td>
<td>2 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Livingroom</td>
<td>7 %</td>
<td>13 %</td>
<td>75 %</td>
<td>4 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Bathroom</td>
<td>5 %</td>
<td>12 %</td>
<td>79 %</td>
<td>2 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Bedroom</td>
<td>7 %</td>
<td>11 %</td>
<td>74 %</td>
<td>4 %</td>
<td>2 %</td>
</tr>
</tbody>
</table>

From Table 2 the answers show that the main reason for thermal discomfort is too low temperature but there are 6 % who experience the opposite in the bedrooms even during the heating season. The main part of the participants however are at an equilibrium state regarding the temperature in the apartment.

**TABLE 3. How often do you usually air during the heating season?**

<table>
<thead>
<tr>
<th></th>
<th>Daily/almost every day</th>
<th>Approximately once a week</th>
<th>A few times every month</th>
<th>Rarely or never air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flagghusen</td>
<td>53 %</td>
<td>26 %</td>
<td>12 %</td>
<td>8 %</td>
</tr>
<tr>
<td>BETSI (1996-2005)</td>
<td>61 %</td>
<td>17 %</td>
<td>12 %</td>
<td>9 %</td>
</tr>
</tbody>
</table>

The answers about how often and how long the residents air their apartments in Flagghusen has been compared with the answers from the BETSI-study for buildings completed during the period 1996-2005. The result concerning frequency is compiled in Table 3 and it is shown that the airing is slightly less frequent for Flagghusen.

**TABLE 4. When you air, do you usually have...? (Sep-Apr)**

<table>
<thead>
<tr>
<th></th>
<th>A window opened the whole day or night</th>
<th>A window opened for a few hours</th>
<th>Cross-ventilation for a few minutes</th>
<th>Never air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flagghusen</td>
<td>12 %</td>
<td>43 %</td>
<td>44 %</td>
<td>4 %</td>
</tr>
<tr>
<td>BETSI (1996-2005)</td>
<td>19 %</td>
<td>50 %</td>
<td>27 %</td>
<td>4 %</td>
</tr>
</tbody>
</table>

Table 4 shows that the duration the occupants air their apartments is slightly longer for the BETSI-study compared to Flagghusen.

**TABLE 5. When you air, do you usually have...?**

<table>
<thead>
<tr>
<th></th>
<th>Window opened the whole day or night</th>
<th>Window opened for a few hours</th>
<th>Cross-ventilation for a few minutes</th>
<th>Never air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airing daily</td>
<td>19 %</td>
<td>48 %</td>
<td>38 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Airing once a week or less</td>
<td>3 %</td>
<td>38 %</td>
<td>52 %</td>
<td>8 %</td>
</tr>
</tbody>
</table>

In Table 5 the answer for Flagghusen in Table 3 and 4 have been cross-examined. Two groups were formed depending on how the residents responded in Table 3, “Airing daily” and “Airing once a week or less”. It is seen in Table 5 that the respondents who air more frequently also air for a longer period of time at the occasion of airing.
TABLE 6. For how long do you air your apartment each day?

<table>
<thead>
<tr>
<th>Time</th>
<th>Winter (Nov-Mar)</th>
<th>Spring, autumn (April, Sep-Oct)</th>
<th>Summer (May-Aug)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No airing</td>
<td>9 %</td>
<td>5 %</td>
<td>1 %</td>
</tr>
<tr>
<td>0-15 min</td>
<td>41 %</td>
<td>21 %</td>
<td>2 %</td>
</tr>
<tr>
<td>15-30 min</td>
<td>12 %</td>
<td>14 %</td>
<td>3 %</td>
</tr>
<tr>
<td>30-60 min</td>
<td>7 %</td>
<td>16 %</td>
<td>13 %</td>
</tr>
<tr>
<td>1-2 h</td>
<td>7 %</td>
<td>13 %</td>
<td>14 %</td>
</tr>
<tr>
<td>2-6 h</td>
<td>3 %</td>
<td>5 %</td>
<td>21 %</td>
</tr>
<tr>
<td>6-12 h</td>
<td>5 %</td>
<td>7 %</td>
<td>14 %</td>
</tr>
<tr>
<td>12-18 h</td>
<td>1 %</td>
<td>2 %</td>
<td>7 %</td>
</tr>
<tr>
<td>18-24 h</td>
<td>0 %</td>
<td>2 %</td>
<td>11 %</td>
</tr>
</tbody>
</table>

Table 6 shows the answers from one of the questions added in the second survey that gives a more detailed view of the amount of time the residents leave their windows open each day, also seasonal variations can be distinguished. During the coldest period of the year (Nov-Mar) 16 % have their windows opened one hour or longer each day. This number increases to 29 % in the spring and autumn (April, Sep-Oct) and further still to 67 % in the summer (May-Aug).

TABLE 7. What is usually the main reason for you to air your apartment during the heating season?

<table>
<thead>
<tr>
<th>Reason</th>
<th>Winter (Nov-Mar)</th>
<th>Spring, autumn (April, Sep-Oct)</th>
<th>Summer (May-Aug)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habit, routine</td>
<td>30 %</td>
<td>29 %</td>
<td>21 %</td>
</tr>
<tr>
<td>Received sufficient amount of new air</td>
<td>44 %</td>
<td>16 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Satisfactory indoor temperature reached</td>
<td>16 %</td>
<td>20 %</td>
<td>5 %</td>
</tr>
<tr>
<td>Too cold ambient air temperature</td>
<td>5 %</td>
<td>18 %</td>
<td>8 %</td>
</tr>
<tr>
<td>Too windy</td>
<td>8 %</td>
<td>10 %</td>
<td>7 %</td>
</tr>
</tbody>
</table>

Table 7 shows the main reasons for airing during the heating season and that there is no cause that stands out in particular, the main reason is habit closely followed by bad air quality. The thermal climate is another cause that the residents report. For this question multiple answers were accepted meaning that multiple reasons can occur in the same apartment. Under “Different reason” the residents had the opportunity to answer in free text and the most frequently occurring statement was the wish or notion of getting fresh air.

TABLE 8. What causes you to stop airing?

<table>
<thead>
<tr>
<th>Reason</th>
<th>Winter (Nov-Mar)</th>
<th>Spring, autumn (April, Sep-Oct)</th>
<th>Summer (May-Aug)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habit, routine</td>
<td>14 %</td>
<td>44 %</td>
<td>16 %</td>
</tr>
<tr>
<td>Received sufficient amount of new air</td>
<td>44 %</td>
<td>16 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Satisfactory indoor temperature reached</td>
<td>16 %</td>
<td>20 %</td>
<td>5 %</td>
</tr>
<tr>
<td>Too cold ambient air temperature</td>
<td>5 %</td>
<td>18 %</td>
<td>8 %</td>
</tr>
<tr>
<td>Too windy</td>
<td>8 %</td>
<td>10 %</td>
<td>7 %</td>
</tr>
</tbody>
</table>

Table 8 shows what causes the inhabitants to stop airing, for this question multiple answers were accepted meaning that multiple reasons occurred in the same apartment. The most significant cause for closing the windows, which occurred in 44 % of the apartments, was that sufficient amount of new air had been received. That ambient conditions influence residents to stop airing is also seen.

3.2 Cross examination of answers

By dividing the answers into different groups depending on the answer to a particular question enables the possibility to investigate the impact on one question upon another.
3.2.1 Groups divided depending on time they air their apartments each day

Here the answers from the questionnaire has been grouped according to the answers seen in Table 3 (winter, Nov-Mar) creating two groups, airing less or more than one hour each day. In this analysis the time chosen as the breaking point between frequent and lesser airing is one hour.

**TABLE 9. With how large opening do you air your apartment during the heating season?**

<table>
<thead>
<tr>
<th>Width less than 0,5 m</th>
<th>Width exceeding 0,5 m</th>
<th>Height less than 0,5 m</th>
<th>Height exceeding 0,5 m</th>
<th>Ajar (up to 10 cm)</th>
<th>Half open (between 20-50 cm)</th>
<th>Fully open (more than 50 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 hour/day</td>
<td>14 %</td>
<td>76 %</td>
<td>6 %</td>
<td>80 %</td>
<td>49 %</td>
<td>39 %</td>
</tr>
<tr>
<td>&gt; 1 hour/day</td>
<td>24 %</td>
<td>73 %</td>
<td>9 %</td>
<td>80 %</td>
<td>71 %</td>
<td>24 %</td>
</tr>
</tbody>
</table>

In Table 9 it is shown by which mean these two groups air their apartments and there are two notable distinctions. The first is that the people who air a shorter period each day open the windows more fully (10 %) and those who air longer is more likely to put the window ajar (71 %). The second thing is that those who air longer tend to use a narrow window more often (24 %) than the other group (14 %).

**TABLE 10. What is usually the main reason for you to air your apartment during the heating season?**

<table>
<thead>
<tr>
<th>Habit, routine</th>
<th>Air quality issues</th>
<th>Too hot</th>
<th>Existing ventilation is not sufficient</th>
<th>Different reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 hour/day</td>
<td>31 %</td>
<td>31 %</td>
<td>19 %</td>
<td>10 %</td>
</tr>
<tr>
<td>&gt; 1 hour/day</td>
<td>38 %</td>
<td>33 %</td>
<td>38 %</td>
<td>13 %</td>
</tr>
</tbody>
</table>

As mention earlier multiple answers were accepted for the question seen in Table 10. It can be observed that causes for airing occur more often in the group that air more than one hour each day. The most significant difference in comparison between the groups is regarding over-temperature, this cause occur twice as often in the group with above one hour airing. Habit is the main reason for airing in both groups together with air quality and temperature.

3.2.2 Groups divided into groups depending on their thermal sensation

Now three groups have been created from the answers of the last row in Table 2 regarding thermal sensation in the bedroom. The bedroom was chosen because there was the largest percentage dissatisfied as well as the biggest spread. Something that was noticed during the grouping was that those who thought it was hot or cold in the bedroom in most cases also had this experience for the other rooms so it is assumed that the answers for the bedrooms gives a good picture of the dwelling as a whole (there was no option in the questionnaire solely regarding the whole apartment for this question). The group “Cold” in Table 11, 12 and 13 consists of residents that answered both “much too cold” and “too cold” in Table 2. The same procedure has been made for the answers regarding too high temperature.

**TABLE 11. For how long do you air your apartment each day?**

<table>
<thead>
<tr>
<th>No airing</th>
<th>0-15 min</th>
<th>15-30 min</th>
<th>30-60 min</th>
<th>1-2 h</th>
<th>2-6 h</th>
<th>6-12 h</th>
<th>12-18 h</th>
<th>18-24 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>9 %</td>
<td>47 %</td>
<td>20 %</td>
<td>4 %</td>
<td>4 %</td>
<td>2 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>10 %</td>
<td>41 %</td>
<td>11 %</td>
<td>8 %</td>
<td>7 %</td>
<td>3 %</td>
<td>6 %</td>
<td>1 %</td>
</tr>
<tr>
<td>Hot</td>
<td>0 %</td>
<td>31 %</td>
<td>13 %</td>
<td>6 %</td>
<td>13 %</td>
<td>13 %</td>
<td>6 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>
In Table 11 the answers for the three groups concerning the time they air their apartment each day is shown. 6% in the group that think it is too cold air longer than one hour each day, for the group experiencing equilibrium this number is 18% and for the last group 45%. Noticeable is that almost 20% of those who experience equilibrium air longer than one hour each day, also this group consists of three quarters of the residents participating in this survey according to Table 2.

**TABLE 12. What is usually the main reason for you to air your apartment during the heating season?**

<table>
<thead>
<tr>
<th>Reason</th>
<th>Cold</th>
<th>Equilibrium</th>
<th>Hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habit, routine</td>
<td>31%</td>
<td>31%</td>
<td>19%</td>
</tr>
<tr>
<td>Air quality issues</td>
<td>38%</td>
<td>27%</td>
<td>38%</td>
</tr>
<tr>
<td>Too hot</td>
<td>11%</td>
<td>21%</td>
<td>44%</td>
</tr>
<tr>
<td>Existing ventilation is not sufficient</td>
<td>22%</td>
<td>7%</td>
<td>13%</td>
</tr>
<tr>
<td>Different reason</td>
<td>9%</td>
<td>16%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table 12 shows the reasons for airing among the three groups. One observations is that the groups who feel it is too cold or too hot both experience a more significant reason to air due to air quality issues or insufficient ventilation compared to the group experiencing equilibrium. Airing out of habit is here the main reason only for the group who experience equilibrium.

**TABLE 13. How can you control the temperature in your apartment?**

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Cold</th>
<th>Equilibrium</th>
<th>Hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airing</td>
<td>36%</td>
<td>51%</td>
<td>69%</td>
</tr>
<tr>
<td>Knobs on the radiators</td>
<td>40%</td>
<td>70%</td>
<td>56%</td>
</tr>
<tr>
<td>Display where the indoor temperature is chosen</td>
<td>16%</td>
<td>17%</td>
<td>0%</td>
</tr>
<tr>
<td>No ability to influence</td>
<td>11%</td>
<td>2%</td>
<td>6%</td>
</tr>
<tr>
<td>Different way</td>
<td>13%</td>
<td>6%</td>
<td>13%</td>
</tr>
</tbody>
</table>

How the three groups believe they can control the temperature in their apartments is shown in Table 13. Airing as a way to control the temperature is most significant for those who experience too high temperature followed by the equilibrium group and least significant for the group who feel their apartments are too cold. Regarding the interaction with the heating system as a way of controlling the indoor temperature over 90% of the equilibrium group consider it useful. This number is about 20% lower for the other two groups. The ability to control the heating system is assumed to consist of answers from three categories “Knobs on the radiators”, “Display where…” and “Different way”. Under the category different way the residents mostly describe ways of controlling floor heating that does not fit under the other categories.

### 4. Conclusions and Discussion

The air quality is perceived good or acceptable by the vast majority of the residents, only 4% think it is bad. Considering thermal comfort the experience of equilibrium conditions vary from 74% to 82% for the rooms in the apartment. Too low temperature is the main issue for those dissatisfied however 6% deem the temperature too high in the bedroom. Both bad air quality and thermal climate are main causes which according to the answers can be reasons for airing. This leads to the conclusion that residents who experience good indoor air quality as well as good temperature conditions air their apartments for periods extending from one hour per day up to 18-24 hours a day. The explanation for this cannot be certain but one theory is that the rather extensive airing is experienced as a necessary measure for achieving a desired indoor climate. This gives room for questions both regarding energy
use of the buildings and functionality of the ventilation system. The residents who experience good indoor air quality and good temperature conditions represent the majority of the answers from the survey. This fact can be interpreted in a way that possible deficiencies with the regulation of the heating system and the supply air-flow might be covered by the behavior of the occupant leading to acceptable indoor conditions first after airing is applied at the cost of higher energy use. This brings forth the subject of user related questions, how do residents interact with the heating system, what do they know about the management of the ventilation system etc. What demands can and should be laid upon the user and what will the consequences be. As mentioned in the introduction a separate paper (Nordquist et al 2013) will discuss several of these issues. Apart from bad air quality and temperature the main reason for airing is out of habit or routine according to the answers. What a habit is and from where it originate can be discussed. Perhaps it is a remnant from another living situation or maybe it is sprung from a repetitive need for airing due to a particular reason. This recurring action of airing due to a problem with for example too high temperature might in time turn into a habit and no longer be thought of as a way of solving an otherwise existing problem. This however is just a theory but definitely worth mentioning as this reason is such a big factor when considering window-opening behavior at least according to the answers in this study.

The last conclusion regards the way the resident’s air depending on the duration. There is a very clear pattern showing that when airing longer than an hour the windows are less likely to be open wide but much more likely left ajar. And for short airing occasions a fully or half open window is more frequently used. One can assume that the short airing with fully open windows is to rapidly get rid of pollutants such as cooking fumes or other smells while airing with a smaller opening for a longer period of time is to lower the temperature. The answer in Table 10 gives a small indication that this might be a plausible explanation.

5. Acknowledgements

First of all BEBO; a cooperation between the Swedish Energy Agency and some large building owners in Sweden working for energy-efficient apartment buildings is acknowledged for financing the study. Secondly we wish to acknowledge those at the department of Building Services at Lund University who supported us throughout the study. Finally we wish to acknowledge the residents who participated in the questionnaire survey, without your share of experience this would not have been possible.

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Numerical investigation of diffuse ceiling ventilation in an office under different operating conditions

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KEYWORDS: Diffuse ceiling ventilation, ventilation efficiency, ventilation, draught, CFD

SUMMARY: Diffuse ceiling ventilation is a novel air distribution device that combines the suspended acoustic ceiling with ventilation supply. A diffuse ceiling distributes the supply air above the acoustic tiles and has proven performance in both laboratory and classroom experiments. This paper is a numerical study of the performance of a six person office equipped with diffuse ventilation ceiling. In total six extreme, yet realistic, operation scenarios were simulated to study the performance including different occupancy, ventilation rates and supply air temperatures. The performance was studied with regard to air change efficiency, air movements, temperatures and stratification. In all scenarios the ceiling performed satisfactorily.

1. Introduction

The main purpose of the ventilation system in a building is to supply fresh air to the occupants and secondary to remove excessive heat. The ventilation system should do so energy-efficiently and with minimal risk of discomfort in the occupied comfort zone. A promising concept for this is diffuse ceiling ventilation which is a novel air distribution device that combines the suspended acoustic ceiling with ventilation supply. The principle of diffuse ceiling ventilation for comfort ventilation is to inject the supply air into the plenum above a standard suspended acoustic ceiling. The plenum thereby works as a pressure chamber and air is distributed to the room below through cracks and perforations. The flow velocity into the room is very small and irregular, hence the term diffuse.

The reported research in this area mostly relies on laboratory experiments where results have been promising. Nielsen & Jakubowska (2008) published results where diffuse ceiling ventilation outperformed five conventional air distribution systems in a laboratory office environment. The findings were supported by Hviid & Svendsen (2013) who carried out experiments in a test facility resembling a small classroom as well as in a real classroom (Hviid & Terkildsen 2012). Fan et al. (2013) has documented good performance of the concept both experimentally and numerically. Numerical investigations by CFD (Computational Fluid Dynamics) were shortly performed on an office by Nielsen et al. (2010) to investigate the level of stratification in heating mode. Hviid & Petersen (2011) demonstrated that diffuse ceiling ventilation may improve the night cooling potential of a classroom.

The objective of the research reported in this paper is to assess the indoor climate performance of diffuse ceiling ventilation in an office environment under six different operating conditions that stresses the concept. The performance is assessed numerically by CFD in terms of thermal conditions, air movements, stratification, and air change efficiency.
2. Test case

The investigations have been performed on an office located in a large newly erected building in the harbour of Aarhus, Denmark. The numerical solution domain has been established from the geometric model of the irregular office room depicted in FIG 1. This room was selected because the large façade/floor ratio has high solar gain and high thermal losses, thus imposing maximum stress on the HVAC strategy. The floor area of the office is 41.4 m$^2$ with a room height of 3.0 m. The room has two facades with the compass orientations 177° / 303°. The windows are arranged as transparent bands with a height of 1.8 m. The parapet is 0.875 m high.

![FIG 1. Plan view of office. Furniture layout reflects potential meeting room](image1)

2.1 Diffuse ceiling

The suspended acoustic ceiling used as diffuse inlet consists of horizontal aluminium lamellas attached to a carrier as depicted on FIG 2 with 20 mm of black acoustic mineral wool batts overlying the lamellas. The finalized ceiling is depicted on FIG 3. The main air paths are the small holes in the universal carrier as well as cracks between batts and suspension profiles originating from the installation. This means that some air enters the room as linear microjets along the carriers, and some air enters diffusively.

![FIG 2. Aluminium lamellas with suspension system](image2)  ![FIG 3. Finalized ceiling](image3)
3. Method

3.1 CFD model

For the simulations the commercial CFD code Ansys CFX version 14.5 was used. FIG 4 depicts the CFD model with six workstations, occupants and computers. The lighting fixtures are not represented as they are off in all scenarios due to daylight control. All internal components of the model are simplified with box-shaped geometric models.

Heat transmission through the façade is modelled by the following U-values and the scenario-dependent external temperature:

- Opaque façade U-value: 0.14 W/(m²·K)
- Window U-value: 0.8 W/(m²·K), g-value perpendicularly: 0.3, incident angle dependent

Solar radiation is modelled by applying convective heat sources on the windows, i.e. it is not directional. The amount of incoming direct, diffuse and reflected solar and sky radiation depends on the simulation scenario as well as time of year and day, and the g-value of the glazing. Radiation exchange between surfaces in the model is not included in the calculations. The radiator is modelled as a surface under the window with a given heat flux depending on the simulation scenario. Each occupant provides a heat gain of 90 W and each computer a heat gain of 60 W.

The heat gains of the domain is balanced by making the internal walls absorb excess heat which occurs when, for instance, the room is heated with warm supply air.

FIG 4. Solution domain with six workstations

The ventilation is supplied partly diffusively through the ceiling surfaces depicted on FIG 4, partly by microjets along the ceiling carriers (linear inlets). The latter are placed where the ceiling lamella finishes to the wall and every 3 m. The airflow distribution is assumed to be 70/30 with most air through the linear inlets. The width of the slot is adjusted to an inlet velocity of 0.23 m/s. The rest of the air is distributed over the diffuse surfaces.

The mesh comprises approx. 3.5 million cells and plane-parallel cell layers are implemented along the walls and heat sources to better capture the fluid flow. The Boussinesq approximation was chosen to model buoyancy driven forces as it provides faster convergence for many natural-convection flows. The applied turbulence model is the k-epsilon model, which is stable and with sufficiently accurate
results for most indoor applications. The turbulence model is combined with the CFX feature ‘scalable wall laws’, thus heat transfer between surfaces and air is made independent of grid size.

The convergence residual criteria were default values (0.0001) and no mass/heat flux imbalances were larger than 1 %. The reported results are transient since the temperature differences create weak unstable air currents which are unresolvable by steady-state calculations.

3.2 Investigated scenarios

The driving forces with diffuse ceiling ventilation are the thermal convective plumes that arise above any heat source. Thus, for air change efficiency we expect that the most critical scenarios are those with small temperature differences throughout the domain and small convective heat sources. Regarding thermal environment and elevated air movements, we expect that large airflow rate with low supply temperature to be the most problematic scenario. Six scenarios are therefore investigated:

1. **Normal operation.** Overcast winter day with occupants and computers. There are no expected critical aspects.

2. **Pre-conditioning.** Winter morning without occupants and computers. The critical aspect is possibly worsened air change efficiency with no occupants.

3. **Air-heating.** Winter morning without occupants and computers. The critical aspect is stratification.

4. **Cooling by low inlet temperature.** Summer day with occupants and computers. The critical aspect is the risk of draught due to low supply temperature.

5. **Cooling by high flow rate.** Summer day with occupants and computers on. The critical aspect is the risk of draught due to high airflow rate.

6. **Night ventilation.** Summer night without occupants and computers. The critical aspect is air change efficiency, subsequently night cooling efficiency, without heat sources present.

The design indoor air temperature is 21 °C in winter and 26 °C in summer. The specific data for each scenario is summarised in TABLE 1.

### TABLE 1. Input to investigated scenarios. The emboldened values indicate the critical aspects.

<table>
<thead>
<tr>
<th>Season</th>
<th>Out. temp.</th>
<th>Flow rate</th>
<th>Supply air temp.</th>
<th>ΔT air</th>
<th>Work-stations</th>
<th>Radiator power</th>
<th>Solar radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Winter day</td>
<td>-5 °C</td>
<td>2 h⁻¹</td>
<td>16 °C</td>
<td>-5 °C</td>
<td>900 W</td>
<td>0 W</td>
<td>87 W</td>
</tr>
<tr>
<td>2 Winter morning</td>
<td>-12 °C</td>
<td>2 h⁻¹</td>
<td>21 °C</td>
<td>0 °C</td>
<td>0 W</td>
<td><strong>249 W</strong></td>
<td>0 W</td>
</tr>
<tr>
<td>3 Winter morning</td>
<td>-12 °C</td>
<td>3 h⁻¹</td>
<td>27 °C</td>
<td>+6 °C</td>
<td>0 W</td>
<td>0 W</td>
<td>0 W</td>
</tr>
<tr>
<td>4 Summer day</td>
<td>28 °C</td>
<td>4 h⁻¹</td>
<td>14 °C</td>
<td>-12 °C</td>
<td>900 W</td>
<td>0 W</td>
<td>1330 W</td>
</tr>
<tr>
<td>5 Summer day</td>
<td>28 °C</td>
<td><strong>6 h⁻¹</strong></td>
<td>18 °C</td>
<td>-6 °C</td>
<td>900 W</td>
<td>0 W</td>
<td>1330 W</td>
</tr>
<tr>
<td>6 Summer night</td>
<td>18 °C</td>
<td>2 h⁻¹</td>
<td>19 °C</td>
<td>-2 °C</td>
<td><strong>0 W</strong></td>
<td><strong>0 W</strong></td>
<td><strong>0 W</strong></td>
</tr>
</tbody>
</table>

3.3 Age of air

The age of air is a measure of the air quality. The air age (Sandberg & Sjöberg 1983) in a given point is a measure of how long a massless particle of air spent on transport from the inlet opening to that point. In the case of perfect mixing the air has the same age throughout the room. In locations with short circuiting or poor mixing, i.e. poor ventilation efficiency, the age differs significantly from the mean age. This age of air index is not dependent on the presence of specific pollutants or source location and eliminates the need for definitions of the occupied zone and breathing zone.
4. Results

4.1 Temperature performance

FIG 5. Thermal, scenario 1

FIG 6. Thermal, scenario 4

FIG 7. Thermal, scenario 2

FIG 8. Thermal, scenario 5

FIG 9. Thermal, scenario 3

FIG 10. Thermal, scenario 6

The thermal performance of the scenarios, FIG 5-FIG 10, is in general satisfactory with very small stratification which is in good agreement with experiments (Hviid & Svendsen, 2012; Fan et al., 2013). Scenario 3 shows critical temperatures in the comfort zone partly due to cold downdraught from the window. Some stratification is present in scenario 5 but it is quite small, 1 K/m, and thus well within the limits of DS/EN ISO 7730.
4.2 Air movements

The air velocities in the winter scenarios, FIG 11 - FIG 16, are satisfactory, i.e. the air velocities in the comfort zone are below 0.15 m/s. In the summer scenarios, the two daytime scenarios (4 and 5) show elevated velocities (approx. 0.3 m/s) at ankle height in some areas. Analyses of these two scenarios show that cool, fluctuating ventilation air drops from the ceiling. This and the convective thermal plumes from occupants, computers, and the warm window create room size vortices along the floor. This behaviour has not been reported, neither by Nielsen et al (2010), nor by Hviid & Svendsen (2013) or Fan et al. (2013). However, a certain displacement effect is expected and this indicates the need for more investigations into the natural convection forces and transient behaviour of diffuse ventilation ceilings.
4.3 Air quality by age-of-air

The age of air shows the air change efficiency in different parts of the room in FIG 17-FIG 22. None of the scenarios show any sign of short-circuiting and stagnant zones. conventional mixing ventilation, which is also validated by experimental data from Hviid & Svendsen (2012), and Fan et al. (2013).

TABLE 2 compares the mean air change efficiency of the room with the analytically derived value of perfect mixing ventilation. The largest deviation is 9 %, hence the diffuse ceiling ventilation performs on par with conventional mixing ventilation, which is also validated by experimental data from Hviid & Svendsen (2012), and Fan et al. (2013).
### TABLE 2. Comparison of simulated air change efficiency with perfect mixing

<table>
<thead>
<tr>
<th>Scen.</th>
<th>Description</th>
<th>Perfect mixing</th>
<th>CFD-results @ outlet</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Winter day, normal operation</td>
<td>1800 s</td>
<td>1640</td>
<td>-9 %</td>
</tr>
<tr>
<td>2</td>
<td>Winter morning, pre-conditioning</td>
<td>1800 s</td>
<td>1793</td>
<td>0 %</td>
</tr>
<tr>
<td>3</td>
<td>Winter morning, air-heating</td>
<td>1200 s</td>
<td>1220</td>
<td>2 %</td>
</tr>
<tr>
<td>4</td>
<td>Summer day, cooling by low supply air temp.</td>
<td>900 s</td>
<td>901</td>
<td>0 %</td>
</tr>
<tr>
<td>5</td>
<td>Summer day, cooling by high flow rate</td>
<td>600 s</td>
<td>576</td>
<td>-4 %</td>
</tr>
<tr>
<td>6</td>
<td>Summer night ventilation</td>
<td>1800 s</td>
<td>1755</td>
<td>-3 %</td>
</tr>
</tbody>
</table>

#### 4.4 Energy efficiency

In terms of energy efficiency, the pressure drop of diffuse ceilings was measured and reported by Hviid & Svendsen (2012) and Fan et al. (2013) to be approx. 0.5-3.5 Pa. Thus, in comparison with conventional mixing diffusers, the diffuse ceiling performs on par at 1/20 pressure drop. For current best-practice ventilation systems with a specific fan power of 1.1 kJ/m³, the pressure savings by the diffuse ceiling constitutes approx. 10% of the supply pressure drop.

#### 5. Conclusion

In general, the diffuse ceiling ventilation concept has performed on par with conventional mixing ventilation where the momentum forces of the supply jet entrains and mixes with the room air. The air change efficiency (age of air) documented that no stagnant zones or short-circuiting were present. The thermal performance does not show stratification in the investigated scenarios, except when used with air-heating. Possibly, a radiator below the window will create sufficient thermal plume to avoid stratification.

The air velocities were satisfactory but the investigations in this paper have disclosed cold down draughts with this type of diffuse ceiling in an office setting during summer. However, these issues have not been reported in the literature, indeed, laboratory experiments performed on similar types of ceilings have not identified any problematic behaviour. Consequently, it is relevant to investigate further the behaviour and consequences of the transient convective forces.

#### References


Application of the energy signature method for evaluation the effect of an exchange from electric coil heating system to a hydronic ground source heat pump system in a church building

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KEYWORDS: Energy use, Energy signature, Ground source heat pump,

SUMMARY:
In this article, the energy performance of a church building built in 1978, where existing electric coil heating system is replaced by a hydronic ground source heat pump system, is assessed and discussed. The energy signature method is used in this analysis where it was found that this installation reduced energy consumption with approximately 66%. The use of billing data and the weather data from a public weather station was successful because they both were of good quality. Thus the problem with missing data was avoided. By only considering data for some of the periods of the day, disturbing effects by the activities of the building was minimized. Finally the energy signature method was found to be useful for evaluation of performance of a heating system in this case.

1. Introduction

The ground heat exchanger in ground source heat pumps (GSHP) is composed of a closed loop pipe system. In the winter, the fluid in the pipes extracts heat from the earth and transfers into the building, while in the summer, it is possible to reverse the system and transfer heat from the building and deposit it to the cooler ground (US Dept of Energy 2013). This method of reloading the system is an available option, but not the most common solution for ground heat exchanger systems utilized in Sweden. GSHPs operate based on a vapor – compression cycle as described by Björk et al (2012) and also in a review article by Mustafa (2006).

GSHPs are often dimensioned with the purpose of meeting the demand for heating and hot water. Generally this is carried out in order to meet 60–80% of the maximum thermal power demand of the building in question (Björk et al. 2012), leading to approximately 90% of the annual energy demand of the building is covered by the heat pump (Swedish energy Agency 2013). The rest will be covered by electricity.

1.1 Coefficient of performance

The coefficient of performance (COP) or heat output per unit of electricity for a heat pump is, is defined as the ratio between acquired useful energy and applied energy (Björk et al. 2012).

\[
COP = \frac{E_u}{E_a}
\]

Where \(E_u\) (acquired useful energy supplied to the system) and \(E_a\) (applied (bought) energy to the system)

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An inventory of the system COP for a number of GSHP installations in apartment buildings has previously been carried out by Levin (2008). In that study, the system outputs were evaluated by metering of the electricity input and the thermal output. In that study COP over the year was in the range of 2.14 to 3.5 with a mean value of 3.0.

1.2 Geothermal energy usage in Swedish buildings

The best potential for geothermal energy in Sweden is believed to exist in regions where there are large bodies of groundwater at significant depths (2–3 km), i.e. areas with thick layers of sedimentary bedrock or fault zones (Geological survey of Sweden, 2013). In general, the rock or soil is reckoned to deliver two times the energy supplied by electricity to the system. Although the geothermal solution may be adequate for a large body of buildings, it is not applicable to all buildings. In particular, buildings where implementation of such a solution is difficult are those built on deep layer of soil. Additionally, buildings with only electric coil heaters require substantial renovation by the need for installation of a hydronic heating system. This however provides the option to choose a heating system with low emission temperatures, which is beneficial for the COP of the system. The most significant drawback of geothermal systems is their initial high cost.

2. Evaluation of energy consumption in buildings

When considering measures for improved energy performance, it is essential to have a reliable method in order to evaluate and compare the status prior to and after these were undertaken. Weather normalization of energy consumption in buildings is needed for comparison between various years, or parts of various years (Layberry 2009) [7]. One method for weather normalization is energy signature modeling which was utilized in this study, as it was considered to provide an adequate representation of the available data for the daily outside temperature and energy consumption (Schulz 2003). Estimation of energy performance indexes, such as the energy signature, call for data of energy use and the present outdoor temperature. The energy use of a building is plotted versus the outdoor temperature. The actual annual energy consumption for a building during a billing period is evident from the utility bills and the temperature can be taken from a weather station.

FIG 1. Åbyberg church (October, 2013)
2.1 Case study – The Åbyberg church

The Åbyberg church is located approximately 30 km north of Stockholm, Sweden. Built in 1978, the church consists of an octagonal brick church hall and a ground floor in stucco wall covering. The roof of the church hall is pyramid shaped whereas the adjoining rectangular shaped building sections have a gable roof (Swedish National Heritage board 2013). The encircling area of the building is approximately 1400 m² with a total heated floor area of 740 m² and a total window area of 60 m². The overall heat transfer coefficient (U-value) for the windows, walls and the ceiling is given by 1.8 W/m²K, 0.3 W/m²K and 0.2 W/m²K, respectively. The rectangular building consists of one floor and a basement with entrances recessed into niches.

With the aim of energy consumption reduction and improvement of the energy performance of the church building, an energy refurbishment measure was undertaken by exchanging the existing electric coil heating system to a hydronic ground source heat pump system. The system has three boreholes at a depth of 210 m. The hydronic heating system has a design output temperature (DOT) of 45ºC, which makes it a low temperature system. In this case no other measures for reducing energy consumption were done in the building.

2.2 Data acquisition

The data for energy consumption in this study was retrieved from the available electricity bills of the building. The data used consisted of readings per hourly basis, for the consumption of the entire building. Hourly reading is in Sweden offered all customers with main fuse larger than 63 amperes. The temperature data was acquired from the SLB weather monitoring station at Märsta (SLB 2013. which is a monitoring station with similar weather conditions as the location of the Åbyberg church.

2.3 Data processing

The calculated time periods both prior and subsequent to the GSHP system installation, have been divided into “non-heating” and “heating” seasons. The latter applies to the period from October, 15 until May, 15 while the rest of the year is considered as the “non-heating” season when the church building does not need additional heating.

The electricity consumption given by the billing data from the electricity provider includes both the consumption related to space heating and the consumption related to the activities in the building. Figure 2 depicts the energy consumption and outdoor temperature plotted against time for the first week of the year 2012. Special occasions, inclusive of social activities occurring on the Sunday morning service, are of particular interest and hence may contribute to higher consumption in daily energy. These peaks are for example explained by the chandeliers in the church room, having a rated power of 9.5 kW and the big dishwasher in the facility. These peaks in power load need to be removed when doing the analysis of the energy savings. In this energy signature analysis merely data for the hours between from 00.00 AM to 06.00 AM were considered, when customarily no other energy consuming activities take place and the electricity is only used for the GSHP system and for the base load of the church building.
FIG 2. The hourly energy consumption and outdoor temperature during the first week of 2012. Note peaks on Sundays!

The average temperatures are calculated as

\[ T = \frac{1}{N} \sum_{m=1}^{N} T_m \]  

(2)

Where \( T_m \) temperature at each hour \( m \)

\( N \) Number of temperature readings

The linear regression of the data for non-heating and heating seasons respectively, a first order equations were produced, using the least square method.

**TABLE 1. Coefficients of the regression lines given in Figures 3, 4 and 5.**

<table>
<thead>
<tr>
<th></th>
<th>Heating season</th>
<th>Non-heating season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base load factor</td>
<td>Temperature load factor</td>
</tr>
<tr>
<td>Prior to GSHP install†</td>
<td>11.951</td>
<td>-0.4766</td>
</tr>
<tr>
<td>Prior to GSHP install† (corrected base load)</td>
<td>9.9903</td>
<td>-0.4766</td>
</tr>
<tr>
<td>Post to GSHP install†</td>
<td>5.2670</td>
<td>-0.2358</td>
</tr>
<tr>
<td>Post to GSHP install† (corrected base load)</td>
<td>3.3063</td>
<td>-0.2358</td>
</tr>
</tbody>
</table>
TABLE 2. Power consumption and utilised power, COP and energy savings at different outdoor temperatures.

<table>
<thead>
<tr>
<th>T [°C]</th>
<th>Qprior [kW/h]</th>
<th>Qpost [kW/h]</th>
<th>COP</th>
<th>χ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>−20</td>
<td>19.55</td>
<td>8.00</td>
<td>2.44</td>
<td>59.1</td>
</tr>
<tr>
<td>−15</td>
<td>17.17</td>
<td>6.82</td>
<td>2.52</td>
<td>60.3</td>
</tr>
<tr>
<td>−10</td>
<td>14.78</td>
<td>5.64</td>
<td>2.62</td>
<td>61.9</td>
</tr>
<tr>
<td>−5</td>
<td>12.40</td>
<td>4.46</td>
<td>2.78</td>
<td>64.0</td>
</tr>
<tr>
<td>−2.3</td>
<td>11.11</td>
<td>3.82</td>
<td>2.91</td>
<td>65.6</td>
</tr>
<tr>
<td>0</td>
<td>10.02</td>
<td>3.28</td>
<td>3.05</td>
<td>67.3</td>
</tr>
<tr>
<td>5</td>
<td>7.63</td>
<td>2.10</td>
<td>0.275</td>
<td>72.5</td>
</tr>
</tbody>
</table>

FIG 3. Åbyberg church (October, 2013) The energy use per hour versus outdoor temperature (in nighttime) versus outdoor temperature for the Åbyberg church for the time period October 15, 2010 to October 14, 2011. Before installment of GSHP.
FIG 4. The energy use per hour versus outdoor temperature (in nighttime) for the Åbyberg church for the time period October 15, 2012 to August 25, 2013. After installment of GSHP.

FIG 5. The daily energy usage (in nighttime) versus outside temperature for the Åbyberg church represented by two different linear functions. The base loads of the non-heating seasons and the corresponding corrected factors for the heating seasons are also shown in the figure.
3. Results

The behavior of the church, prior to installment of the GSHP system is calculated from the data shown in Figure 3 for the period October 2010 until October 2011. The new system started to operate in September 2012. Data for post installment is given in Figure 4 for the period October 2012 until August 2013. The coefficients of the regression lines for the energy signatures are presented in Table 1. They are provided with an accuracy of four digits, which obviously is higher than motivated by the input data.

A comparison between Figures 2 and 3 conveys that the installment of the GSHP system has contributed to a substantial decrease of the daily energy consumption. The regression lines from the data are compiled in Figure 5 which also shows how the base load factor of the non-heating season. This is approximately 1.96 kW and refers to the normal use of the building, also in nighttime. It should be adjusted for when calculating energy savings. This is done by subtracting the base load values for the non-heating season’s pre and post to the GSHP installment from the power need, as illustrated in figure 5.

A comparison between the base load factors for the non-heating season prior to and after installment of the GSHP system exhibits an increase of the daily energy usage by 2.68%, which is virtually no difference. Nonetheless, the slope of the temperature dependent portion of the signature graph is considerably lower in the aftermath of GSHP system installment. The coefficients for the adjusted power need are given in Table 1 and results from these calculations at a few different temperatures are shown in Table 2. It is evident that the energy use was reduced because of the GSHP installation. An estimate of the saving can be performed by determining the ratio between the power need at a certain temperature prior and post to GSHP installment. This ratio is clearly temperature dependent and a comparison of the energy consumption is given in Figure 5. One choice that can be motivated is the mean temperature of the heating season post to the GSHP installment was −2.3 °C. Results for calculations at a few different temperatures are given in Table 2.

The reduction in need for electrical power at −2.3 °C becomes 65.6%, and practical COP 2.9, which is actually in the realm of results obtained in the study of Levin [6].

The process in these calculations is a bit different from what Levin did. In the calculation of the COP data for squared energy $E_n$, is the energy consumption at a certain outdoor temperature prior to the installment and $E_p$ is the energy consumption post the installment. The reduction in electric energy is in this case a measure of the coefficient of performance of the entire installation. This can be motivated because no other changes were made to the building. This is a way to use data available data in a quite simple but still efficient way.

4. Conclusions

The conducted study has exhibited the usage of a GSHP system as an energy refurbishment measure in an existing church building. The replacement of the original electric coil heating system with a GSHP system has resulted in an improvement of energy consumption of approximately 66% or a COP of 2.9. This is quite close to the results of Levin (2008).

The energy signature method is exemplified to be useful for evaluation of performance of a heating system. By only considering data for some of the periods, disturbing effects by the activities of the building users can be minimized. Otherwise a number of peaks would have partly hidden the effect of the heat pump. The billing data and the weather data from a public weather station are both of good quality. Thus the problem with missing data can be avoided.
Conclusively, it has been exemplified how the GSHP indeed is a useful and energy saving heating source for the considered church building. It has been shown that the energy signature method can be applied in order to assess the results of energy saving measures in buildings and that available data in terms of the daily outside temperature and hourly energy consumption, can be utilized for evaluation of the energy efficiency.

5. Acknowledgements
We express our gratitude to the Swedish research council Formas for financial support and to the Åbybergskyrkan congregation for provision of data.

6. References


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Transfer of energy efficient building concepts to subtropical climate– The first MINERGIE P® based building in Japan

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KEYWORDS: Subtropical climate, vapor-open building envelope, MINERGIE, Japan, design optimization, in-situ measurement

SUMMARY: While there are solid experience values for energy efficient buildings in moderate climate in Europe, the transfer of these concepts to differing climate and socio cultural conditions is a field of experimentation in building physics. Started as a cooperation project between Switzerland and Japan and now continued by including Sweden as a partner, the first Japanese residential building based on the MINERGIE P® standard has recently be realized in central Japan.

This presentation will offer a summary of the applied concept for the building envelope and housing services. The focus will be on measures to deal with the high humidity loads in subtropical industrialized country with related demand for comfort conditions and regular earthquakes straining the construction and the measures to achieve the MINERGIE P® targets in Japanese climate.

1. Introduction

With regard to the resource depletion and the global climate change, it is widely recognized that the construction industry is playing a key role for the rational use of resources and the realization of a more sustainable society (CIB 1999). On a global scale, the construction industry is contributing to about 50% of the manmade greenhouse gas emissions and to about 40% of the resource consumption (UNEP 2003). Energy consumption in buildings is of key importance in this regards and in order to improve the energy efficiency of buildings, several design protocols for building envelope and equipment have been proposed and implemented, though mainly in cold/mild climate regions. As a successful example the MINERGIE® Building Association of Switzerland has established an energy certification method labelling buildings to MINERGIE® and MINERGIE-P® standard. Due to the promotion driven by subsidies from local governments in Switzerland and the general perception that such labeled buildings are worth more in economic terms, more than 10,000 housings have been certified by this energy label in Switzerland so far. The Passivhaus Institute from Germany established similar energy labeling methods for buildings in Germany and other countries, mainly in Europe. A recent study has shown that the actual energy performance of certified Passivhaus buildings match the calculated energy demand (Passivhaus Institute) with the best exactness achieved again in cold and mild climates. These two examples show that the implementation of energy efficient building technologies accompanied by a labeling system can contribute to the further enhancement of the sustainability of the construction industry.

In order to address the energy performance of buildings on the global level, the implementation of such design protocols has been promoted recently. The key for a working concept as well as local acceptance is considering the local frame conditions when a certain technology is deployed in a certain place. Especially the climatic, craftsman skills and user behavioral difference may result in a serious damage in building components and/or inhabitants’ health if not properly taken into account.
Within a series of research projects that started as a cooperation project between Switzerland and Japan and are now continued by including Sweden as a partner, the authors have developed an innovative vapor-open wooden building envelope system for subtropical regions. In June 2013, a test house, whose concept was based on MINERGIE®, was realized in central Japan. This paper introduces the concept of the construction system, introduces the framework of the adoption of MINERGIE® certification, reports the designing and construction processes of this test house and presents the preliminary results of the measurement of the indoor climate and the temperature and humidity inside the envelope.

2. Energy efficient building concepts for subtropical regions

2.1 Subtropical climate
Energy consumption by buildings is of growing concern in subtropical regions because of the high growth rate in urbanizing areas in these regions (CIB & UNEP-IETC 2002). FIG 1 shows the subtropical regions defined by Köppen-Geiger climate classification. The major difference between cold/mild regions and subtropical regions is the long and hot-humid summer. This causes significant energy consumption for cooling and dehumidifying in addition to the heating load in winter. From the view point of building physics, such a climatic condition is very challenging because it results in both heating and cooling demands in buildings. Consequently the direction of the moisture flux - due to the gradient of vapor pressure between exterior and interior - reverses throughout the year. In summer the moisture transfer happens from outside to inside and in winter vice versa. Inappropriate design of the building envelope, which fails to deal with the moisture flux in the exterior wall, may result in the interstitial condensation in the exterior walls.

One way to deal with this would be sealing both sides of the wall with water vapor tight layers. In order to create a robust solution the desirable way however is making the envelope vapor-open, especially in earthquake-prone regions where rifts in barriers can never be completely prevented. Directly implementing the conventional designing method for cold regions introduced above does not solve the fundamental problems in subtropical regions, but rather introducing a novel envelope system for subtropical regions has been required.

FIG 1. Subtropical regions according to Köppen-Geiger climate classification

2.2 Vapor-open envelope system for subtropical regions
A new building envelope system was developed within the research team led by the authors. This envelope system mainly consists of layers based on renewable, hygroscopic and vapor permeable materials, namely the external insulation layer made of wood fiber board, the structural layer made of
cross laminated wooden panel and the interior finishing layer made of a pre-dried composite of wood and clay. The illustration of the envelope system and the materials for each layer is shown in FIG 2. This system allows the moisture flux to move through the wall in both directions. By defining the appropriate thickness to each layer, it is possible to avoid moisture related problems inside the wall. Besides the building physical considerations, the design philosophy of the envelope also comprises ecological, economic and social aspects. The components are based on renewable materials, and so it may be produced using local resources, which contributes to the less transportation for each component. Local production also promotes the local economy creating local value chain. The local design conditions, namely local climatic conditions and socio cultural aspect such as user behaviors (preferred room temperature/humidity, heating/cooling strategies and so on) can be taken into account. Flexibility and adaptability to specific local conditions is assured by the layered structure of the envelope. This system enables the material of each layer and its thickness to be selected independently for its primary function alone. Therefore the thickness of the insulation layer, which gives not only the thermal resistance but also the moisture sorption capacity, can be determined according to the local climatic condition without interrupting the other components such as the structural element. By this flexibility, an actual wall make-up can be determined considering the local conditions of both sides of the wall easily.

By one dimensional transient heat and moisture transfer simulation program, hygrothermal property test and full scale testing with a climate chamber, the performance of the wall was verified (Goto et al. 2011). Then, the whole building heat and moisture balance simulation method for buildings with this system was also developed in order to predict the indoor climate and heating and cooling demand (Goto et al. 2012a). Combining these methods and Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA), the authors proposed the optimization method for the thickness of the insulation layer within the Japanese economic and climatic conditions (Goto et al. 2012b).

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3. Adaptation of MINERGIE® to subtropical conditions

MINERGIE® is an energy label for new and refurbished buildings. It is mutually supported by the Swiss Confederation, the Swiss Cantons along with trade and industry. Assuring comfortable living environment is the origin of MINERGIE®. A wholesome level of comfort is argued to be made possible by high-grade building envelopes and the controlled ventilation. In Switzerland the MINERGIE® Standard is widely accepted and recent studies have found that on the free market labeled houses achieve a 6% higher sales price than non-labeled ones of similar performance (Salvi et al 2008). This shows the potential of such labels to be also perceived as a quality proof. By now, the building sector has developed a wide range of products and services for MINERGIE® buildings. Suppliers include architects and engineers as well as manufacturers of materials, components and systems. The diversity and competition of this market furthers quality and lowers costs.
Specific energy consumption is used as the main indicator to quantify the required building quality. Only the final energy consumption is relevant. The measures applied to achieve the goal are in many aspects not pre-described and the label follows the idea of naming the goal but not the way. This makes the label very flexible in regards to transferring it to different climate conditions as long as the target numbers are achievable. The experience with about 10,000 labeled buildings in Switzerland allows the association to identify the most cost competitive ways to achieve the standard (Mosteiro et al. 2014). These are listed in the figure below, being compared with the ones chosen for the building in Japan. In addition to the general criteria, it was decided to restrict the relative humidity in the exterior walls not to exceed 80%RH throughout the year in order to assure the longevity of the house in the case of prototype house.

**TABLE 1. Comparison of MINERGIE P® in Switzerland and Japan**

<table>
<thead>
<tr>
<th>MINERGIE P® (Switzerland)</th>
<th>Prototype house in Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy demand</strong></td>
<td></td>
</tr>
<tr>
<td>Weighted energy index accounting for heating, ventilation, hot water, and air conditioning of 30 kWh/m² taking losses for extraction, transportation and distribution into account</td>
<td>Target as in Switzerland, based on a monthly calculation as well as dynamic modelling (29.2 kWh/m²a)</td>
</tr>
<tr>
<td><strong>Renewable energy</strong></td>
<td></td>
</tr>
<tr>
<td>Prerequisite</td>
<td>PV (4.18 kWp) and solar thermal</td>
</tr>
<tr>
<td><strong>Heating and cooling demand</strong></td>
<td></td>
</tr>
<tr>
<td>&lt;60% of legally allowed annual heat demand for new homes (SIA 380/1:2009 limit) or &lt;15 kWh/m², max. 10 W/m² for air heating</td>
<td>Not applicable</td>
</tr>
<tr>
<td><strong>Controlled outdoor air ventilation and indoor air quality</strong></td>
<td>Controlled outdoor air ventilation prerequisite. Heat recovery required. Proof of thermal comfort during summer necessary</td>
</tr>
<tr>
<td><strong>Air intrusion</strong></td>
<td>&lt;0.6 h⁻¹ air exchange rate at 50 Pa pressure difference</td>
</tr>
<tr>
<td><strong>Opaque walls Glazing</strong></td>
<td>20–35 cm (U-value: &lt;0.15 W/(m² K))</td>
</tr>
<tr>
<td></td>
<td>Triple panes (U-value for glazing: &lt;0.6 W/(m² K))</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td>Should not exceed construction costs of a conventional building by more than 15%</td>
</tr>
</tbody>
</table>

Based on LCA, LCCA and hygrothermal analysis considering the specific design conditions as well as the MINERGIE P® criteria, the insulation thickness was decided to be 18 cm. For the openings air-tight and triple grazing windows (0.7 W/m²K) were installed. PV panels cover the south roof (4.18 kWp) combined with solar water heater panels for domestic hot water. The building orientation and the shading of the openings were carefully decided considering the balance of solar gain in summer and winter. As for HVAC system, radiators for heating and cooling-dehumidification and mechanical ventilation with heat exchanger were employed. The façade consists of cladding with venting layer.
Three main differences can be identified when transferring the standard:

1. Any kind of solar technology (PV, solar thermic) is cost competitive to passive measures (insulation) at a much earlier stage. From a cost viewpoint there will be a focus on active technologies when limiting the assessment to an annual balance.

2. The envelope is affected by both energetic as hygro-thermal conditions in its design to a much higher extend than in Europe. In this case the minimal insulation thickness was 14cm out of hygrosorptive reasons and 18cm was chosen because the customer wanted some safety and at the same time felt to set an example for better insulated houses. 18cm of insulation results in the better environmental LCA result while in terms of an economic LCC a lower insulation combined with more PV would have performed better.

3. Controlled ventilation is mandatory simply to achieve comfort in summer within the set conditions. To avoid excessive de-humidification an enthalpy exchanger is an attractive option.

4. Construction of a test house

4.1 Planning
It was decided that a building with the envelope system would be realized in Ohmihachiman (central Japan) which has a typical subtropical climate with hot-humid summer and cold-dry winter. The general design of the building was done by local architects and the technical supervision was done by the research team. The building is a detached residential building where two to four persons (two adults and up to two children) are supposed to reside. The surface of the insulation was designed to be covered with vapor-open water-tight membrane. Air-tight membrane is employed between the insulation and the structural panel. The concrete foundation was designed to have a flat surface and to be covered with asphalt sheet so that the control of heat and moisture transfer through it becomes the least intricate. The roof was based on the conventional design with air venting layer. FIG 3 shows the plan and elevation of the test house.

4.2 Construction
The structural panels were pre-cut and pre-assembled so that the work at the building site could be minimized. The assembled panels were carried in the building site on the 5th March 2013, and the building frame (floors, walls and roof) was constructed in three days. Subsequently, windows, plumbing, electric cables, insulation, housing services, façade, roofing and others were installed. FIG 4 shows the construction processes. The construction processes were carefully supervised by the research team so that no faulty works were to be done until the insulation and the water-tight membrane was completed. Because of the lack of experience with this construction system, several
significant faults were observed and modified (e.g. insufficient air-tightness at the bottom of the exterior walls between the structural panel and the insulation which would result in the direct flux of ambient air into the inside of the wall and eventually in moisture condensation).

**FIG 4.** The processes of the construction ((a): the erection of the load bearing element (b): the installing of wood fiber insulation)

### 4.3 Completion and measurement set-up

The construction was completed on the 26th June 2013. **FIG 5** shows the finished house.

In order to measure the indoor climate and the conditions inside the external walls, 21 temperature and humidity sensors were installed. **FIG 6** shows the sensor and sensor node. The measuring points are; northern side wall on the ground floor (5 points across the wall from the living room to the exterior), living room, kitchen, northern side wall on the 1st floor (5 points from the bathroom to the exterior), west side wall on the 1st floor (5 points from the master bedroom to the exterior), northern side roof (4 points from the attic to the exterior). Figure 1(b) shows a sensor installed inside the insulation layer.

The measured results are available online simultaneously. The measurement started in September 2013.

**FIG 5.** The completed house ((a): east side façade, (b): living room on the ground floor)

**FIG 6.** The installation of sensors. ((a) sensor inserted between air-tight membrane and insulation, (b) a sensor node box)
5. Result and discussion
The planning and the construction of the test house were successfully completed. Currently the monitoring is running. FIG 7 shows the temperature and humidity of the five points across the west side wall of the master bedroom (in ambient air in venting layer of the façade, inside insulation layer (80mm deep from the exterior side surface), between insulation and air-tight membrane, between structural panel and clay board and in master bed room).

Performance of the system is currently in line with the expectations but no final statement can be given yet as no full annual cycle has been recorded.

6. Conclusions
This paper reports the designing and the construction processes of a test house in central Japan with a novel vapor-open wooden building envelope system and based on the Swiss energy label MINERGIE P®. Throughout the designing and the construction process, it was found that close communications among the designers, the constructors and the client is essential in order to realize a building with new features as it is designed. Unless the construction work is carefully supervised, the measurement of the house in the use phase might not meet what is supposed to be measured.

The MINERGIE P® label in general was found to be of sufficient flexibility to allow for feasible solutions in the Japanese climate. In order to assess whether the frame conditions of the label finally lead to cost efficient solutions that are in line with the solutions that are optimal from an environmental viewpoint the market for such concepts first has to grow in Japan.

The energetic and hygrothermal performance of the building must be validated with the measured data once sufficient data becomes available.

7. Acknowledgements
The authors would like to express their special gratitude to the customers of the house in Japan, Iida family, for their perseverance, trust, willingness to try something new and kind allowance to monitor the performance of the building.
Acknowledgement also goes to the commission technical innovation (CTI) for whose funding enabled the initial project, Hans Ruedi Kriesi from the MINERGIE association for his support in the initial calculations and Stefan Wiesendanger from Zehnder group for his support on solutions concerning the heat exchanger.

References


The potential of thermal energy storage in food cooling processes in retail markets for grid balancing

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KEYWORDS: Energy efficient supermarkets, smart energy grid, adaptive energy consumption, energy efficiency, thermal buffering, electrical buffering

SUMMARY:
An upcoming demand for higher energy efficiency in the society requires multiple actions to reduce the amount of unutilised energy. Supermarkets are part of the sixth largest energy consumers in Germany, the food industries, and hold a great potential for increase of its energy efficiency and at the same time contribute to buffering capacity needed in grids that have a large share of renewables.

A state of the art supermarket designed according to the demands of Passive House Institute has been built by REWE in Hannover Germany. Measurements are proving it to have energy consumption substantially lower than an average supermarket of the same size. Monitoring also proves a substantial amount of buffering capacity in the cooling processes.

Extrapolation shows a substantial potential for buffering grid fluctuations due to delaying cooling processes in Germany especially when complementing the system with ice storage.

1. Background – Storage demand in renewable grids
Any electrical grid with a large share of renewables faces problems with fluctuations in energy supply and therefore needs buffering or storage capacities (Farhangi 2010). In this context the NPO Agency for Renewable Energy (Agentur für Erneuerbare Energien e. V.) reviewed several governmental and non-governmental studies on future storage demands for the German grid (Renews, 2012). According to this the additional demand for electrical storage and buffering will likely reach 18 TWh by 2030 with renewables reaching 50% of power generation in Germany. By 2050 the demand of storage and buffering capacity will reach 30 TWh with renewables reaching 80% of power generation in Germany.

Besides direct storage the concept of delaying electricity consumption and therefore tailoring consumption to demand is another option to manage the grid. Large energy consumers should therefore be assessed on their potential to react flexible in their consumption. One such area of consumption is food cooling.

2. Energy consumption of food retail markets
Food production and distribution processes are two of the main consumers of energy in many societies. Together, they currently rank as the sixth largest within the processing industry in Germany, with an annual electricity consumption of 54 865 TJ and a heat consumption of 7 742 TJ in 2011 (Destatis, 2013). One dominating reason for this high level of energy consumption is the need for cooling food in warehouses, during transport, and finally in the supermarkets.
From monitoring of supermarkets in UK it’s clear that the energy consumption for supermarkets is exceptionally high in comparison to residential buildings and even offices. FIG 1 shows the annual energy consumption of Saintsbury markets in the UK sorted by net sales area ranging from 500 to almost 3000 kWh/m²a, offering similarly a high potential for shifting loads.

**FIG 1. Variation of electrical energy intensity of 2,570 UK retail food stores with sales area from 80 m² to 10,000 m² (Tassou et al, 2011)**

The implemented refrigeration system is found to be responsible for 39-47% of the annual energy demand in food retail markets in Sweden and the US in recent surveys (Arias, 2005).

These cooling processes offer the potential to buffer electrical energy in a thermal process with a higher efficiency than any kind of conventional electrical storage and are therefore in focus of the current discussion.

In general, supermarkets are not particularly energy efficient, as energy costs pale when compared with turnaround and profit (Arias et al. 2006). Rising energy prices and the need for companies to present themselves as environmentally friendly have, however, caused a re-think among supermarkets in recent years, resulting in a number of promising projects and technological developments (Arteconi et al. 2009 and Ostermeyer et al 2008). The potential for improving energy efficiency, reducing energy consumption, and the resulting emissions is very high in this sector (Ardito et al. 2013).

Obviously efficiency measures should be applied first in supermarkets from an environmental and in the end also from an economic viewpoint instead of designing inefficient cooling processes to create artificial consumption just to create load shifting potential. After applying economically feasible efficiency measures it has to be assessed how much energy is still consumed by the cooling processes. As the different components of cooling cabinets, cabinet, doors and heat pump are provided by different companies and the cabinets often run in complex networks the only sure way to assess the energy consumption is to monitor it in existing markets. This paper therefore takes measured data from a state of the art market and extrapolates from there.
3. State of the art food retail markets
Throughout the year, supermarkets need energy for heating to create a comfortable indoor environment and for cooling food storage at different temperature levels. Innovative concepts therefore utilize cascade heat pump systems to achieve high efficiency for the different temperature levels, and recover the process heat to help cover the heat energy demand by two-pipe or three-pipe based Cooling-Heating-Networks. With the heat recovery system alone, the heat energy consumption can be reduced substantially, about 30 to 40%, however peak demand related problems remain (Ostermeyer et al. 2008). The Passivhouse Institute Darmstadt in cooperation with Chalmers TU and REWE built on such concepts and designed the passive house standard for supermarkets to push even further.

3.1 The first Passive House Supermarket in Hannover/ Germany
In Hannover, the first Passive House Supermarket in Germany (Zero:e Park, 2012), run by the REWE Group, was built in November 2012, based on a heating and cooling system as the one described above, and on specific tailoring of the envelope in order to reduce the additional heating demand after recovery to 15kWh/m² year.

All equipment within the supermarket was selected using a top-runner approach, which meant that only the most energy efficient products were installed. This includes high performance glazing in front of all cooling cabinets which, besides changing the energetic behaviour of the cabinet also resulted in complex hygro-thermal issues as humidity is not anymore condensing in the cabinets but remains in the sales room potentially causing the growth of fungi and mould.

Installing doors in front of the cooling cabinets and running them in a cooling network via a centralized heat pump in a cascade with the freezing cycle results in a consumption pattern that is extremely complex. The main challenge is that the performance of a single cabinet influences the complete system. The market therefore serves to assess the overall concept in general but the performance of the cooling and freezing processes in particular. FIG 2. shows some pictures of the market.

FIG 2. The first supermarket in Passive house Standard in Hannover

The market is monitored by nearly 200 sensors allowing for solid assessment of its performance. In addition it is equipped with a weather forecasting system. This will allow predicting future energy consumption based on similar conditions in the past which will be critical when starting to shift loads in the market at a later stage.
3.2 Monitoring results

The project results so far show that the energy consumption has been significantly reduced beyond the expectations in the design phase. FIG. 3 shows the overall consumption of the market which has now nearly completed an annual cycle. The consumption relatively stable at 8000 to 12000 kWh/week with a predicted annual consumption of around 250 kWh/m² net floor area.

**FIG 3**: overall energy consumption (system border, market, all kWh in electricity), source FrigoData monitoring

FIG 4. Shows the cooling processes are in a range between 3000 kWh/week in winter and peaking at around 5000 kWh/week in summer.

**FIG 4**: energy consumption for food cooling (system border, market, all kWh in electricity), source FrigoData monitoring

Peak loads in general are in line with the consumption with the exception of the starting phase of the market that included the heating of the formerly cold thermal building mass and some drying of still humid concrete parts.

Electricity consumption for food cooling (as opposed to freezing) is the most attractive consumption to be delayed in the market for two reasons:

1. The temperature level needed for the process allows for ice storage which would result in rather small modules making use of the phase change of water
2. The process heat from freezing processes is needed for regulating the sales room air temperature. Delaying both cooling and freezing would let the sales room cool down.
Delaying only freezing and not the cooling consumption is not possible because of the design of the cascade system.

Based on the current monitoring in the market in Hannover there is a potential to delay a consumption of 400 to 600 kWh/d. The necessary delay of 24 hours or more is currently not possible by thermal means alone which is limited to a delay of around 6 hours. 24 hours and more could be achieved though by ice storage modules which is the next step to be taken. This also would create synergies with a remaining problem in the system which is the fluctuating energy demands of individual refrigerators and, to a lesser extent, the freezer units. As in order to be able to recover the process heat, all cooling devices have to be run in a combined cooling liquid grid (152a or 134a for cooling, CO2 in the freezing area of the cascade system), erratic demand in a single device can affect all other devices and the overall system efficiency, as the refrigerators no longer have individual heat pumps. Ice storage could flatten the individual load of the cabinets and therefore improve the overall COP of the system.

4. Conclusions and outlook

Already with a single store buffering 100 kW over the time of six hours, impressive numbers would be achieved by the REWE Group alone. As their supermarkets are refurbished every 15-20 years, nearly all 3,000 stores could be fitted with these systems by 2030. Taking this idea even further, supermarkets in Germany could together contribute substantially to grid buffering. If they could be outfitted with ice storage the numbers would be even more impressive while at the same time further improving the performance of the cascade network.

In a long term scenario, about 5% of the needed storage and buffering capacity in Germany could be covered by food retail markets and cooling processes – without the need for new infrastructure and the resulting environmental effects.

The use of supermarkets as buffering and storage units for the electrical grid is a unique and world-first move. An increase in the proportion of renewable energy sources will result directly in the need for an improved storage and buffering capacity. The creation of such capacities therefore directly benefits society by allowing it to reduce its dependency on nuclear and non-renewable energy production and the problems associated with these.

What remains to be seen is whether the identified storage opportunity will result in supermarket consortia selling this capacity to power generators, like wind parks, or aiming to become self-sufficient via own energy generation for example by photovoltaic.

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