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COMBINED THERMAL MEASUREMENT AND SIMULATION FOR THE DETAILED ANALYSIS OF FOUR OCCUPIED LOW-ENERGY BUILDINGS

U.D.J. Gieseler, F.D. Heidt[1], W. Bier
Division of Building Physics and Solar Energy, University of Siegen
57068 Siegen, Germany

ABSTRACT

This paper describes four simulation models, which reproduce energy and temperature measurements of occupied buildings very well. These buildings represent small to medium size residential low-energy buildings of different construction type, which are typical for mid-Europe. For the simulation, the software TRNSYS is used. The reproduction of measured energy and temperatures in time steps of 15 minutes is well suited for precise predictions on heating energy demand and comfort of the buildings and modifications of them. Results are used to develop generalized guidelines for the efficiency of energy saving measures, which are helpful for an advanced design and evaluation of low-energy buildings.

INTRODUCTION

The heating energy demand of a building or its user, respectively, is influenced by the construction, building services, weather, surroundings and the way of its usage. This energy can be measured. Hereby, however, the impact of the individual influencing factors is not revealed. Stationary computer models of buildings are usually too coarse to reveal all details of temperature distributions or energy flows, which are relevant for energy demand and comfort. Dynamical simulations can be very complex. However, in practice, most of the numerous parameters can not be determined precisely, because these are not fixed by the construction plans and/or are difficult to measure in a building. In the ideal case, a detailed computer model is available, which is validated by comparison with measurements of high resolution in time. Such models are described in this paper.

Validated computer models for thermal building simulation have the advantage, that the accuracy of temperature prediction of the model on short time scales is known. This allows to make reliable predictions on time dependent effects. One example is the impact of user behaviour on the heating energy demand, another one is the utilization factor of solar gains.

The main focus of this study is heating energy demand and comfort of low-energy residential buildings in mid-Europe. The approach provides the possibility to evaluate energy-saving methods under given boundary conditions. The influence of local weather conditions and user behaviour can be investigated. The essential data for a verification of the simulation model have been collected recently (Schulze-Kegel and Heidt, 2000). Two passive-solar and two low-energy residential buildings were chosen, for which the simulation environment TRNSYS (Klein et al., 1976) has been adapted. By parameter variation of the models, the measured heating energy demand and indoor air temperatures are reproduced, the latter with a time resolution of 15 minutes. After this validation, standard users profiles are used.

Due to these validations, results are precise enough to establish a ranking list with respect to energy efficiency and comfort for a broad range of measures for low-energy buildings. These results will be made available in a suitable form for architects and building designers. This contributes to an optimisation of energy consumption and investment costs for buildings, under consideration of the thermal comfort.

BUILDINGS AND MEASUREMENTS

In the years 1996 to 1999, four buildings have been monitored for at least one year. These buildings (objects 1 to 4) are shown in Figs. 1 and 2. In Table 1, the key constructional parameters are given. The buildings use quite different heat sources, whereas all of them are equipped with a ventilation system. Objects 3 and 4 are supported by flat-plate thermal solar collectors and earth heat exchangers (EHX). The latter is used primarily in winter. In Table 1, also the measured energy demand for heating as well as two other conditioning factors for heating are given, which are the heating degree days and the average set temperature for heating. Measurements are recorded with time resolution of 15 minutes and consist of:

- Indoor air temperature of every room. Pt100 sensors were mounted to walls at 1.8 m to 2 m height in open boxes. In massive buildings (objects 1 and 3), wall temperatures are also measured.
- Heat energy delivered to the rooms. These data are based on temperature and flow measurements of the heat transport medium.
- Electric energy for ventilation and household.
- Domestic hot water consumption.
- Weather data, consisting of solar radiation on the horizontal and a vertical plane towards south, outdoor temperature, wind and humidity.

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[1] Contact author email: heidt@physik.uni-siegen.de

Table 1: Key constructional data and measurements.

	Object 1	Object 2	Object 3	Object 4
Location (latitude, longitude, altitude)	51.46°/7.01°/120 m	50.95°/7.85°/260 m	51.03°/7.87°/250 m	51.28°/7.39°/200 m
Finishing of construction	May 1995	June 1997	March 1998	May 1998
*A*_NHFA (net heated floor area)	403 m^2	200 m^2	204 m^2	163 m^2
*V*_air (volume of heated air)	1097 m^3	600 m^3	619 m^3	479 m^3
*A*_wall (encasing heated volume)	358 m^2	193 m^2	221 m^2	215 m^2
*A*_roof	218 m^2	189 m^2	130 m^2	105 m^2
*A*_floor	170 m^2	115 m^2	105 m^2	101 m^2
*A*_window	104.5 m^2	65.0 m^2	50.5 m^2	45.3 m^2
*U*_wall	0.24 W/(m^{2}K)	0.23 W/(m^{2}K)	0.13 W/(m^{2}K)	0.10 W/(m^{2}K)
*U*_roof	0.16 W/(m^{2}K)	0.21 W/(m^{2}K)	0.13 W/(m^{2}K)	0.10 W/(m^{2}K)
*U*_floor	0.36 W/(m^{2}K)	0.32 W/(m^{2}K)	0.11 W/(m^{2}K)	0.12 W/(m^{2}K)
*U*_window	1.6 W/(m^{2}K)	1.3 W/(m^{2}K)	0.8 W/(m^{2}K)	0.8 W/(m^{2}K)
Heating system	ground heat pump (19.7 kW heat)	district heating (max. 20 kW)	gas (4 -11 kW), solar (4.8 m^2), EHX (99 m)	liquid gas (2.4 kW), EHX (16 m)
Heat distribution	floor heating	floor heating	fresh air, radiators	fresh air
Control temperature for heating	room air	ambient air	extract air, room air	extract air
Heat recovery of ventilation system: *h*	exhaust only	65%	83%	90%
Air tightness: *n*_50 value	1.2/h	2.0/h	0.4/h	0.6/h
Domestic hot water	electric heated	not installed	combined with heating system	solar (7.4 m^2), electric heated
Measured heating energy demand	**82.4 kWh/(m^{2}a)**	**72.9 kWh/(m^{2}a)**	**27.8 kWh/(m^{2}a)**	**9.8 kWh/(m^{2}a)**
Period of measurement	1.8.97 - 31.7.98	19.7.98 - 18.7.99	1.11.98 - 31.10.99	16.11.98 - 15.11.99
HDD(20/12) in measurement period	2668 Kd	4165 Kd	3835 Kd	2612 Kd
Average heating set temperature	21.5 °C	19.5 °C	20.0 °C	20.0 °C

Fig. 1: Object 1 (left): The building in Essen-Kraienbruch, Germany, is a three story multi-family house in massive construction with basement.
Object 2 (right): The building in Wenden-Hünsborn, Germany, is a 1½-story single family house in wooden framework construction without basement.

Fig. 2: Object 3 (left): The building in Wenden-Hillmicke, Germany, is a two-family house from pre-built concrete elements with two upper floors and heated basement.
Object 4 (right): The building in Lindlar-Hohkeppel, Germany, is a single family house in wooden construction with two upper floors and without basement.

During the measurement period, the buildings were occupied. Object 2 was used as a demonstration building with promotion office occupied by one person. The other buildings have been used according to their purpose, i.e. as residential buildings. Influences of the occupants on internal gains (other than electricity), ventilation losses and adjustment of mechanical services and thermostats were not monitored. The raw data have been averaged over intervals of 15 minutes and recorded. These data and its documentation, as well as more information on the buildings, are available on the internet (Schulze-Kegel and Heidt, 2000).

SIMULATION MODELS

For the simulation of the thermal behaviour of all four buildings, the simulation software TRNSYS, Version 14.2, has been used. The major part is a TYPE 56 model with 8, 7, 8 and 10 zones for objects 1, 2, 3, and 4, respectively.[2] The information on wall, roof and floor constructions, windows and building services are taken from construction plans. In addition, the surroundings of the buildings are taken into account for the calculation of the shading situation. This has been achieved by using the tool SOMBRERO (Niewienda et al., 1996), with which shading coefficients and view factors on arbitrarily oriented surfaces can be calculated. The results are used as input for TRNSYS simulations. For parameter studies on the influence of the building orientation, the surroundings should not be taken into account.

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[2] The code of TYPE 56 in our copy of TRNSYS 14.2 has been modified by us to achieve a proper edge correction for the *U*-value of windows. This modification leads to equivalent results like the window model of TRNSYS 15.

Table 2: Used modules (TYPEs) of TRNSYS (without data input and output modules).

Common to all buildings:	
TYPE 2	Controller
TYPE 14	Forcing function
TYPE 16	Solar radiation processor
TYPE 33	Psychrometrics
TYPE 56	Multi-zone building
TYPE 69	Sky temperature
Special TYPES for objects 3 and 4:	
TYPE 1	Solar collector
TYPE 4	Storage tank
TYPE 5	Heat exchanger
TYPE 31	Pipe
TYPE 34	Shading (also for object 2)

Therefore, TYPE 34 was used alternatively. Other used TYPEs are listed in Table 2. For most of the building services (heating, ventilation, heat recovery), equations were used instead of TYPEs. This keeps the simulation models simple, and has lead to a quite good agreement between measurements and simulation results regarding the room temperatures and heating demand (see next section). For all simulations, which are compared with measurements, the measured weather data has been used. In addition, all possible information on the user behaviour is included, which could be extracted from the measured data. These are household electricity consumption, significant changes of heating and ventilation controls, as well as the use of shading devices and the user-induced infiltration. With exception of household electricity consumption, influences of the users must be derived from the measured indoor temperatures, as described below.

One example of a simple model for building services is that of the district heating for object 2. This object is a demonstration building of a building manufacturer. No thermostats are used in the building. Heating power depends merely on outdoor temperature, according to the heating control characteristics. This linear characteristics has been derived from the measured data, and the result for the heating power is for daytime (between 6:00 h and 16:00 h) H = 6.10 kW – 0.255 · T_{OUT} kW/°C with maximal power $H_{\max}$ = 8.6 kW. For outdoor temperatures above 10 °C, the slope increases by −0.1 kW/°C, so that heating is off for outdoor temperatures above 20 °C. At night, the power was reduced by 4.72 kW. This simple model of the heating system is sufficient to reproduce the characteristic temperature variation inside this building, which is an oscillation with frequency of one day, caused by the day/night variation of the heating power. The simulation result for the averaged air temperature in object 2 is shown in Fig. 3 for a period of 45 days. The outdoor temperature varies between 20.2 °C (day 23) and 1.1 °C (day 30). The lower part of the figure shows the temperature difference $\Delta T = T_s - T_m$ between simulation and measurement. This difference is most of the time smaller than 0.5 K, which shows a quite good agreement between measurements and simulations. For almost the whole period shown, the heating is on, and this is the reason of the quite high indoor temperatures of above 24 °C during the days 20 to 23, with average outdoor temperature of 11.5 °C.

User induced ventilation by opening windows and doors can exert a big influence on indoor temperatures and heating demand. For the detailed comparison between simulation and measurement, these influences have to be included. Although the n_{50} value was measured, the infiltration rate is an almost free parameter of the model, because it is influenced by the user. Realistic limits for the infiltration rate are given by the standard DIN EN 832 (1992), which suggests for detached houses with balanced ventilation systems $e{\cdot}n_{50}$ as infiltration rate, with screening values of e between 4% and 10%. Nevertheless, to use the difference between simulated and measured room or zone temperature as indicator for the quality of the model, singular infiltration events (window openings) should be included in the simulation model. In cases where window sensors are not installed, room air temperatures can be used to determine the infiltration by window openings during the heating period. If no *wall* heating is used and air as well as wall temperatures are measured, these temperatures can be used as an indicator for window ventilation during the heating period. When the air temperature drops below the temperature of an outside wall, this is a signal for window ventilation.

Even without measurement of the wall temperature, indoor air temperatures can be used to determine the occurrence of window ventilation in winter. Without a ventilation system, this is always the case when the air temperature decreases faster than it would drop without internal heating. For longer time scales, and for a uniform temperature distribution in the building, the temperature difference $\Delta\Theta(t) = T_{\text{in}}(t) - T_{\text{out}}$ between the mean indoor temperature $T_{\text{in}}(t)$ (walls and air) and (constant) outdoor air temperature T_{out} decreases according to:

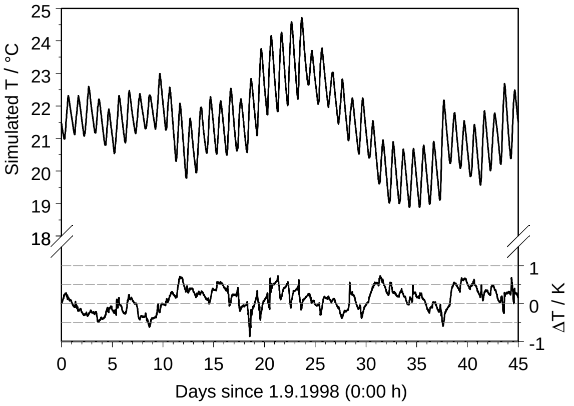

Fig. 3: Simulated indoor air temperature for object 2 (weighted by zone volumes). The lower part shows the difference between simulated and measured air temperature.

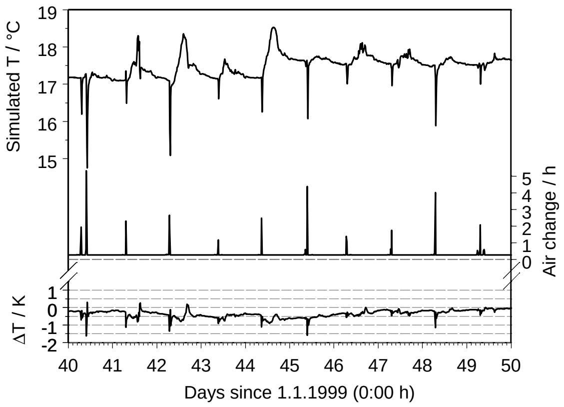

Fig. 4 Simulated indoor air temperature and air change by infiltration and window ventilation for the guest room in object 3. The lower part shows the difference Δ*T* between simulated and measured air temperature.

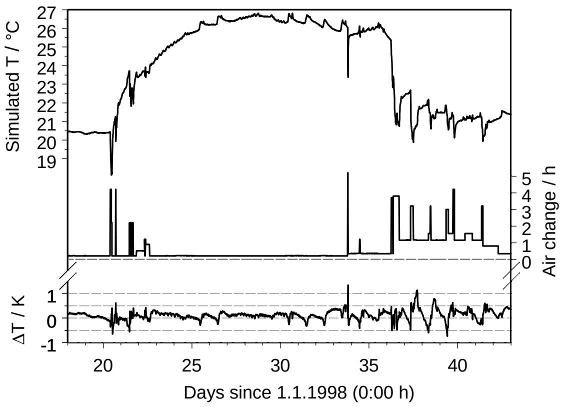

Fig. 5: Simulated indoor air temperature and air change by infiltration and window ventilation for a ground floor apartment in object 1. The lower part shows the difference Δ*T* between simulated and measured air temperature.

$$\Delta\Theta(t) = \Delta\Theta_0 \cdot \exp\left\{-\frac{t}{R \cdot C}\right\}, \qquad (1)$$

with R the resistance of the envelope with respect to heat losses due to transmission and infiltration (in K/W), C the heat capacity of the building (in Wh/K), and $\Delta\Theta_0 = \Delta\Theta(t = 0)$. The resistance is given by:

$$R = \frac{1}{U_{\text{ext}} \cdot A_{\text{ext}} + e \cdot n_{50} \cdot V_{\text{air}} \cdot r_{\text{air}} \cdot C_{\text{air}}}, \qquad (2)$$

where U_{ext} is the mean U-value of the envelope with area A_{ext}, which encases the heated air volume V_{air}. The infiltration rate is $e \cdot n_{50}$ and the heat capacity of the air is $r_{\text{air}} \cdot C_{\text{air}} = 0.34$ Wh/(m³K).

If the time constant $t = R \cdot C$ of a building is known, Eq. (1) can be used to find an upper limit for temperature gradients induced by a lack of heat gains. For the object 3, the parameters are: $U_{\text{ext}} = 0.192$ W/(m²K), $A_{\text{ext}} = 506.5$ m², $V_{\text{air}} = 619$ m³, $e = 0.07$ and $n_{50} = 0.4$. This gives a resistance of $R = 9.7 \cdot 10^{-3}$ K/W. The capacity can be estimated from the external walls, roof and floor (456 m²) and internal walls (303 m²), which are all 0.14 m thick concrete elements with $r \approx 1000$ kg/m³ and $c \approx 0.3$ Wh/(kg K). The total heat capacity is then roughly $C \approx 3.2 \cdot 10^4$ Wh/K. The resulting time constant is $t = R \cdot C = 310$ h for the object 3. This means, that at constant outdoor air temperature of -10 °C, the indoor air temperature of 20 °C would drop by 2.2 K within 24 hours, if no heating or other gains, nor ventilation is available.

Faster temperature gradients can only be caused by ventilation. The standard case, which is relevant for object 3, is a running ventilation system without heating, but with heat recovery. The energy-effective air change rate n is given by the infiltration rate $e \cdot n_{50}$, ventilation rate n_{vent} and heat recovery value h of the ventilation system according to:

$$n = e \cdot n_{50} + (1 - h) \cdot n_{\text{vent}}. \qquad (3)$$

The resulting temperature difference $\Delta\Theta(t)$ between indoor air and outdoor air for a homogeneous mixing, and if heat flow between walls to indoor air is neglected, is given by:

$$\Delta\Theta(t) = \Delta\Theta_0 \cdot \exp\{-t \cdot n\}. \qquad (4)$$

In object 3, the ventilation is running with $n_{\text{vent}} = 0.414$ and $h = 0.83$, which results in an effective n of about 0.1 h^{-1}. According to Eq. (4), the mere mixing of outdoor air at 0 °C with indoor air of 20 °C at a rate of $n = 0.1$ h^{-1} results in an indoor air temperature drop of less than 0.5 K for 15 minutes. This is a strong upper limit for temperature decrease due to controlled ventilation (with heat recovery), as no heat transfer from internal walls (or the interior) to the air has been considered.

These estimations show, that in object 3, or similar buildings, a temperature drop of more than 0.5 K from normal room air temperatures during a time step of 15 minutes (strictly: more than given by Eq. 1 and Eq. 4) is almost certainly caused by window ventilation. Figure 4 shows an example of how window ventilation events have been included in the simulation, and how they influence the room air temperature. The simulated air temperature in the guest room (ground floor) is presented. Strong ventilation events occurred between 6:00 h and 10:00 h and they lasted about 0.5 hours. The difference Δ*T* between simulated and measured air temperatures is shown in the lower part of Fig. 4, and is most of the time less than 0.5 K. During the shown period the outdoor air temperature varies between -18.4 °C (day 43) and 6.3 °C (day 49). The air change rate needed to fit the measured air temperature is up to about 5/h, which is typical for most of the user induced ventilation events in all four objects.

Figure 5 shows a very interesting period, which occurred in object 1. The simulation zone represents a 2 bedroom apartment with 74 m² floor area. The temperature of the apartment was raised significantly for a period of about 2 weeks. The reason is either an adjustment or a malfunction of one room thermostat. A failure of the temperature sensor could be excluded from analysis of wall and room temperatures in neighbouring zones, which showed a corresponding temperature development. Electricity demand and DHW measurements indicate, that the apartment was not used during this period (at least from day 23 until 33). For the simulation results shown in Fig. 5, not only weather data and electricity were used from measurements, but in this case also the measured heating energy. In the period of absence, an infiltration rate of 0.2 h^{-1} gives an almost perfect agreement between simulated and measured air temperature. This rate is then used as the basic value of infiltration for this apartment. To fit the strong temperature variations outside this period, individual ventilation events have to be included. These must have been generated by window ventilation. The fastest decline of the room temperature between 6:00 h and 17:00 h on day 36 could be modelled with a ventilation rate of 3.7 h^{-1} to 3.8 h^{-1}. The measured zone temperature falls thereby from 25.2 °C to 20.8 °C, whereas the ambient temperature was between 5 °C and 7 °C. The largest gradient in the measured air temperature was 0.67 K within 15 minutes. Note that all given measured and simulated temperatures and infiltration rates in this example are average values for a zone, which represents a 2 bedroom apartment. The infiltration rates for individual rooms can be significantly different from the average value (i.e. higher).

Figure 6 shows the average indoor air temperature over a period of 110 days for object 4. For this simulation, only the measured weather data and electricity consumption has been used. Periods of strongly increased infiltration, caused by window ventilation, have not been identified in the shown period. During two time periods (day 64 to 66, with ambient temperature between -0.6 °C and 2.4 °C, and day 122 to 127, with ambient temperature between 0.6 °C and 10.7 °C) the heating and ventilation was shut down. The reproduction of the indoor air temperature is quite difficult in such a "passive house" with very low energy demand, because persons have a very strong influence on the heating energy demand and air temperature. On a 15 minute basis, as shown in Fig. 6, the agreement does not reach such a high level like in the examples shown before. Nonetheless, the overall agreement between simulation and measurement is quite good in all buildings, as shown in the next section. (See Bier, 2002, for a detailed description of the simulation models of objects 3 and 4.)

VALIDATION OF MODELS

The aim of the validation is to create very realistic simulation models with respect to energy demand and temperature. The energy demand is mostly important on time scales of months or for the whole heating period. For comfort aspects, not an average air temperature, but also temperature variations on short timescales are relevant. The simulation model should therefore reproduce the measured temperatures on the shortest available timescale, which is 15 minutes in the cases considered here. For the optimisation of the models, the air temperatures are analysed for all individual rooms or zones, respectively. This optimisation is an iteration process, in which significant user influences are included and model parameters are varied in their possible boundaries, so that the heating energy demand, mean house temperature and air temperatures of the zones on 15 minute basis are as close as possible to the measurement. The influence of the user is mostly by:

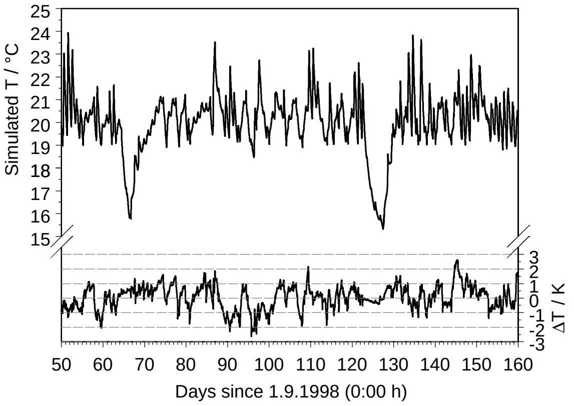

Fig. 6: Simulated average indoor air temperature for object 4. The lower part shows the difference ΔT between simulated and measured air temperature.

- Ventilation by individual window openings. These events are identified by strong temperature gradients, as described above. Unresolved events will contribute to the infiltration.
- Electricity consumption. Measured data are included in the simulations. A matter of optimisation is the distribution of these internal gains on the individual zones and their usability.
- Changes of the indoor temperature level. For individual rooms this was technically possible only in objects 1 and 3. Such events are identified by abrupt changes of the temperature.
- Time on which heating and/or ventilation were switched on or off, respectively. The operation of building services are measured by electricity demand of pumps or vans.
- Shading by internal or external blinds or shutters. If a measured room temperature is lower than the simulated temperature for only some of all days with significant direct sunlight, shading is included in the simulation on these days.

Most of these user induced influences are individual events, which should be kept as small as possible in number. In principle, all of such events add a degree of freedom to the simulation, and with an infinite number of degrees of freedom, every measured temperature distribution can be reproduced, although not necessarily with the right heating energy demand. Therefore, the number of such events has to be kept to the absolute minimum, and every event should

Table 3: Key values for the validation of the TRNSYS simulations.

	Object 1	**Object 2**	**Object 3**	**Object 4**
Validation period	06.01.1998 - 30.04.1998	01.09.1998 - 31.12.1998	16.12.1999 - 31.03.1999	28.01.1999 - 11.03.1999
Measured heating energy demand (delivered to rooms) for the validation period	40.1 kWh/m²	33.1 kWh/m²	12.9 kWh/m²	2.6 kWh/m²
Deviation of the simulation	0.0 kWh/m²	0.0 kWh/m²	0.1 kWh/m²	0.1 kWh/m²
Mean temperature difference m on 15 minute basis for $T_{\mathrm{diff}} = T_{\mathrm{s}} - T_{\mathrm{m}}$	0.0 K	0.0 K	- 0.1 K	0.0 K
Standard deviation s for T_{diff}	0.2 K	0.3 K	0.2 K	0.5 K

have a very high significance in the measured data. In object 4, almost no ventilation events have been detected. A time period with very frequent ventilation in object 3 is shown in Fig. 4. In general, ventilation, shading and temperature control events have been included roughly about once a week.

Important for the simulation model itself are the intrinsic parameters of the building and its services. Some of these parameters for the building are:

- infiltration rate,
- U-value of windows (and also of opaque elements),
- heat bridges, especially at windows,
- heat capacitance of zones,
- coupling air flow between zones,
- convective heat transfer coefficients of walls,
- solar absorption of surfaces.

Examples of parameters for building services are:

- efficiency of heat recovery,
- air change rate by ventilation in each zones,
- maximum heating power within these zones,
- dead band temperature of heating control,
- losses of the heating system (tank, pipes, ducts).

All of these parameters for buildings and its services are given in principle by the construction plans and subsequent measurements (e.g. n_{50}-value, air change rate of ventilation system). However, within certain limits, the parameters of the actually realized building can deviate from these values. For example, according to DIN EN 832 (1992), the infiltration rate can vary between 1% and 10% of the n_{50}-value, which itself has a certain measurement error. In addition, the users can significantly increase the infiltration rate by window ventilation. This parameter is rather vague and variable, but it exerts simultaneously a major influence on the heating energy demand. The influence of small U-value variations on the heating energy demand could hardly be distinguished from variations in the basic infiltration rate (i.e. without user influences), because the different time dependence on the ambient temperature could not be resolved. However, in contrast to the infiltration rate, the U-values in the simulation model are much more limited by the construction plans.

The different parameters were chosen after analysing their influence in appropriate time periods. One example is the determination of the U-values, heat capacity and basic infiltration rate for object 4. These parameters could be fixed by analysing two periods without heating (day 64 to 66 and day 122 to 127, see Fig. 6), because interfering influences by users and building services did not occur. Figure 5 shows such a period, which was very useful for the determination of parameters for object 1. For every parameter, the most effective and direct way of determination was chosen, instead of applying some kind of optimisation algorithm for the whole parameter space.

For the validation, a time period with high data reliability was chosen inside the heating period. In Table 3, these validation periods are given, together with some results of the validation. These consist of the measured heating energy demand and the deviation of the simulated heating energy demand. The volume averaged simulated air temperatures T_{s} of all zones are compared with the measurements T_{m} every 15 minutes. All of these differences $T_{\mathrm{diff}} = T_{\mathrm{s}} - T_{\mathrm{m}}$ in the validation period form for each building a Gaussian distribution with mean value m and standard deviation s. These values are shown in Table 3.

The good agreement of simulations with measurements for both, the heating energy demand (delivered to rooms) and the mean temperature, indicates a successful modelling of the building envelope and its transmission and ventilation losses. The small standard deviation for T_{diff} indicates, that the simulation model is also quite accurate on shorter timescales. Note that a better agreement between simulation and measurement is hardly possible without considering influences of temperature stratification and wall surface temperatures. Such influences have not been taken into account in the present study.

The reproduction of the user behaviour was necessary to yield the best possible validation of the simulation models. For further analysis with these models, a standardized user profile will be assumed. The number of persons living in a building depends on the floor plan and the size of living space. For every building, appropriate numbers and occupancy schedules for persons are assumed. The corresponding internal gains amount for a heating period (1.9. to 31.5.) to 14.4 kWh/m² for object 1, 10.3 kWh/m² for object 2, 12.5 kWh/m² for object 3 and 12.6 kWh/m² for object 4. From the measured electricity demand, a

Table 4: Yearly values for TRNSYS simulations and measurements with standard user profiles.

	Object 1	Object 2	Object 3	Object 4
Heating set temperature (from measurements)	21.5 °C	19.5 °C	20.0 °C	20.0 °C
Measured heating energy demand in kWh/(m²a)	82.4	72.9	27.8	9.8
Simulated heating energy demand in kWh/(m²a)	79.6	75.8	26.5	9.5
Difference in kWh/(m²a)	- 2.8	2.9	- 1.3	- 0.3
Difference in %	3.4%	4.0%	4.7%	3.1%

typical hourly profile was derived, with sums up to 18.0 kWh/m² for a heating period. Additional ventilation and shading is used only, if the room temperature exceeds the set temperature for heating by more than 4 K. For the simulation results shown in Table 4, these standard user profiles have been used. Only the set temperature for heating has been adopted from the measured data by analysis of the average air temperature. This temperature is given in Table 4, too. The simulated indoor air temperatures can no longer coincide strongly with the measurements, whereas the yearly heating energy demand depends mostly on the building and the mean weather conditions. Therefore, only the heating energy demand is shown here, which is calculated with the validated building model and for the measured weather. The results of Table 4 show, that with deviations of less than 5% for the heating energy demand, the simulation models still agree quite good with the measurements, even without detailed consideration of the individual user patterns.

PARAMETER STUDIES

The developed simulation models of the four objects represent small and medium sized residential buildings of different construction types with heating energy demand of between very low and typical, with respect to recently built houses in Germany. The building models are validated according to their energy demand and indoor temperature, and can, therefore, be used to analyse the impact of various parameters on the heating energy demand and comfort.

For a direct comparison of the four buildings, the influences from the location can be eliminated by using the same weather data, orienting the main facade (living room) towards south, and considering only shading by the building itself and not by its surroundings.

The results for such a simulation are shown in Table 5. The influence of the location on the heating energy demand is quite high. Objects 3 and 4 show a comparable heating energy demand. These buildings are characterised by a similar level of thermal insulation and heat recovery (see Table 1). The almost coincident simulations results demonstrate clearly, that the difference by a factor of 2.8 in the measured heating energy demand was caused mainly by the difference of local weather conditions. Table 5 also presents simulation results with additional window ventilation. Here, the infiltration rate of the whole building was increased by 3 h^{-1} for half an hour between 8:00 h and 8:30 h at every day of the year. This value of the infiltration rate is roughly the average of those rates, which were derived for window ventilation during the validation phase of the simulation models. Its effect on the heating energy demand is much smaller than that of the climate. Note, that the maximum power of 2.4 kW for object 4 is not sufficient to maintain the room temperature of 20 °C in all rooms and at all times for the Stockholm climate. This power can, however, not be increased without significantly exceeding temperatures of 50 °C for the fresh air. As a result, the degree hours for room temperatures of less than 18 °C in one bedroom of object 4 reach 335 Kh for Stockholm climate, and even 508 Kh with additional window ventilation.

One advantage of such validated simulation models is, that quantitatively reliable results can be achieved even for problems where variations of indoor air temperature are important. Results for the passive houses, objects 3 and 4, are described by Bier (2002). Examples are the cost efficiency of ventilation systems with heat recovery (Gieseler et al., 2002a) and the impact of window ventilation on heating energy demand and comfort. In addition, studies on the impact on the heating energy demand due to modifications of the building envelope have been performed, i.e. variations of window size and *U*-value of windows, walls, roof and floor (Gieseler et al., 2002b). Moreover, the results can also be used to investigate the applicability of stationary thermal models for the energy demand and the errors resulting thereof.

Table 5: Yearly heating energy demand from TRNSYS simulations at different locations for identical usage, shading and operational conditions.

Location of weather data from METEOTEST (1997) and corresponding heating degree days (20/12)	Object 1	Object 2	Object 3	Object 4
	Heating energy demand in kWh/(m²a)			
Trier (D), 3505 Kd	83.5	73.5	15.6	15.2
Trier (D), 3505 Kd, additional window ventilation	86.6	76.7	18.0	17.2
Stockholm (S), 4586 Kd	120.5	102.1	27.9	24.5
Stockholm (S), 4586 Kd, additional window ventilation	124.0	106.0	30.9	27.1

SUMMARY AND OUTLOOK

With the use of measured weather data at the corresponding locations the TRNSYS simulations of four buildings reproduce the yearly heating energy demands within less than 5%. Considering also details of the building usage and especially by adjusting the infiltration rate, the heating energy demands and the *mean* building temperatures can be reproduced simultaneously. Moreover, the standard deviation s of the difference between simulated and measured air temperatures for every 15 minutes is between s = 0.2 K and s = 0.5 K for the four buildings, over periods of about one to four months. This proves the correct implementation of models for the surroundings (shading), the building itself (envelope and services) and the individual usage (internal gains, control of heating and ventilation). With these building models, the impact of the main influencing factors on the real heating energy demand can be analysed quite precisely. Regarding the cost efficiency of energy saving measures, these can be classified into four categories. For each of the categories 1 to 4, preliminary results have been reported (Bier, 2002; Gieseler et al., 2002a; Gieseler et al., 2002b; Gieseler and Heidt, 2002). These can be summarized as follows:

Category 1: Measures, which lead to small to moderate energy savings without additional costs:

i. Compact building envelope design.
ii. Redistribution of window area towards south to increase passive solar gains.

Category 2: Measures, for which investment costs pay up during their lifetime:

i. Additional insulation of the opaque envelope, leading to about U = 0.28 W/(m²K).
ii. Ventilation systems in cold climates (> 4000 Kd) with moderate or standard heat recovery efficiency (65%).

Category 3: Measures, which lead to significant energy savings, but which generally do not pay up during their lifetime:

i. Ventilation system with heat recovery in milder climates (< 4000 Kd).
ii. Additional insulation of the opaque envelope, leading to U-values lower than U = 0.28 W/(m²K) down to U = 0.10 W/(m²K).

Category 4: Measures, which lead to moderate energy savings, with comparatively high costs:

i. Enhancing south facing areas of standard or high quality windows ($U \leq 1.4$ W/(m²K)), in excess of that needed for daylight and visual comfort.
ii. Highly insulating windows, which exceed significantly the current standards, i.e. windows with U = 0.7 W/(m²K) instead of U = 1.4 W/(m²K).
iii. Earth heat exchangers, which are merely used to preheat fresh air in residential buildings in milder climates (< 4000 Kd).

These results will be extended by the investigation of further building services, like heat pumps and solar collectors. Another matter of analysis will be reasons for the observed differences in overheating within the described buildings. Furthermore, the simulation models are well suited to calculate the utilization factor of solar gains depending on window area and for different types of buildings.

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