Statistical simulation of user behaviour in low-energy office buildings

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ABSTRACT

A large number of design guidelines and tools are available for the design of passive cooling systems. However, the building engineer should take several uncertainties into account since the actual use of the building, the building physical properties or the user behaviour are uncertain. One promising approach to include these uncertainties in the design procedure is the use of statistical models: The design parameter is defined by a mean value and its deviation. From a control theoretical point of view, the deterministic controlled system responds to random disturbance variables by a statistically distributed response function. Considering the institute building of Fraunhofer ISE (Herkel et al., 2001) as example, this study shows how statistical simulations can be applied to the design process of passive cooling in low-energy office buildings, cf. (Voss et al., 2005b).

1. INTRODUCTION

For this study, a validated building model is used to investigate the impact of user behaviour on the thermal building performance. The influence of material properties and parameters in the air-flow network on the room temperature have been analysed by a sensitivity analysis in order to prepare and to evaluate a validated simulation model. This model validation has been carried out using data sets from April and July 2002 (Pfafferott et al., 2003), while the statistical simulation with regard to the user behaviour uses a data set from the summer of 2003. All simulations have been carried out using the simulation program ESP-r, cf. (Clarke, 2001).

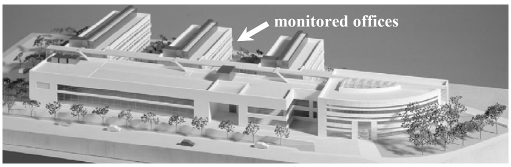

Figure 1: View of the Fraunhofer ISE building from West. The monitored offices are located in the middle building wing on the 2nd and 3rd floor with South orientation.

The functionality (and the programming) of Monte Carlo-Simulations is briefly described in Ref. (Macdonald and Strachan, 2001).

In preparation for the statistical simulation, several investigations on detail phenomena concerning the thermal behaviour of the Fraunhofer ISE building were carried out to provide a reliable simulation model, cf. (Pfafferott, 2004).

The statistical simulation is supposed to deal with uncertain input parameters and should show whether typical occupancy patterns are effective for modelling the thermal building behaviour and how far statistical models can be used successfully to take uncertainties into account. The procedure can be described according to the control theory:

- *Excitation function*. The input parameters are statistically analysed with regard to the use

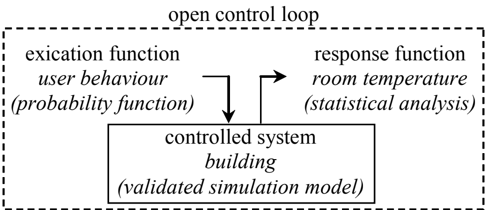

Figure 2: Methodological approach.

of the building (i.e. equipment and occupancy) and user behaviour (i.e. ventilation and sun-shading). Through this comprehensive data evaluation, statistical models for the simulation input are derived.
- *Controlled system*. Using these data series as input parameters, the thermal building performance is simulated: Many parameter combinations are considered by the simulation, and each is distributed around a true mean value. It is reasonable to assume that the parameters are normally distributed. As all input parameters are varied simultaneously, the room temperature is also distributed around a true mean value.
- *Response function*. The simulated room temperatures are statistically analysed and compared with the monitored room temperatures.

For further information concerning the building, the HVAC system and its operation the reader is referred to SolarBau: Monitor (2005).

2. DATA EVALUATION

For the statistical data analysis and simulation, (1) the time period and (2) the sample of offices must be defined. For this data sample, the variation in time of room temperatures and the heat gains are analysed. The user behaviour is analysed with special regard to the ventilation.

Time period. Starting from the hourly ambient air temperatures in 2003, a typical period can be defined. The period June 12 to July 23, 2003 is short enough to carry out many simulation runs in a row and long enough to cover different summer weather conditions since similar ambient air temperatures and sun positions in this time period will produce likely consistent user behaviour.

Office sample. 16 offices in the Fraunhofer ISE building are considered for the statistical data evaluation and simulation. Since all rooms are located on the first and second floor in the same part of the building, the climate impact from the outside is the same. However, the mean room temperatures (during the summer period) vary from 25.9 to 26.9 °C, since the offices vary in the daily attendance, the office equipment (internal heat gains) and the user behaviour regarding sun protection (solar heat gains) and ventilation (heat losses).

As this article focuses on the methodology of statistical simulation, the following procedure shortly describes the data analysis for 16 offices during the summer period.

The statistical models are deduced from a long-term monitoring.

2.1 Variation in time of room temperatures

The following procedure provides the variation in time of room temperatures and its statistical distribution:

1. Preparation of hourly room temperatures in each of the 16 offices.
2. Calculation of daily mean room temperature and daily temperature fluctuation in each office.
3. From this time series, mean room temperature, 16 and 84 % quantile are identified for each day. The minimum/maximum temperatures specify the limit of variation.

Exemplarily for this procedure, Figure 3 shows the time behaviour of the daily mean room temperature (in 16 offices) and its daily deviation/variation in all rooms:

- The daily mean room temperature varies from 22.3 to 28.8 °C.
- The mean deviation is 0.4 K and varies from 0.15 to 0.9 K.
- The mean variation is 1.45 K and varies from 0.7 to 2.5 K.

As the climatic and the building physical boundary conditions are (almost) identical in all rooms, the *temperature variations* result mostly from *variations in use* of the offices.

2.2 User behaviour regarding ventilation

The following procedure provides the user be-

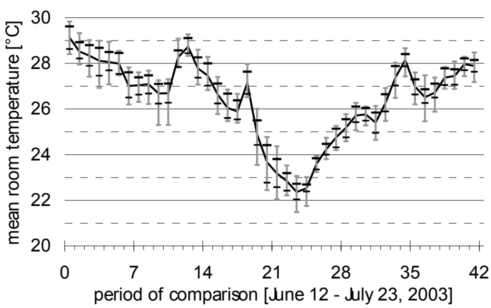

Figure 3: Mean room temperatures with minimum / maximum (grey lines) and 1-σ deviation (black dashes).

haviour regarding ventilation and its statistical distribution:

1. Preparation of the hourly status (open or closed) of door, ventilation flap (indoor), sky light (outdoor) and window in each of the 16 offices. If a room has more than one window/sky light these openings will be combined by an OR-relation.
2. The time series differentiates working days and weekends.
3. All data lines are sorted by the time of day.
4. From this information, relative frequencies of opening are calculated for each ventilation component and for each hour of the day.
5. Using the hourly data regarding the status of all openings in each of the 16 offices, the local distribution of hydraulic resistances (mean value and statistical distribution) is calculated using an air-flow network with resistances, parallel (16 offices) and in series (office – corridor).

Figure 4 shows the average user behaviour in 16 offices during 30 working days: As expected, *doors* are closed outside business hours. More or less than 50 % of all doors are opened during the working hours. In general, *windows* are opened at arrival and are closed bit by bit when the ambient air temperature is increasing. In the morning more windows are turned open, while in the afternoon most open windows are tilted. At least 50 % of all windows are open during night. At least 80 / 90 % of all *sky lights* above the window and *louvers* above the door are opened during the whole day. These flaps are manipulated very rarely.

The *exhaust fan* delivers an air change rate of 1 h^{-1} (480 m³/h for 8 offices) during the working hours and 5 h^{-1} (2,400 m³/h for 8 offices) during night ventilation in each floor. If the hydraulic resistance was the same in each of the offices, each office would get the same fraction of the air-volume flow which is 1/8 or 12 % of the total air-volume flow. Due to the changing distribution of open and closed flaps, doors and windows, the air-flow network (hydraulic resistances in series) constantly changes. Some offices get less than 4 % and other rooms up to 18 % of the air flow.

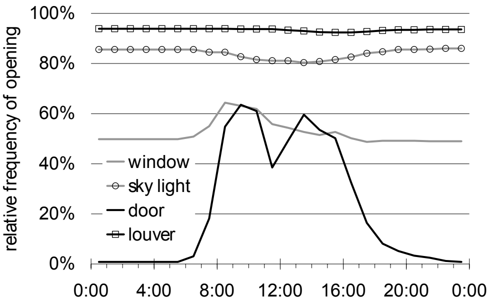

Figure 4: Time dependent user behaviour with regard to ventilation during the working days. (Manual opening of ventilation components.)

2.3 Variation in time of heat gains

The following procedure provides occupancy patterns, the time variation of electricity consumption, the use/control of sun-shading and their statistical distributions:

1. The hourly heat gains due to persons are calculated from the signal of an ultrasonic sensor and correspond to 80 W/person. Missing or incorrect data are substituted by an average time profile which is calculated from all available sensors.
2. The total electric power consumption [W_{total}] is hourly measured. Furthermore, the electricity consumption [$kWh_{office}/(m^2\ d)$] in an office depends on the electric connection power and the estimated operation time of the equipment. Using the connection power and the current attendance for each office, the total electricity consumption can be divided into the electricity consumption in each office [W_{office}].
3. The hourly solar heat gains are calculated from the solar radiation on the window, which is calculated from meteorological data, taking into consideration shading from adjacent buildings and the facade as well as the position of the venetian blinds. The data acquisition is realised by a web camera. The error-prone data evaluation by image processing results in some data gaps which are substituted depending on their length of time: If the status of the venetian blind is not recognised, the last valid value will be extrapolated. If the data gap covers several hours, the missed value will be substituted by the mean value of all known positions.
4. Through this process, hourly data for internal (persons and lighting/equipment) and solar heat gains are available for each office. The

simulation deals with 16 different time profiles for heat gains.

Figure 5 outlines the daily heat gains in all of the 16 offices for 30 working days and its variation. The heat gains vary from one room to the next and can vary from one day to the next:

- Due to the different application of computers, the daily heat gains from equipment (grand average: 137 Wh/(m² d)) varies from 58 to 295 Wh/(m² d).
- Since the rooms can be occupied by as few as one and as many as four persons and the mean attendance in the office is variably long (e.g. laboratory workers), the mean daily heat gains from persons (grand average: 54 Wh/(m² d)) varies greatly from 26 to 103 Wh/(m² d).
- In comparison, the variation in solar heat gains (grand average: 158 Wh/(m² d)) is relatively small: The room, in which the occupants close the venetian blinds most frequently, gains meanly 106, the room with rarely closed blinds 210 Wh/(m² d).
- The mean heat gains are slightly higher in the 8 offices in the 2nd floor (362 Wh/(m² d)) than in the 1st floor (333 Wh/m² d)).
- Heat gains can vary heavily from one day to the next: In some offices, the standard deviation reaches 70 % (equipment), 93 % (persons) and 43 % (solar) of the mean value.

The 8 offices on the 2nd floor are 0.4 K cooler than the 8 offices on the 3rd floor. As the impacts (i.e. thermal stratification, sun-shading by adjacent building parts and the higher heat gains) on the temperature difference cannot be distinguished from each other, the 16 offices are evaluated together. Confirmatory, a sensitivity analysis shows that the internal heat gains and the user behaviour are the dominant parameters in the energy balance compared to the thermal stratification or the sun-shading by adjacent building parts.

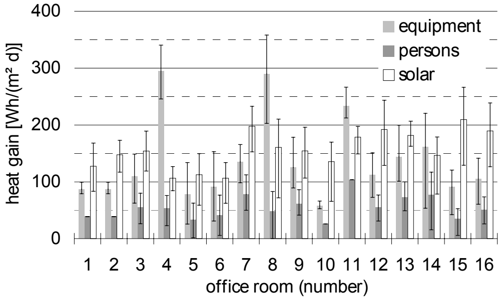

Figure 5: Daily heat gains and 1-σ deviation.

Based on this statistical analysis and the validated simulation model (building physics and ventilation model), the heat flows and the room temperature can be modelled statistically, taking into account user behaviour with respect to attendance, use of electric equipment, sun-shading (manual control of venetian blinds) and use of windows/sky lights (outdoor) and doors/louvers (indoor).

3. STATISTICAL SIMULATION

There are approximately 10^{18} possible combinations from the 16 heat gain series and the status of ventilation components within the period of 1,008 hours, but the number of simulation runs can be reduced to 1,000 by the use of statistically distributed input parameters. The Monte-Carlo simulation deals with statistical input parameters which are defined by a true average and a realistic deviation. All input parameters are varied at the same time. The validated simulation model is applied to the statistical simulation, which requires that all internal surfaces have adiabatic boundary conditions.

The following procedure describes the program flow of the statistical simulation according to the Monte-Carlo simulation concept:

1. Calculation of user behaviour concerning the window opening. For each hour of the day, the status of window, sky light, louver and window is calculated with the Gauß function. Mean value and standard deviation are known from the data analysis. The time series is mathematically conservative: The opening status increases or decreases over the time but does not oscillate from one hour to the next.
2. Random determination of mechanical air change according to the status of openings.
3. The hourly time series of the internal and solar heat gains for one room is taken from the data analysis. At the next time step, the next room is chosen. After 16 simulation runs, the procedure starts with the first room again.
4. For each simulation run, the hourly room air

temperatures are saved.

5. The statistical analysis corresponds to the data analysis of the monitored room temperatures according to Section 2.1.

The aim is to model the heat gains as close to reality as possible and to investigate the user behaviour with regard to ventilation.

3.1 Room temperature: Variation in time

Since the input variables are statistically distributed, the calculated room temperatures are statistically distributed as well. The simulated temperatures are compared with the monitored room temperatures in order to evaluate the statistical input models. Figure 6 shows that the mean temperature variation in the simulation closely approximates the variation in measurements.

- In this 42-days period, the mean measured and simulated room temperatures differ from each other by 0.2 K.
- Every day, the simulated room temperatures meet the monitored temperatures within the standard deviation.
- As expected, the deviation (of 16 offices) is higher in the simulation than in the monitored data at each day since the balancing heat transfer between adjacent rooms (validated simulation model) is disconnected by the adiabatic boundary conditions (statistical simulation model).

While Figure 6 shows a good agreement in the mean temperatures, Figure 7 evaluates the dynamic temperature behaviour:

- In this 42-days period, the mean measured and simulated daily fluctuations differ from each other by 0.5 K. Since temporary fluctuations of heat gains or losses cannot be balanced by heat conduction from/to adjacent rooms due to the adiabatic boundaries, the simulation shows generally a higher daily fluctuation.
- The variation in time is very similar. The simulated daily temperature fluctuations match those measured during 39 of the 42 days.
- Noteworthy, the deviation (of 16 offices) in the simulation is smaller than in the monitored room temperatures on some days. High variations in measurements may be explained by the measuring system and the local position of temperature sensors.

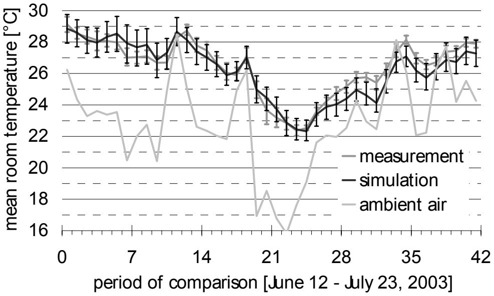

Figure 6: Daily mean room temperatures: The measured room temperature is 26.4 °C and the simulated 26.2 °C. (The mean ambient air temperature is 22.9 °C.)

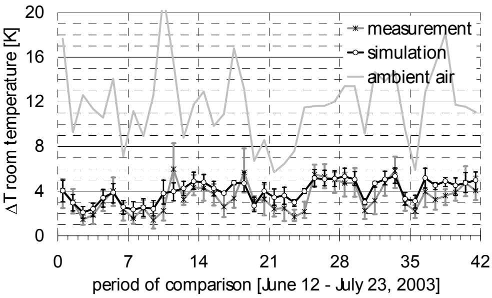

Figure 7: Daily fluctuation of room temperatures: The measured fluctuation is 3.5 K and the simulated 4.0 K. (The fluctuation of the ambient air temperature is 11.8 K.)

Both the daily energy balance (mean room temperature) and the dynamic thermal building behaviour (temperature fluctuation) are simulated realistically using the user model.

3.2 Room temperature: Analysis

The duration curve, according to Figure 8, estimates the comfort criteria concerning the room temperatures and its occurrence frequency. The simulation comes to a similar conclusion concerning overheating but shows a slightly wider tolerance band. The room temperature should not exceed 26, 27 or 28 °C.

Notice. Due to the heat gains, the daily mean room temperature is always higher than the daily mean ambient air temperature. However, the maximum hourly room temperature is below the maximum hourly ambient air temperature due to the heat storage capacity of the room, cf. Figure 9.

Figure 9 shows clearly that the simulation

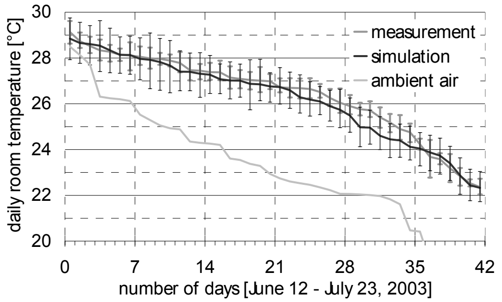

Figure 8: Duration curve for daily mean temperatures: The ambient air temperature exceeds 26 °C for 6, the measured room temperature for 27 and the simulated room temperature for 25 of 42 days.

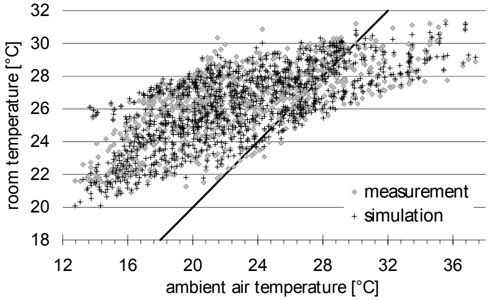

Figure 9: Hourly room temperature versus ambient air temperature (All hours from 00:00 to 23:00).

(hourly room temperature from 1,000 simulation runs) and the monitoring (hourly room temperature from 16 offices) result almost in the same benchmark: The room temperature exceeds the ambient air temperature for 822 (measurement) and 809 hours (simulation), respectively, of the 1,008 analysed hours.

Notice. The passive cooling system is designed in order to hold the room temperature in the comfort range. During this extreme weather situation, the room temperatures do not meet the commonly used comfort criteria according to DIN 1946-2 (1994) or ASHRAE 55 (2004). Figure 9 can also be used to evaluate the thermal comfort.

The results of this comprehensive data evaluation reveal that the thermal building model combined with the statistical user model simulates the thermal building performance accurately.

4. CONCLUSIONS

Three lessons can be learned from the statistical simulation:

1. A statistical data analysis provides adequate user models for application in building simulation.
2. The Monte-Carlo simulation is an appropriate tool to calculate the thermal building performance with a true mean value and its statistically relevant deviation.
3. Statistical simulations can be advantageously applied to the design process and enhance the significance and clarity of simulation results.

The design of passive cooling concepts should consider the user behaviour realistically according to this statistical data analysis, cf. (Voss et al., 2005a).

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