Long-term monitoring data from a naturally ventilated office building

Marcel Schweiker*, Michael Kleber & Andreas Wagner

Data was collected in the field, from an office building located in Frankfurt, Germany, over the period of 4 years. The building was designed as a low-energy building and featured natural ventilation for individual control of air quality as well as buoyancy-driven night ventilation in combination with a central atrium as a passive cooling strategy. The monitored data include in total 116 data points related to outdoor and indoor environmental data, energy related data, and data related to occupancy and occupant behaviour. Data points representing a state were logged with the real timestamp of the event taking place, all other data points were recorded in 10 minute intervals. Data were collected in 17 cell offices with a size of ~20 m², facing either east or west). Each office has one fixed and two operable windows, internal top light windows between office and corridor (to allow for night ventilation into the atrium) and sun protection elements (operated both manually and automatically). Each office is occupied by one or two persons.

Background & Summary

The introduction of the European "Energy Performance of Buildings Directive" in 2001 gave a strong incentive to reduce excessive energy consumption through a holistic approach in terms of building design and integrated energy concepts. Within this context, the program SolarBau, introduced by the German Federal Ministry of Economic Affairs, funded ambitious demonstration projects within the non-residential building sector setting benchmarks in terms of low primary energy consumption. Buildings in Germany are benchmarked through their primary energy demand for heating, cooling, ventilation, lighting and domestic hot water (DHW). The monitored building described here had a projected value of 107 kWh/m²a.

Within this program, a strong focus was set on various passive cooling strategies in combination with a higher insulation standard than required by German regulations in the year of construction (see Table 1 for details). Daylight factors above standard at the workspaces were achieved by proper window design and light directing devices (venetian blinds with different blind positions and ceiling panels above the desks). At the same time, occupants' interactions with windows and blinds – essential aspects in the context of passive cooling concepts – was addressed1–3 as well as their thermal comfort under these conditions. A two-year monitoring after commissioning of the building was compulsory for a proof of concept for all funded buildings.

Influencing factors on the occupants' behaviour with regard to the operation of windows and blinds are, among others, the indoor and outdoor environmental conditions such as temperatures, relative humidity levels, air quality levels, and lighting levels4,5. Due to their daily and seasonal variation, long-term monitoring data, i.e. at least a full year, is essential to capture their influence on occupants' behavioural patterns.

The monitored building is located in Frankfurt am Main, Germany. Key characteristics of the building are presented in Table 1. An important design feature to enhance natural night ventilation is a large atrium with an extended "chimney" around which the offices are located. This enables a buoyancy-driven airflow from the windows through the offices themselves, into the traffic zones, and then up into the chimney where the air leaves the building. The airflows through the offices are levelled out by the opening angle of the top lights, located above the manually operable windows. Directly exposed concrete ceilings in the offices enable the activation of thermal mass as an essential part of passive cooling by night ventilation. Furthermore, the atrium increases the usage of natural lighting for the interior traffic zones.

Only the meeting rooms, the offices to the south behind the double-skin facade, offices with suspended ceilings and a number of special purpose areas are actively cooled, but are not part of this dataset.

The occupant is able to open the windows manually. For operating the top–light windows (see Fig. 1) occupants have to use the control panel which is located beside the door (opposite to the façade). Through this panel,
occupants can also control the exterior Venetian blinds and the artificial lighting of the office. Outdoor noise due to traffic was only present in the area of the south facing rooms, which are not part of this dataset. No other noise sources are known. Outdoor air quality was high, given outdoor CO2-levels (included in data) being mean 465 ppm ± 52 (standard deviation).

The dataset published consists of long-term data from January 2005 to December 2008, i.e. starting 2 years after the construction, when initial problems with controls where already solved. The data published has a 10-minute interval for continuous data and the event data with individual time stamps and consists of data from 17 offices.

The data has been analysed and used by several authors. A first analysis of the indoor environmental conditions and energy revealed that indoor air quality levels were high, that the primary energy consumption was at a low level as predicted, and that the monitoring was a useful measure towards an optimized operation. Schakib-Ekbatani et al. questioned the fit between occupant behaviour and the building concept and found several occurrences of occupants’ window opening behaviour contradicting the natural ventilation concept. An additional analysis of the data applied a data mining framework for identifying occupancy patterns and found four archetypal working profiles.

### Methods

**Monitoring concept.** In order to collect long-term data automatically and frequently, all sensors were connected to the building management system (BMS) of the building. Data were gathered in 10-minute intervals or as event data. Data was stored for one day locally and send at night as csv-files to the server of the researcher. Data was stored in a MySQL database.

A weather station was located on the top of the building at 2 m above the roof, i.e. around 30 m above street level. The weather station is providing data regarding the outdoor conditions for all offices, such as temperature or wind speed. However, the microclimate on the façades can differ, e.g. depending on the intensity and direction of wind. The precipitation meter was not heated. However, snowfall is seldom. There are no direct obstacles close-by affecting the wind speed or direction. Still, wind speed and direction might have been affected by the buildings in the neighbourhood.

All offices included in this data base have a size of ~20 m² and are facing east or west (see also Table 2). Each office has one fixed and two operable windows with top light windows above, internal top light windows between office and corridor (to allow for night ventilation into the atrium) and external sun protection elements (operated both manually and automatically). One or two persons occupy each office.

Presence of occupants was measured by an infrared sensor located in the middle of the ceiling panel, which is suspended from the ceiling above the work places.

| Type of building | Multi-storey office building |
|------------------|-----------------------------|
| Dimension        | 17,402 m² (8,585 m² heated) |
| No. of Employee  | ~350 employees              |
| Location         | Frankfurt, Germany          |
| Thermal characteristics | High energy standard of building envelope |
|                   | Walls: U-values 0.24 to 0.5 W/m²K |
|                   | Windows: U-values 1.5 W/m²K, solar transmittance <40%, light transmittance 70% |
| Structural system | Reinforced concrete construction |
| Type of observed spaces | Office rooms |
| Year of construction | 2002 |
| No. of floors    | 2-level underground car park + 4 office floors + 1 floor apartments on top |
| Window dimensions | Windows: Top lights |
| Windows, orientation | Mostly E and W |
| Window opening   | All windows open inwards. No obstacles prevented window opening except those potentially added by occupants (e.g. plants or papers placed in front of window) |
|                   | Windows: Manual opening through window handle by occupants only; windows had hinges on one side and could be fully opened (rotated) to any degree up to 90° opening angle Top lights: automatic control + manual opening through switch next to office door by occupants, windows had hinges at the bottom and opened on top; any degree up to 90° was possible at manual control; at automatic control for night-time ventilation the angle was predefined in order to balance pressure difference between floors and achieve almost the same volume flow for each floor and office. |
| Window control options | Automated 10 minutes flush ventilation before working hours through top lights in the façade and between office and corridor |
|                   | Afterwards: Top lights: Tilt (automatic + occupant driven mode), Windows: Tilt-and turn (occupant driven) |
| Shading devices   | External sun protection (automatic + occupant driven mode) with different angle of blinds in the upper part to provide daylight guidance. Sun protection consists of light metal Venetian blinds with a slats width of 80 mm and a reflectance of 60%. |
| Predicted annual primary energy consumption | 107 kWh/m² |
| Monitored annual primary energy consumption | 100 kWh/m² in third year of monitoring |

Table 1. Building characteristics.

---

| Dimension          | 17,402 m² (8,585 m² heated) |
|--------------------|-----------------------------|
| No. of Employee    | ~350 employees              |
| Location           | Frankfurt, Germany          |
| Thermal characteristics | High energy standard of building envelope |
|                    | Walls: U-values 0.24 to 0.5 W/m²K |
|                    | Windows: U-values 1.5 W/m²K, solar transmittance <40%, light transmittance 70% |
| Structural system  | Reinforced concrete construction |
| Type of observed spaces | Office rooms |
| Year of construction | 2002 |
| No. of floors      | 2-level underground car park + 4 office floors + 1 floor apartments on top |
| Window dimensions  | Windows: Top lights |
| Windows, orientation | Mostly E and W |
| Window opening     | All windows open inwards. No obstacles prevented window opening except those potentially added by occupants (e.g. plants or papers placed in front of window) |
|                    | Windows: Manual opening through window handle by occupants only; windows had hinges on one side and could be fully opened (rotated) to any degree up to 90° opening angle Top lights: automatic control + manual opening through switch next to office door by occupants, windows had hinges at the bottom and opened on top; any degree up to 90° was possible at manual control; at automatic control for night-time ventilation the angle was predefined in order to balance pressure difference between floors and achieve almost the same volume flow for each floor and office. |
| Window control options | Automated 10 minutes flush ventilation before working hours through top lights in the façade and between office and corridor |
|                    | Afterwards: Top lights: Tilt (automatic + occupant driven mode), Windows: Tilt-and turn (occupant driven) |
| Shading devices    | External sun protection (automatic + occupant driven mode) with different angle of blinds in the upper part to provide daylight guidance. Sun protection consists of light metal Venetian blinds with a slats width of 80 mm and a reflectance of 60%. |
| Predicted annual primary energy consumption | 107 kWh/m² |
| Monitored annual primary energy consumption | 100 kWh/m² in third year of monitoring |

Table 1. Building characteristics.
Air temperature, relative humidity and CO2-level were measured inside each office close to the office door at 1.1 m height through a device attached to the walls separating the offices from the corridor.

Occupants can change the status of top-light windows, blinds, and lighting through a set of buttons close to the office door. Windows can be opened directly at the façade. Status of windows was measured through reed-contacts connected to the buildings’ BMS system. Position of the blinds was measured based on blinds’ motor run time.

The data points available in the database are presented in Table 3. These data can be grouped into outdoor environmental data, indoor environmental data, energy related data, and data related to occupancy and occupant behaviour.

**Data Records**

All data records listed in this section are available from the project pages on Open Science Framework (OSF) and can be downloaded without an OSF account. We licensed the data under a CC0 1.0 Universal license.

**All datasets.** File format: comma separated values file (.csv). Data is available as one file for each sensor including date and time column. All date formats are in the format day, month, year, i.e. dd.mm.yyyy. Devices in use are recorded with 1 or 100, those not in use with 0. This translates to open windows being in the data recorded as 1 and completely closed blinds with values 100.

---

**Fig. 1** Window positions and dimensions of one office.
Incoming datasets were analysed according to their completeness and validity. An error message was sent to the researchers in case these checks revealed problems. These analyses mainly targeted for checking availability of data and to filter implausible or missing values. Missing values in air temperature, relative humidity, and CO₂ concentration were marked by a value of “0” and filtered automatically. Implausible values, e.g. indoor air temperatures above 35 °C, were flagged by the monitoring software and manually inspected using the visualization tools of the monitoring software. The monitoring software used was MoniSoft¹¹.

The air temperature sensors were checked and calibrated during commissioning by the facility management and later comparison through a high-quality comfort meter equipment in sample rooms showed good conformity. All other sensors had been calibrated by the manufacturer, but could not be calibrated again during operation.

| Room ID | Room air temperature | Occupancy | Window control | Top window control | Sun protection | Electricity demand lighting | Electricity demand plugs | CO₂ Concentration |
|---------|----------------------|-----------|----------------|-------------------|---------------|---------------------------|-------------------------|------------------|
| E01     | E01Tair              | E01Occ    | E01W           | E01WT             | E01SP         |                           |                         | E01CO2           |
| E02     | E02Tair              | E02Occ    | E02W           | E02WT             | E02SP         |                           |                         | E02CO2           |
| E03     | E03Tair              | E03Occ    | E03W           | E03WT             | E03SP         |                           |                         | E03CO2           |
| E04     | E04Tair              | E04Occ    | E04W           | E04WT             | E04SP         |                           |                         | E04CO2           |
| E05     | E05Tair              | E05Occ    | E05W           | E05WT             | E05SP         |                           |                         | E05CO2           |
| E06     | E06Tair              | E06Occ    | E06W           | E06WT             | E06SP         | E06EIL                    | E06EIP                |                  |
| E07     | E07Tair              | E07Occ    | E07W           | E07WT             | E07SP         | E07EIL                    | E07EIP                | E07CO2           |
| E08     | E08Tair              | E08Occ    | E08W           | E08WT             | E08SP         |                           |                         | E08CO2           |
| E09     | E09Tair              | E09Occ    | E09W           | E09WT             | E09SP         |                           |                         | E09CO2           |
| E10     | E10Tair              | E10Occ    | E10W           | E10WT             | E10SP         |                           |                         | E10CO2           |
| E11     | E11Tair              | E11Occ    | E11W           | E11WT             | E11SP         |                           |                         | E11CO2           |

| Room ID | Room air temperature | Occupancy | Window control | Top window control | Sun protection | Electricity demand lighting | Electricity demand plugs | CO₂ Concentration |
|---------|----------------------|-----------|----------------|-------------------|---------------|---------------------------|-------------------------|------------------|
| W01     | W01Tair              | W01Occ    | W01W           | W01WT             | W01SP         | W01EIL                    | W01EIP                |                  |
| W02     | W02Tair              | W02Occ    | W02W           | W02WT             | W02SP         |                           |                         |                  |
| W03     | W03Tair              | W03Occ    | W03W           | W03WT             | W03SP         |                           |                         |                  |
| W04     | W04Tair              | W04Occ    | W04W           | W04WT             | W04SP         |                           |                         |                  |
| W05     | W05Tair              | W05Occ    | W05W           | W05WT             | W05SP         | W05EIP                    | W05CO2                |                  |
| W06     | W06Tair              | W06Occ    | W06W           | W06WT             | W06SP         |                           |                         |                  |

Table 2. Orientation and variables available for each office. *Note that no data file is provided for this sensor, because no event was recorded over the monitoring period.

| Categories of data | Subcategories of measured data | Variable | Interval | Sensor Range | Accuracy |
|--------------------|--------------------------------|----------|----------|--------------|----------|
| Inhabitants        | Other                          | Presence (all rooms) | Event | — | — |
|                    | Other                          | Window state (open/closed) | Event | — | — |
|                    | Other                          | Top-light window state (open/closed) | Event | — | — |
|                    | Other                          | State of sun protection (open/closed) | Event | — | — |
| Indoor conditions  | Hygro-thermal                  | Air temperature | 10 minutes | 0–40 °C | ±0.1 K |
|                    | Hygro-thermal                  | Relative humidity (all rooms) | 10 minutes | 0–100% | ±1% |
|                    | Indoor Air Quality             | CO₂ level (3 rooms) | 10 minutes | 300–3500 ppm | ±3% |
| External conditions| Hygro-thermal                  | Air temperature | 10 minutes | –40 to +45 °C | ±0.1 K |
|                    | Hygro-thermal                  | Relative humidity | 10 minutes | 0–100% | ±2% |
|                    | Visual                         | Illuminance (4 orientations + horizontal) | 10 minutes | 0–100,000 lx | ±5% |
|                    | Solar radiation                | Horizontal solar radiation | 10 minutes | 0–1300 W/m² | ±2.5% |
|                    | Other                          | Precipitation (Amount and event) | 10 minutes | — | — |
|                    | Other                          | Wind speed and direction | 10 minutes | 0–360° 0–20 m/s | — |
| Energy             | Heating/cooling                | Overall heat quantity pellet boiler and gas boiler | 10 minutes | — | ±1% |
|                    | Lighting                       | Lighting energy (3 meters for 5 rooms) | 10 minutes | — | ±0.5% |
|                    | Equipment                      | Plug loads separated by IT and other (3 rooms) | 10 minutes | — | ±0.5% |
|                    | Other                          | Total electricity use of building | 10 minutes | — | ±0.5% |

Table 3. Variables, their categories and subcategories according to the ontology for building monitoring¹³, and intervals.

**Code book.** File format: comma separated values file (.csv).

**Technical Validation**

Incoming datasets were analysed according to their completeness and validity. An error message was sent to the researchers in case these checks revealed problems. These analyses mainly targeted for checking availability of data and to filter implausible or missing values. Missing values in air temperature, relative humidity, and CO₂ concentration were marked by a value of “0” and filtered automatically. Implausible values, e.g. indoor air temperatures above 35 °C, were flagged by the monitoring software and manually inspected using the visualization tools of the monitoring software. The monitoring software used was MoniSoft¹¹.

The air temperature sensors were checked and calibrated during commissioning by the facility management and later comparison through a high-quality comfort meter equipment in sample rooms showed good conformity. All other sensors had been calibrated by the manufacturer, but could not be calibrated again during operation.
Usage Notes
By the general and open csv format the researcher is free to use whatever software s/he finds suitable for analysing or visualising the data. For comfort analysis the R-package comf is recommended12. For further analyses, it needs to be considered, that top window and blind states were either changed through the BMS or manually by occupants. The algorithm of automatic controls of top windows and blinds is unknown. The authors assume that it will be possible to identify automated and manual controls by means of statistical analyses.

Window state and blind status changes were recorded by the BMS and are available with their original time stamp. Blind events are all changes, i.e. also changes of blind position e.g. between 20 and 80% closing.

Note that the official monitoring period by the original research team ended in October 2006. After that, data was still automatically received, but the status of sensors not checked anymore. Therefore, the number of sensors having failures and not providing data continuously increases, which needs to be considered when using data points after 2006.

Code availability
Custom code was used to validate the incoming data from the BMS for completeness and validity. The code had been very specific according to the system configuration and is not available anymore. Its value for future applications or future data usage would be very low because 90% of the code was written to check the syntactically correctness of the data. While the authors expected such syntactical correctness being granted for data exported from a BMS, the first month of monitoring (not included in the database) showed several problems with the structure of the data, which required many lines of custom code, very specific to the BMS in place and therefore not generalizable to any other application.

Received: 8 May 2019; Accepted: 14 August 2019; Published online: 26 November 2019

References
1. Wagner, A. & Schakib-Ekbatan, K. User satisfaction as a measure of workplace quality in the office. In Work Environments: Design in Physical Space, Mobility, Communication (ed. Schmitt, C.) 54–57 (Basel: Birkhäuser Architektur, 2011).
2. Toftum, J., Andersen, R. V. & Jensen, K. L. Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions. Build. Environ. 44 (2009).
3. Schakib-Ekbatan, K., Wagner, M. & Lussac, C. Occupant satisfaction as an indicator for the socio-cultural dimension of sustainable office buildings development of an overall building index. in CISBAT, École Polytechnique Fédérale de Lausanne (2011).
4. Schweiker, M., Carlucci, S., Andersen, R. K., Dong, B. & O’Brien, W. Occupancy and Occupants’ Actions. In Exploring Occupant Behavior in Buildings (eds Wagner, A., O’Brien, W. & Dong, B.) 7–38 (Springer, 2018).
5. Hong, T., Taylor-Lange, S. C., D’Oca, S., Yan, D. & Corognati, S. P. Advances in research and applications of energy-related occupant behavior in buildings. Energy Build. 116, 694–702 (2016).
6. Kleber, M. & Wagner, A. Results of Monitoring a Naturally Ventilated and Passively Cooled Office Building in Frankfurt a M, Germany. In Proceedings of EPIC 2006 AIVC Conference: Lyon, France (2006).
7. Wagner, A., Kleber, M. & Parker, C. Monitoring Results of a Naturally Ventilated and Passively Cooled Office Building in Frankfurt, Germany: Int. J. Vent. 6, 3–20 (2007).
8. Schakib-Ekbatan, K., Zaktici, F. Z., Schweiker, M. & Wagner, A. Does the occupant behavior match the energy concept of the building? - Analysis of a German naturally ventilated office building. Build. Environ. 84, 142–150 (2015).
9. D’Oca, S. & Hong, T. Occupancy schedules learning process through a data mining framework. Energy Build. 88, 395–408 (2015).
10. Schweiker, M., Kleber, M. & Wagner, A. Long-term monitoring data from a naturally ventilated office building. Open Science Framework, https://doi.org/10.17605/OSF.IO/2YDZG (2019).
11. Kleber, M. & Wagner, A. Monitoring Low-Energy Buildings by a self-developed Software Tool. In Proceedings of the IBPC Conference in Istanbul, Turkey (2009).
12. Schweiker, M. comf: An R Package for Thermal Comfort. Studies. R J. 8, 341–351 (2016).
13. Mahdavi, A. & Taheri, M. An ontology for building monitoring. J. Build. Perform. Simul. 10, 499–508 (2017).

Acknowledgements
This research was supported by the German Federal Ministry of Economics and Technology (BMWi) with the project ID’s 0335007 F and 03ET1289B.

Author contributions
All authors provided feedback on all steps, especially critical feedback on the paper. M.S. prepared the data repository and wrote the paper. M.K. was involved in the data collection, data preparation and writing of the paper. A.W. was involved in the data collection and writing of the paper.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to M.S.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
