Calibrated Simulation Models for Indoor Comfort Assessment: The Case of a Healthcare Facility in Vienna

Luca Zaniboni –Free University of Bozen-Bolzano – luca.zaniboni@natec.unibz.it
Giovanni Pernigotto –Free University of Bozen-Bolzano – giovanni.pernigotto@unibz.it
Matthias Schuß –Vienna University of Technology – matthias.schuss@tuwien.ac.at
Kristina Kiesel –Vienna University of Technology – kristina.kiesel@tuwien.ac.at
Andrea Gasparella –Free University of Bozen-Bolzano – andrea.gasparella@natec.unibz.it
Ardeshir Mahdavi –Vienna University of Technology – bpi@tuwien.ac.at

Abstract

Design activity on healthcare buildings cannot be limited to the energy aspects and must account also for the indoor thermal comfort conditions. Indeed, the occupants of this category of buildings are affected by different kinds of unhealthy statuses and particular attention is required in order to ensure conditions adequate to therapies and medical treatments. Even if simulation can be a helpful tool in designing new buildings, also in case of complex clinics and hospitals, a proper calibration is a necessary step for the existing building stock. In this way, discrepancies between simulated and measured building energy performance and thermal behavior can be reduced, improving the reliability of the model itself and allowing its use for many purposes, from the assessment of energy performance to the evaluation of indoor thermal comfort.
In this work, experimental and numerical modelling activities have been performed in order to develop a calibrated model of part of a healthcare building in Vienna, Austria, for the assessment of both thermal performances and comfort conditions. The facility was built in the early '90s, with later expansions, and is composed of many environments characterized by different therapeutic activities. Many properties of the building envelope and system are unknown and initial values have been assumed from direct inspections and documentation on construction standards. After zoning the healthcare, for each ambient, long-term measurements of the air temperature were recorded every 10 minutes from March to June 2015 and used to calibrate the model. During the same period, occupants were interviewed about their thermal comfort sensations and detailed short-term measurements were collected to calculate Fanger's Predicted Mean Votes and Percentages of Dissatisfies. The simulated air temperature and internal surface temperature profiles have been used to evaluate the same indexes by comparing them with those calculated from the measured data and people's votes.

1. Introduction

Design and renovation of existing buildings into high efficiency ones require taking into account also the occupants' thermal comfort, which depend on both building's use and occupants' activity and personal conditions. Among different types of buildings, healthcare facilities are particularly critical to design, with the aim to ensure high standards of indoor comfort, since employees' and patients' comfort perceptions are different (Hwang et al., 2007; Khodakarami et al., 2012; Skoog et al., 2005; Verheyen et al., 2011). To this extent, building energy simulation, BES, can be a helpful tool to support the designers' activity. As regards existing facilities, however, simulation models require calibration. Only with a good estimation of input and boundary conditions, it is possible to simulate in an effective way the thermal comfort of healthcare environments' occupants.
To meet the design targets, moreover, BES codes have often to be coupled with optimization tools. For example, Ferrara et al. (2015a and 2015b) focused on school buildings and used GENOPT to run TRNSYS simulations aimed at optimizing a classroom from the point of view of both total energy demand and thermal comfort. Ascione et al. (2016) coupled EnergyPlus and a genetic algorithm

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2018. Building simulation applications BSA 2017. bu,press.
https://doi.org/10.13124/9788860461360
CC BY-SA

written with Matlab to optimize the hourly setpoint temperatures, based on weather forecasting and occupancy profiles, selecting the best solutions according to economic and comfort constraints. Arambula et al. (2017) exploited the genetic algorithm implemented in jEPlus+EA to calibrate and simulate an EnergyPlus model of an Italian school building.

In this work, a portion of a healthcare facility in Vienna, Austria, has been analyzed. After collecting short and long-term measurements, global comfort according to Fanger's model (ASHRAE 2013; ISO, 2005) has been assessed and contrasted with the results by interviews submitted to occupants. A TRNSYS model has been developed and calibrated by means of two steps: first, by comparison with the collected air temperature measurements, and then against the calculated Fanger's indexes - predicted mean votes, PMV, and predicted percentage of dissatisfied, PPD. After calibration, the developed model can be useful for several redesign tasks, encompassing the analysis of scenarios for long term thermal comfort optimization, able to manage effectively the discrepancies among the different occupants' perceptions and to minimize overall energy costs.

2. Methods

2.1 Case Study and Measurements

This study regards the "Physikalisches Institut Leopoldau" (Fig. 1), a private physiotherapy center, located on the ground floor of a 20-year old building in Vienna, Austria. The analysed area, equal to about 103 m^2, includes 22 therapy rooms, where therapies are performed from 7:00 am until 8:00 pm, from Monday to Friday.

Two kinds of measurements were collected: detailed short-term measurements and long-term measurements. Short-term measurements regarded air temperature, relative humidity, mean radiant temperature, and air speed. An Ahlborn ALMEMO 2590 system with 4 probes was used. The monitored quantities were recorded with accuracies of 0.1 °C for air and mean radiant temperatures, 2 % for relative humidity and 0.01 m s^{-1} for air velocity. Short-term measurements were repeated 3 times in all rooms of the therapy zone: on 12/03/2015 from 3:00 pm until 7:00 pm, on 25/03/2015 from 2:00 pm until 8:00 pm and on 21/04/2015 from 11:00 am until 4:00 pm. The time interval was set at 200 s for the first two measurement campaigns and 60 s for the last one.

Fig. 1 – Physiotherapy Center layout with the area of interest for this analysis highlighted in red

Long-term measurements of temperature were collected with 8 HOBO U12 data loggers and probes, with nominal accuracies of ±0.35 °C. Each sensor was positioned at a height of 1 m, chosen to match the need of registering air temperatures and relative humidity sufficiently representative of the indoor conditions, without disturbing the activities performed in the rooms. Considering an average duration of 30 minutes for treatments, a measurement time-step of 10 minutes was set. The measurement campaign started on 08/03/2015 and ended on 18/06/2015. The collected data were compared first with short-term measurements, in order to check the presence of errors. Furthermore, short-term measurements were used to derive correlations for the estimation of the mean radiant temperature, not directly recorded during the long-term campaign.

2.2 Questionnaires

In order to evaluate the employees' and patients' opinions about comfort conditions, questionnaires were based on ASHRAE 7-points thermal sensation scale and developed according to ASHRAE Standard 55 (2013), ISO 7730 (2005), and other previous case studies in the literature (Azizpour et al., 2013; Huang et al., 2007; Skoog et al., 2005; Van Gaever et al., 2014; Verheyen et al., 2011). Date, time, and room where therapy was performed were asked, in order to match the answers with the measurements in the data analysis. The questionnaires were divided into three sections, one to be filled in by the employee (section A) and two by the patient, before (B) and after the therapy (C). All sections included questions about the opinion on the temperature when completing the survey ("too cold", "cold", "slightly cold", "neutral", "slightly warm", "warm", "too warm").

2.3 Simulation Model Definition

The simulation was performed using TRNSYS 3D 2017, while the calibration was made partially manually and by means of the software GENOPT. The analysis included only one thermal zone, the area with therapy rooms located in the old part of the building, highlighted in Fig. 1. The model was prepared using Google SketchUp (Fig. 2), and imported into TRNSYS 17.

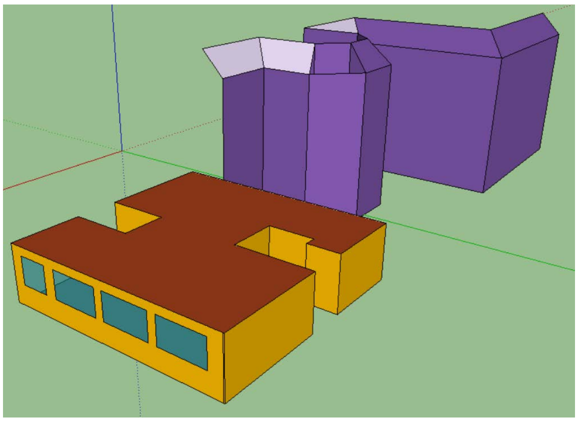

Fig. 2 – The 3D model of the analyzed area of the physiotherapy center prepared by Google SketchUp 8

The weather data were provided by the ZAMG (Zentralstalt für Meteorologie und Geodynamik), the Austrian central office of meteorology and geodynamic, and included dry bulb temperature and global horizontal irradiation in Vienna from 1 March to 30 June 2015, with a 10-minute time-step.

A first hypothesis about the walls composition was made looking at the building schematic plans and sections. The walls were set as slightly externally insulated (5 cm of polystyrene) and made of 25 cm of concrete. The initial values of the thermal conductivity, density and thermal capacity of the layers materials were taken from ISO 10456 (ISO, 2008). Initial convection factors were set according to the standard pre-set values used by TRNSYS. Solar absorptance was set to 0.3 for walls and ceiling, and 0.6 for the floor. All surface emissivity were set equal to 0.9. The thermal bridges initial values were taken from UNI 14683 (UNI, 2008), considering the internal dimensions. The windows were analyzed in a previous work (Zaniboni et al., 2016a and 2016b), which involved in-situ survey and modelling of glazing parameters by means of LBNL Window 6, considering two layers of 4 mm clear glass separated by 32 mm air gap. Internal shading devices were modelled but no control was implemented since they were used for most of the time for privacy reasons. The ventilation rate was calculated equal to 2.64 ACH, taking the values recommended by UNI 10339 (1995) for physical therapies and daily staying.

Three types of internal gains were present: 1. lighting gains; 2. electrical gains due to other electrical equipment (comprising also the therapy machines); 3. metabolic gains due to the people's activities in the facility. The lighting system and electrical equipment were monitored in detail. For the first one, the capacity installed in each room, together with its utilization factor, was already known (Zaniboni et al., 2016a) and the corresponding thermal gain was set at 60 % radiative and 40 % convective. On the contrary, the utilization factors of the electrical equipment were more uncertain and set to be able to match with the overall electrical energy recorded for the whole facility for some weeks. In this case, the heat gain was set half convective and half radiative. Averaging the thermal gains by patients and employees estimated starting from their metabolic rates, first attempt values of 52 W per occupant were set for each of the convective and the radiative part. Since the occupancy profiles of the building were known, the total gains from the metabolic rate were calculated from the sum of the gains from the patients and therapists who were present.

No data about the heating system were available and, consequently, heat capacity was modelled as ideal, half radiative and half convective, and without nighttime or weekend setbacks, since the focus of the analysis was put on the occupancy period. The system ON/OFF control was modelled with TRNSYS Type 2, a function switching the system ON and OFF if the air temperature overpasses the temperature setpoint plus or minus a default band. The band was set to 0.5 °C and the temperature setpoint was set to 24 °C, coherently with observations on the measured air temperature profiles.

2.4 Simulation Model Calibration

Since many uncertain variables were present, a preliminary sensitivity analysis was performed. It was decided, concerning the materials of opaque components, to calibrate the most affecting properties, i.e. the conductivity of the insulation layer and the specific heat capacity of the massive concrete layer. All convection coefficients were calibrated while all absorptance and emissivity were left equal to their initial values. Regarding the windows, only the thermal transmittance of frames was calibrated since the glazing properties were already assessed in a previous study (Zaniboni et al., 2016a). Among thermal bridges, only those between the window's frame and the surrounding opaque component were involved in calibration. The internal gains, the lighting ones, were not calibrated, since they had already been determined with sufficient precision in a previous contribution (Zaniboni et al., 2016a). On the other hand, the gains from other electrical equipment and occupants required calibration. The same held for the air-change rate by infiltration and ventilation and for the equivalent air specific heat capacity, which was varied to take into account the effect on thermal inertia of additional internal elements, such as furniture. Finally, setpoint temperature was calibrated while the ON/OFF band range was not.

Material properties were varied by 50 %, because of the lack of knowledge about the material conditions. Assuming a poor ventilation rate, confirmed also by negative answers about indoor air quality in questionnaires, air-change rate was varied from 0.15 to 2.64. The equivalent air specific heat capacity was varied from 0.812 to 5.012 kJ kg^{-1} K^{-1} and setpoint temperature was varied between 21 and 27 °C. All other parameters were changed by 30 %.

Considering that the temperature setpoint was the most impactive variable, in order to minimize the calibration time and optimize the GENOPT code, it was manually calibrated first, with a step of 0.5 °C. The value leading to the minimization of the root mean square difference, RMSD, with respect to the long-term air temperature measurements (i.e. from 09/03/2015 to 18/06/2015, weekends excluded), was adopted and the remaining variables calibrated with GENOPT. Ten steps were set per each variable, with 90 particles and 100 generations, which means a total of 9000 simulation attempts.

2.5 Simulation Model Validation Through Comfort Indexes

PMV and PPD indexes (ASHRAE, 2013; ISO, 2001 and 2005) were derived from both measured and simulated data during occupancy time in order to validate the calibrated model. In both cases, a metabolic rate of 2 met was assigned to employees while 1 met was assumed for patients (ASHRAE, 2013; ISO, 2005). The clothing level values were determined from the answers to the questionnaires according to ASHRAE Standard 55 (ASHRAE, 2013).

Regarding the indexes calculated from measurements, air temperature, and humidity, they were taken from long-term measurements while the mean radiant temperature was estimated as functions of the air temperature. Specifically, we used only regression models derived from short-term measurements correlating mean radiant and air temperatures with indexes of determination R^2 larger than 0.7. When those models were not available, i.e. for therapy rooms 9, 11, 12, 13, and 14,

mean radiant temperature was assumed equal to air temperature. Short-term measurements of air speed were used as average conditions in calculations.
Considering the indexes determined from simulations, TRNSYS temperature outputs were used in calculations, together with average humidity and air speed by measurements. Since one thermal zone was simulated, we determined the mean radiant temperature as an area-weighted average of simulated surface temperatures of externally exposed components (i.e. floor, ceiling, windows, external walls) and internal components assumed at a simulated air temperature.
Finally, in both cases, the PMV and PPD, evaluated at the same time in which votes were collected, were compared for both patients and employees.

3. Results

3.1 Calibration

After calibration, RMSD decreased from 1.86 °C to 0.92 °C. The calibrated variables and the values reached after the calibrations are reported in Table 1. The profile of the measured and simulated air temperature inside the thermal zone are reported in Fig. 3, during the whole period and for 20 days at the end of March.

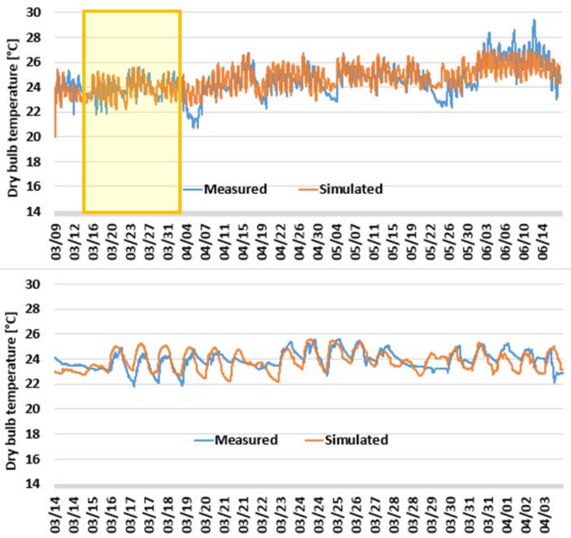

Fig. 3 – The comparison between the air temperarure profiles (measured and simulated) during the whole period and for the last 20 days of March, 2015

Table 1 - List of the variables varied in calibration

Variable	Initial	Final
Thermal conductivity (insulation layer) [W m^{-1} K^{-1}]	0.044	0.062
Linear thermal resistance of wall-window thermal bridge [m K W^{-1}]	2.232	1.339
Specific heat capacity of massive concrete layer [kJ kg^{-1} K^{-1}]	1.000	1.000
Internal surface wall convection coefficient [W m^{-2} K^{-1}]	3.056	3.056
External surface wall convection coefficient [W m^{-2} K^{-1}]	17.778	22.044
Internal surface ceiling convection coefficient [W m^{-2} K^{-1}]	0.700	0.826
Internal surface floor convection coefficient [W m^{-2} K^{-1}]	0.694	0.694
Window's frame thermal transmittance [W m^{-2} K^{-1}]	1.667	1.267
Internal gains by electrical equipment [W]	696.50	487.55
Internal sensible gains by occupants [W]	52.00	39.52
Air-change rate [ACH]	2.640	0.897
Setpoint temperature [°C]	24.0	26.0
Equivalent air specific heat capacity [kJ kg^{-1} K^{-1}]	1.012	2.312

As we can observe, the main discrepancies regard nighttime and weekends. This may be caused by the presence of a nighttime and weekend setback, neglected in the current calibration, which focused on the occupation period. Larger differences can be detected also in some days in June. In this case, the source of deviations may be related to solar gains and shading.

3.2 PMV and PPD Indexes

Analyzing the collected long-term measurements, air temperature resulted always between 23 °C and 25 °C during the occupancy time. The comparison with short-term measurements, confirmed that temperatures were within the range of 24 - 26 °C and showed that relative humidity was in the range of 25 – 55 %. Air speed was very slow and well under the 0.2 m s^{-1} and 0.1 m s^{-1} was taken as a reference for thermal comfort calculations. 83 questionnaires were collected for the interested area.

The comparison between the PMV and PPD indexes at the time in which questionnaires were filled in by the occupants and the corresponding votes is reported in Fig. 4. Considering the patients, there is a good agreement between the average values of comfort indexes evaluated from measurements, votes collected by questionnaires and indexes calculated from the simulated model. On the contrary, there are discrepancies when considering the employees, with the average PMV calculated from measurements slightly larger than average PMV calculated from simulation outputs and both significantly larger than the employees' votes. As a whole, comfort indexes overestimate the fraction of the dissatisfied employees.

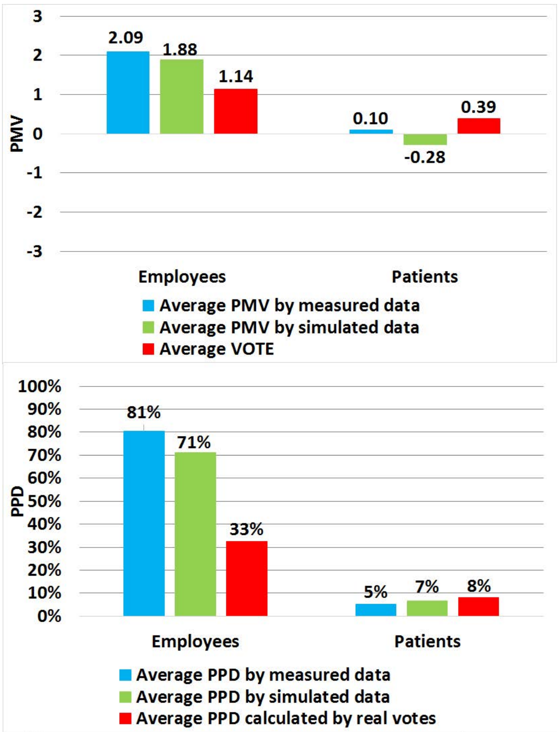

Fig. 4 - Comparison among PMV and PPD indexes obtained by measured and simulated internal temperatures and real votes

The same quantities are represented in box and whiskers charts in Fig. 5. They show that, in the case of the employees, interquartile range is significantly larger for real votes, while it has approximately the same size for PMV. Considering the patients, the three interquartile ranges are more homogeneous.

Fig. 6 reports a comparison between average hourly PMV and PPD indexes calculated by measured and simulated data. In this case, the indexes do not refer to the time in which the employees and the patients compiled the questionnaires but to the whole occupancy time. Also in this case, the two groups of indexes are similar. A slightly overestimation of PMV and PPD calculated by simulation data can be registered in the morning but the trend is reversed during the afternoon.

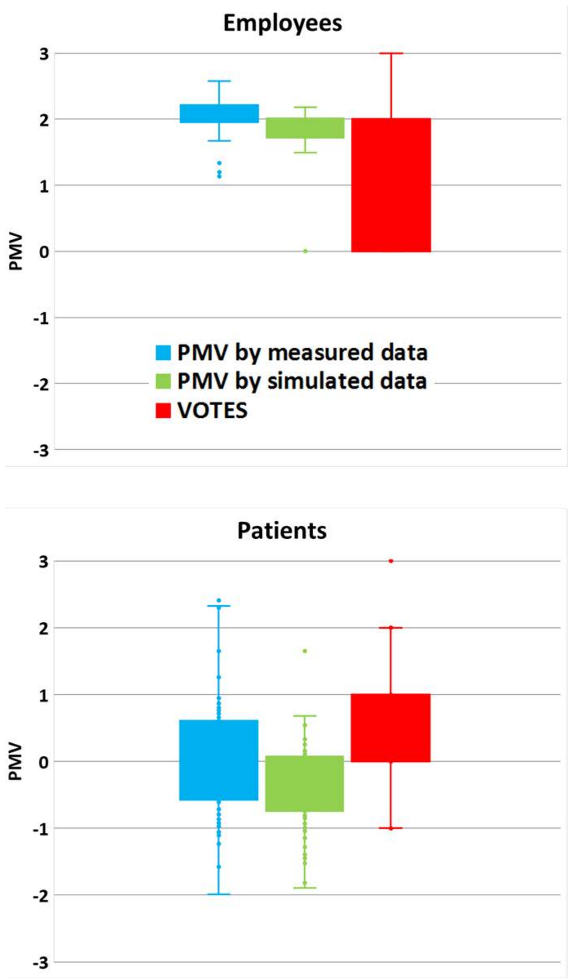

Fig. 5 – Comparison among PMV and PPD indexes obtained by measured and simulated internal temperatures and real votes – box and whiskers chart

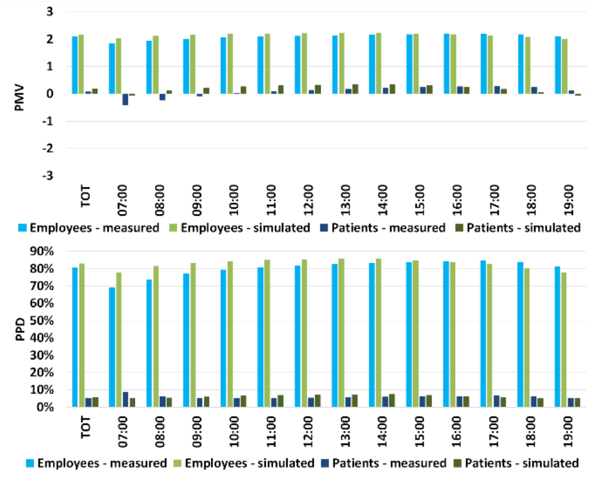

Fig. 6 – Hourly and daily comparison between PMV and PPD indexes obtained by measured and simulated internal temperatures

4. Conclusion

In this work, a calibrated model for a thermal zone of a healthcare building in Vienna, Austria, was developed for the assessment of both thermal behavior and comfort conditions. Many properties of the building envelope and system were not known and initial values were assumed from direct inspections and documentation on technical standards. Air temperature measurements taken during the months of March, April, May and June 2015 were used to calibrate the model. During the same period, the occupants were interviewed about their thermal comfort sensations and detailed short-term measurements were collected to calculated Fanger's Predicted Mean Votes and Percentages of Dissatisfies. Simulated air and surface temperature profiles were used to evaluate the same indexes, then compared to the ones calculated by the measured data and people's votes for validation purposes.

Thanks to these analyses, we observed that, although we started with a limited amount of data, it was possible to develop a calibrated model able to estimate, with sufficient accuracy, the Fanger's indexes for the considered thermal zone and allow for further analyses regarding retrofitting and control strategies.

Acknowledgements

This study has been funded by the project "Klimahouse and Energy Production" in the framework of the programmatic–financial agreement with the Autonomous Province of Bozen-Bolzano of Research Capacity Building. The authors kindly thank the Zentralanstalt für Meteorologie and Geodynamik (ZAMG) for providing the meteorological data.

References

Arambula Lara, R., E. Naboni, G. Pernigotto, F. Cappelletti, Y. Zhang, F. Barzon, A. Gasparella, P. Romagnoni. 2017. "Optimization Tools for Building Energy Model Calibration". *Energy Procedia* 111:1060-1069. doi: 10.1016/j.egypro.2017.03.269.

ASHRAE. 2013. *ASHRAE Standard 55: Thermal environmental conditions for human occupancy.* Atlanta, U.S.A.: ASHRAE.

Ascione, F., N. Bianco, C. De Stasio, G.M. Mauro, G.P. Vanoli. 2016. "Simulation-based model predictive control by the multi-objective optimization of building energy performance and thermal comfort". *Energy and Buildings* 111: 131-144. doi: 10.1016/j.enbuild.2015.11.033.

Azizpour, S., S. Moghimi, E. Salleh, S. Mat, C.H. Lim, K. Sopian. 2013. "Thermal comfort assessment of large-scale hospitals in tropical climates: A case study of University Kebangsaan Malaysia Medical Centre (UKMMC)". *Energy and Buildings* 64: 317–322. doi: 10.1016/j.enbuild.2013.05.033.

Ferrara, M., M. Filippi, E. Sirombo, V. Cravino. 2015. "A simulation-based optimization method for the integrative design of the building envelope". *Energy Procedia* 78: 2608-2613. doi: 10.1016/j.egypro.2015.11.309.

Ferrara, M., E. Sirombo, E. Fabrizio, M. Filippi. 2015. "Comfort filters in a total energy demand optimization method for the passive design of a building". *Energy Procedia* 83: 418-427. doi: 10.1016/j.egypro.2015.12.161.

Hwang, R.L., T.P. Lin, M.J. Cheng, J.H. Chien. 2007. "Patient thermal comfort requirement for hospital environments in Taiwan". *Building and Environment* 42: 2980–2987. doi: 10.1016/ j.buildenv.2006.07.035.

ISO. 2001. *ISO 10551. Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales.* Geneva, Switzerland: ISO.

ISO. 2005. *ISO 7730:2005. Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*. Geneva, Switzerland: ISO.

ISO. 2008. *ISO 10456. Building materials and products – Hygrothermal properties – Tabulated design values and procedures for determining declared and desigh thermal values*. Geneva, Switzerland: ISO.

Khodakarami, J., N. Nasrollahi. 2012. "Thermal comfort in hospitals – A literature review". *Renewable and Sustainable Energy Reviews* 16: 4071– 4077. doi: 10.1016/j.rser.2012.03.054.

Skoog, J., N. Fransson, L. Jagemar. 2005. "Thermal environment in Swedish hospitals: summer and winter measurements". *Energy and Buildings* 37: 872-877. doi: 10.1016/j.enbuild.2004.11.003.

UNI. 1995. *UNI 10339. Air-conditioning systems for thermal comfort in buildings – General, classification and requirements – Offer, order and supply specifications*. Milan, Italy: UNI.

UNI. 2008. *UNI EN ISO 14683. Thermal bridges in building construction - Linear thermal transmittance - Simplified methods and default values*. Milan, Italy: UNI.

Van Gaever, R., V.A. Jacobs, M. Diltoer, L. Peeters, S. Valanduit. 2014. "Thermal comfort of the surgical staff in the operating room". *Building and Environment* 81: 37-41. doi: 10.1016/j.buildenv.2014.05.036.

Verheyen, J, N. Theys, L. Allonsius, F. Descamps. 2011. "Thermal comfort of patients: Objective and subjective measurements in patient rooms of a Belgian healthcare facility". *Building and Environment* 46: 1195-1204. doi: 10.1016/j.buildenv.2010.12.014.

Zaniboni, L., K. Kiesel, M. Schuß, G. Pernigotto, A. Gasparella, A. Mahdavi. 2016. "Evaluation of on-site PV-based electrical energy production: a case study". In: *Proceedings of the 12th REHVA World Congress 2016*. Aalborg, Denmark.

Zaniboni, L., K. Kiesel, M. Schuß, G. Pernigotto, A. Gasparella, A. Mahdavi. 2016. "Indoor evaluation of a health care facility: a case study". In: *Proceedings of the 12th REHVA World Congress 2016*. Aalborg, Denmark.