



AALBORG UNIVERSITY
DENMARK

Aalborg Universitet

CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 6

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). *CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 6*. Department of Civil Engineering, Aalborg University.

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Key figures for joint assessment of indoor environmental quality (IEQ) and energy consumption in modern buildings – a literature review

Ana Tisov^{#1}, Jan Siroky^{*2} and Jakub Kolarik^{#3}

[#]*Department of Civil Engineering, Section for Building Energy, Technical University of Denmark, Kgs. Lyngby, Denmark*

¹ana.tisov@gmail.com

³jakol@byg.dtu.dk

^{*}*ENERGOCENTRUM PLUS, s.r.o., Prague, Czech Republic*

²jan.siroky@energocentrum.cz

Abstract

Energy efficiency in buildings should not be reached on the expense of indoor environmental quality (IEQ). This statement is often used in connection to design and certification of sustainable buildings. The fact that it is also valid during the actual operation seems to be often forgotten. Nodaway's energy management and operational diagnostics focus mostly on energy consumption. Consequently also present key figures comprise performance indicators related to energy use. The fact that modern buildings are not spared from IEQ related problems indicates that there is a need for joint assessment of energy and IEQ performance. The aim of this paper was to review relevant literature to form a scientific background for development of key figures enabling the joint assessment of energy and IEQ. The review resulted in forty cited publications. Majority of them focused explicitly on energy performance and indoor environment was mentioned only marginally or was not mentioned at all. We can also conclude that energy related key figures are well established and used for standard energy management as well as in different optimization algorithms involving analysis of measurements and calibrated simulations. One publication was identified that integrates thermal comfort into broader matrix of key figures. Methods for long-term evaluation of IEQ indicators suggested by standard EN 15251 seems to be usable for determination of key figures for joint assessment. Further research is needed to determine and test key figures that would directly combine performance indicators related to both energy use and IEQ.

Keywords – *key figure, performance indicator, energy management, indoor environmental quality, operational diagnostics*

1. Introduction

Energy efficiency in buildings should not be reached on the expense of indoor environmental quality (IEQ). This statement is often used in connection to design and certification of sustainable buildings. The fact that it is also valid during the actual operation of buildings seems to be often forgotten. Today's buildings are frequently equipped with a sophisticated Building Management System (BMS) that is capable of

detailed monitoring of both IEQ and energy consumption. However, collected data are seldom used for proper “operational diagnostics”. Additionally, even if this is the case, current focus is mostly on energy consumption, while IEQ parameters are expected to be within a “reasonable range”. The attention is paid to them only when building occupants complain about a specific problem. Then the focus is to solve the particular complain and it is very rarely that indoor climate is analyzed in broader perspective. At the same time, proper and detailed analysis of measured data collected by BMS can be used to answer several important questions. For the first – on the level of particular building – it can be investigated, whether energy is utilized effectively, thus whether the operation of HVAC systems provides comfortable indoor environment. For the second – for large amount of buildings – it can be investigated, which parameters influence the relationship between energy consumption and provided IEQ. For example influence of building type, age or type of utilized HVAC system on general ability of buildings to provide comfortable indoor environment can be studied. To ensure effective analysis of BMS data with respect to both IEQ and energy consumption it is necessary to identify suitable key figures that will enable such joint assessment. Key figures are currently commonly used in energy management; for example the most frequent one [energy consumption for heating]/[m² of heated area] does not take indoor environment into account. The aim of this paper was to review relevant literature regarding analysis of building energy consumption as well as studies focused on field evaluation of IEQ to form a scientific background for development of key figures enabling joint assessment of energy and IEQ performance.

2. Methods

The literature review presented in the current paper was conducted using the Web of Science database accessed via license of the Technical University of Denmark. Following keywords were used for a primary search (the keywords were consequently used in different combinations, combinations used in the primary search are also listed): *operation diagnostics, building operation optimization, energy performance, commissioning, commercial building*, energy management, thermal comfort [AND] field study, indoor environmental quality [AND] energy performance, data management [AND] BMS system* [AND] analysis, visualization tool*, energy use [AND] climate, degree day method, EN 15251, simulation model*, performance metrics* [OR] indicator*, regression analysis*. The identified articles were structured into four main areas according to their main topic: Energy Management, Commissioning, Operation Diagnostics, Indoor Environmental Quality (IEQ) studies and Standards and Legislation. In the paper, first general characteristics of reviewed articles in particular areas are summarized. Consequently, the details regarding both energy related and IEQ related key figures identified in the reviewed papers are discussed.

3. Results and discussion

3.1 General overview

Energy Management in buildings is practically based on analysis and controlling of a range of suitable key figures [1]. Those are, however, almost exclusively related to energy use and/or production in buildings. Current building regulations obviously promote importance of energy savings in buildings. In European Union for example, this is supported by implementation of the Energy Performance of Buildings Directive (EPBD) directive introducing energy rating schemes for new and existing buildings [2]. Energy consumption of newly designed or existing building can be estimated by using simulation models [3 - 7]. Donnell et al. [3] introduced a “scenario-modeling method” prediction of energy performance during design phase by means of simulation models. Moreover, during commissioning and operation phase, measured data provided by BMS system can be used to “fine tune” the simulation model. Costa et al. [4] points out such models can be used for optimization of energy performance during whole operational life of a building. However, in order to achieve sufficient accuracy an extensive measurement framework has to be available in order to gather data for model calibration. Additionally a study by Carling et al. [8] emphasizes that significant resources are needed in order to build accurate simulation models, which leads to higher costs and that accurate models tend to be associated with long computation time. Publications by Zhao and Magoules [5], Catalina et al. [9] and Lam et al. [10] present further methods for building energy prediction. These include statistical (regression) method [9, 10], use of support vector machines, grey box modeling and application of neural networks [5]. In the aforementioned publications the models were mostly used for research purposes. In “daily” (nowadays well established) energy management [11] rather the degree-day method [12, 13] and the bin method [14] for forecasting and comparison of energy consumption are used. These methods are popular due to their simplicity and are accurate for rough estimations, but as described in [14] the user should be aware of their limitations. Despite the popularity there exists also a criticism with respect to accuracy of aforementioned methods related to precise estimates of building performance [5, 9]. This criticism led into attempts for additional improvements, like for example so called wet-bulb cooling degree method presented by Krese et al. [13] whose results showed that the improved wet-bulb cooling degree method outperformed the traditional cooling degree day method in the majority of analyzed cases.

As it can be seen from several case studies conducted as a part of IEA Annex 40 [8, 16, 17] building information and control systems in modern buildings mostly fulfill “monitoring” function and are able to illustrate dynamics of building operation like changes in internal gains and weather dependent loads, but do not allow direct and easy analysis of causes for changes in building behavior. Such analysis often requires export of logged data and their time consuming processing by means of additional analytical tool. Therefore, the level of detail and accuracy of such analysis can vary from one building to another, which makes it hard to perform reliable comparison [3].

Commissioning and Operation Diagnostics are two terms whose meaning may, to some extent overlap [11]. According to [18] the commissioning process is often applied when building is taken into operation, before it is handed to an owner. The authors indicate that in the contrary to the current situation, commissioning should be

continuously repeated through whole life cycle. The report defines four types of commissioning: initial, retro-, re- and on-going- commissioning process. Authors conclude that if commissioning process is performed in such structured and continuous manner it helps to bridge gaps between different aspects like for example expectations of the owner (expressed in the design project) and current performance of the building [18]. Nowadays, dynamic simulation models have a potential to be used as a part of commissioning process [3, 4, 19]. Deviations between design simulation and simulation calibrated with measured data can be thus used to indicate a need for commissioning measures [19]. Differences between model output and real measurement data can be also used for fault detection [8, 16, 19]. Bauman [17, 20] specifies Operation Diagnostics as a process of inspecting building and system operations in order to reduce energy consumption while still maintaining thermal comfort. Thus the aim of operation diagnostics is to find faults and reasons for poor operation through the analysis of data provided by BMS and suggest optimization measures. This description strongly reminds goals that can be defined for ongoing commissioning; however, Bauman explicitly mentions one indoor environmental parameter – thermal comfort. Review of identified case studies [3, 17, 20] reveals that monitoring of BMS data provides large amount of data readings (caused by both large amount of registered data points and relatively short logging intervals), which needs to be “manually” analyzed, because BMS system self does not offer any preprocessing. Bauman [17] draws attention to the fact that there is a lack of common methods that can be used to assess the data. Fault detection and diagnostic (FDD) seems to be a driving force in efforts to change the current situation [11, 21]. Yu et al. [22] reviews FDD methodologies for ventilation systems while Bonvini et al. [23] deals with an algorithm for both whole-building and component-level FDD. Katipamula and Brambley [24] proposed an automated FDD method for HVAC system. A single dominant fault in the system could be found automatically without manually analyzing high amount of data. Major limitation of the aforementioned method was that if multiple faults occurred at the same time the FDD method failed. Nevertheless, operational diagnostics should include more than rigorous diagnostics of evident faults in the HVAC system. It should be also able to detect less visible and slight derivations from expected/required performance. For example “chronically low” morning temperatures in offices towards north would not be necessarily classified as a fault, but they certainly mean aggravated performance.

Indoor Environmental Quality (IEQ) studies reviewed in relation to building energy management would obviously provide valuable input regarding determination of common key figures. However, we could only identify IEQ studies dealing strictly with analyses of indoor environmental conditions without taking energy consumption into account [25, 26]. Despite this fact, the IEQ studies provide valuable information on which indicators should be considered in the case of joint assessment. Kim and Haberl [27] conducted a comprehensive study of sixteen IEQ parameters based on ASHRAE/CIBSE/USGBC Performance Measurement Protocols [28]. Large amount of measurement data was presented on a psychrometric chart, which provided effective visualization. Since BMS normally do not provide information on specific IEQ parameters like TVOC concentration or room air velocity, a comprehensive

instrumentation cart was used in the study. Portable instruments have to be placed in a building when there is a need for deeper analysis. Even though advanced instrumentation chart does not represent a common tool used by environmental systems operators, the method using the psychrometric chart for display of large amounts of measured data seems to be interesting way of providing overview regarding thermal environment in the building. On the other hand it is not suitable when a simple key factor should be determined. Dols et al. [29] indicated a need to implement indoor air quality (IAQ) commissioning as a part of a general commissioning process due to the growing awareness of importance of good indoor climate. As part of the indoor environmental measures, authors proposed detailed measurements of the HVAC system and building's indoor climate after a month of use. The article does not address any IAQ commissioning during the later time of building operation in the case that there no direct indications of aggravated indoor environment occur (for example in a form of occupant complaints, etc.).

Standards and legislation should obviously create framework to support operational diagnostics of buildings, as they define recommendations and requirements for both energy consumption and indoor environment. The EPBD [2] is a very good example, because it prescribes energy certificates for new and existing buildings, but at the same time a standard dealing directly with IEQ conditions has been issued under its umbrella [30]. Relation of the EPBD to ongoing commissioning has been widely discussed in report produced by the "Building EQ" project [31]. As authors of its final report point out, nowadays, after the certification, usually there is no continuous evaluation of the building performance in order to reach or maintain an energy-efficient operation. This results in aggravated performance. Authors conclude that in the case of for existing buildings there is a lack of alignment between requirements prescribed by energy certification methodology applied for continuous commissioning. Similarly, also several publications reviewed in the present paper indicate a lack of consistent methodology. For example the findings of Donnell et al. [3] show that in practice for commercial buildings there was a lack of standardized methods for operation checking that would include all necessary information - guidelines and tools necessary for analyses. A study by Attia et al. [15] revealed that buildings analysts in general have different knowledge, background, training and education and rarely have skills and training specifically required for the optimum building management. According to Andre et al. [32] there is a need for proper benchmarking to support building performance analysis, which would allow for comparison of actual key figures to a reliable reference.

On the other hand, there exist several comprehensive publications, which can serve as guidelines for commissioning analyses [14, 18, 31, 33]. Donnell et al. [3] point out the fact that guidelines are often interpreted differently by individual building managers. There seems to be lack of standardized process that would lead to structured, efficient analysis. Donnell et al. [3] describe that most of current performance benchmarks fail to contain enough meta-data for a comparison with systems in a specific building since they usually originate from perspective code compliance. Similar is for energy performance guidelines, which are done externally, where

requirements are defined by obtaining results from whole-building energy simulation models or even by a rule of thumb. On the contrary Andre et al. [32] sees benchmarking as reliable and adaptable. Attia et al. [15] interviewed practitioners dealing with building performance optimization. The study showed that there was a lack of standard systematic approach since in most cases the practitioners followed different methods for analysis. Attia et al. point out that missing standard that would help building managers when analysing and transforming BMS data to useful information leads to unreliability, mistrust, and inaccurate building performance information.

3.2 Building energy key figures

Key figures have been extensively used in energy management for many years to evaluate whether the energy consumption develops reasonably along time, evaluate consequences of energy saving measures or perform comparison with requirements and planned targets. In general, energy consumption can be relatively simply presented as time-series plot and such visualization already has high informative value [31]. Energy consumption is also commonly presented as monthly heating/cooling primary energy consumption [34] per area unit (kWh/m^2) or per heated building volume (kWh/m^3) [31]. So called energy signature – a linear curve presenting average monthly energy consumption plotted against the average monthly outdoor temperatures complemented with so called basic consumption, which is outdoor temperature independent [18, 21, 31]. Visualization of energy signatures is often implemented in BMS or control systems. Several publications mention so called “carpet plots” as useful tool providing detailed overview about energy consumption, often diversified to heating and/or cooling [16, 17, 31, 35]. Jagemar and Olsson [31] mention also other examples of key figures like energy consumption per number of occupants. In general, many performance indicators can be used as a denominator to determine a specific key figure. Their use can be very “industry dependent” like for example MJ/hospital-bed day. Catalina et al. [9] uses energy consumption of buildings of different age against average U-value of their envelope. Moreover, the study investigated also correlation between energy consumption and building morphology by introducing so called building shape factor (a ratio between heated volume of a building and an area of all surfaces that are in contact with exterior, ground or non-heated spaces). Several publications conducted comparison of measured and simulated energy consumption based on monthly values to identify reasons for aggravated performance indicated by measurements [9, 19, 35, 36]. Such a method is gaining increasing attention especially in the USA [19, 21], but IEA Annex 40 [18] presented also several case studies from Europe. Detailed analysis of data regarding HVAC systems as well as improving their operation by resolving malfunctions has been shown by several publications [16 - 18, 35] to lead to notable energy savings. One concrete example can be analysis of energy consumption “per component” (chiller, fan etc.) in relation to occupancy schedule.

3.3 Key figures and performance indicators related to IEQ

Measured BMS data regarding energy consumption and operational parameters are commonly analyzed during operation diagnostics whereas as from IEQ parameters only

room air, respective operative temperature are normally considered. The reason for that is mainly that temperature measurements are relatively easily available. Case studies presented in [17, 18] analyzed operative temperature data by means of carpet plots. By using the carpet plot it was possible to observe for a certain time of the year indoor temperature a thermal comfort behavior and see when operative temperature exceeded certain acceptable range. The carpet plots were also used by Baumann [17]. His analysis of data obtained from BMS showed several malfunctions of a heating system. The room temperature data were used together with operational data on heating coil valve position and heating coil pump operation. Costa et al. [4] suggested using predicted and measured CO₂ values to evaluate a real occupancy pattern, which can be further used in energy-IEQ related analyses. Kim and Haberl [27] conducted comprehensive IEQ inspections and measurements done in buildings where the occupants complained about bad indoor environment. As mentioned earlier authors proposed an analytical method where measured data were displayed on a psychrometric chart. They claimed that it had a potential to improve the use of continuously measured IEQ data and benchmarking procedures which are required in [28] to validate design decisions. Annex F in European standard EN 15251 [30] describes three methods that can be used for evaluation of simulated or measured long-term IEQ data. These methods seem to be suitable to produce desirable IEQ performance indicators, but it seems that they are not widely used in practice. "Method A" defines percentage hours outside the required comfort range. It presents a simple method, which can be easily visualized by means of a duration diagram. "Method B" proposes calculation of so called Degree Hours, which represent sum of hours during which the temperature requirements were violated (separately for heating and cooling period) multiplied by a weighing factor expressed as a difference (in °K) between actual and limit temperature. "Method C" is similar to method B, but comfort range is defined by means of Predicted Mean Vote (PMV) index, while weighing factor is defined as a ratio between Predicted Percentage of Dissatisfied (PPD) corresponding to actual and comfort-limit PMV values.

4. General discussion

The literature review described in the present paper showed that main focus of building performance analyses conducted so far seems to be energy performance. This is somewhat understandable when considering the fact that reduction of greenhouse gases and preservations of fossil fuel resources are currently top political agenda with respect to sustainable development [38]. Furthermore energy performance optimization represents also a large potential for saving operation costs. According to Katipamula and Brambley [24] commercial buildings in the USA waste about 15% to 30% of energy they "buy". In contrast to publications dealing explicitly with energy performance, in very few articles the IEQ was considered during the analysis. None of the articles dealt with energy performance in direct connection to IEQ conditions prevailing in the building. Key factor methodology defined by Costa et al [4] should support energy managers in determining the optimal building operation strategy in relation to both energy consumption and thermal comfort. It was based on utilization of

calibrated simulation model. The method seems to provide promising results, however requires comprehensive measurements. Moreover, as thermal comfort metric was based on the PPD index, its determination in practice would be burdened by assumptions with respect to clothing of occupants, their activity level and air velocity in building premises [25]. The reviewed articles that represented IEQ studies exclusively dealt with assessment of indoor climate without taking energy use into account. When looking at the reviewed case studies, they mostly dealt with identification of major factors that influence energy consumption or with operation diagnostics of buildings, which should determine an “optimization potential”. With respect to IEQ, only operative temperature and/or CO₂ concentration levels were investigated, but no joint key figures were determined. Therefore even though there was an overview about IEQ conditions in the particular study, the data could not be used for more general analyses where certain patterns could be investigated using joint key figures for large amount of buildings. Andre et al. [32] describes a benchmarking procedure for HVAC systems, but the actual quality of indoor environment does not receive much attention. Oppositely, we hypothesize that for example methods for long term evaluation of IEQ specified by EN 15 251 [30] could, together with energy consumption per unit area, form an effective key figure. We haven’t identified any publication that would utilize aforementioned long-term evaluation methods. Carlucci and Pagliano [39] addressed several issues related to them. Their conclusions actually support our hypothesis as they state that “single numerical values summarizing the variety of comfort conditions encountered in the various thermal zones of a building over a certain period of time cannot provide a substitute for a detailed design of a building, rather they can guide its optimization”.

From the practical point of view there is a gap between state-of-the-art methods and real word scenarios - many of the building owners or operators do not work with historical operational data. They, despite the evidence in literature that it provides significant energy savings, do not recognize value of operational diagnosis using historical data. Moreover, major part of these savings can be achieved with no or minimal additional investments - usual payback of continuous operational diagnosis deployment is less than two years [40]. In this perspective, attempts to include IEQ seem to be far low on the agenda, but as expenses incurred in employee salaries exceed building energy and maintenance costs by a factor of 80 to 100 [41], we consider joint assessment of energy and IEQ performance to be highly relevant.

5. Conclusions

- Majority of reviewed publications focused explicitly on energy performance and indoor environment was mentioned only marginally or was not mentioned at all.
- One publication was identified that integrates thermal comfort into broader matrix of key figures.
- Methods for long-term evaluation of IEQ indicators suggested by standard EN 15251 seems to be usable for determination of key figures for joint assessment.

- Further research is needed to determine and test key figures that would combine performance indicators related to both energy use and IEQ

References

- [1] G. J. Levermore. Building energy management systems: applications to low energy HVAC and natural ventilation control. E&FN Spon, (2000) SBN 9780419261407.
- [2] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.
- [3] J. O'Donnell, M. Keane, E. Morrissey, V. Bazjanac. Scenario modelling: A holistic environmental and energy management method for building operation optimisation. *Energy and Buildings* 62 (2013) 146-157.
- [4] A. Costa, M. Keane, P. Raftery, J. O'Donnell. Key factors – Methodology for enhancement and support of building energy performance. Conference Paper for 11th IBPSA Conference. Glasgow, Scotland, 27-30 April 2009.
- [5] H.-x. Zhao and F. Magoulès. A review on the prediction of building energy consumption. *Renewable and Sustainable Energy Reviews* 16 (2012) 3586– 3592.
- [6] R. A. Cox, M. Drews, C. Rode, S. B. Nielsen. Simple future weather files for estimating heating and cooling demand. *Building and Environment* 83 (2015) 104-114.
- [7] S. Burhenne and D. Jacob. Simulation models to optimize the energy consumption of buildings. Proceedings of the 8th International Conference for Enhanced Building Operations (ICEBO), Berlin, Germany, 20-22 October 2008.
- [8] P. Carling, P. Isakson, P. Blomberg J. Eriksson. Experiences from evaluation of the HVAC performance in the Katsan building based on calibrated whole-building simulation and extensive trending. (2003).
- [9] T. Catalina, J. Virgone, E. Blanco. Development and validation of regression models to predict monthly heating demand for residential buildings. *Energy and Buildings* 40 (2008) 1825–1832.
- [10] J.C. Lam, K. K.W. Wan, D. Liu, C.L. Tsang. Multiple regression models for energy use in air-conditioned office buildings in different climates. *Energy Conversion and Management* 51 (2010) 2692–2697.
- [11] B. L. Capehart and M. R. Brambley. *Automated Diagnostics and Analytics for Buildings*, The Fairmont Press, Inc. (2015) ISBN 978-0-88173-733-2.
- [12] J. H. Eto. On Using Degree-days to Account for the Effects of Weather on Annual Energy Use in Office Buildings. *Energy and Buildings*, 12 (1988) 113 – 127.
- [13] G. Krese, M. Prek, V. Butala. Analysis of building electric energy consumption data using an improved cooling degree day method. *Strojnicki Vestnik—J. Mech. Eng.*, 58 (2012) 107–114.
- [14] ASHRAE. *ASHRAE Handbook – Fundamentals*, I-P ed. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, USA, 2009.
- [15] S. Attia, M. Hamdy, W. O'Brien, S. Carlucci. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. *Energy and Buildings* 60 (2013) 110-124.
- [16] P. Carling, P. Isakson, P. Blomberg, J. Eriksson. Simulation-aided commissioning of the Katsan building. (2003) 40-D-M5-SWE-AF/KTH.
- [17] O. Baumann. Operation Diagnostics – Verification and Optimization of Building and System Operation by Multi-Dimensional Visualization of BEMS Data. Report presented at the International Conference for Enhanced Building Operations (ICEBO), Berkeley, CA, USA October 13-15 October 2003.
- [18] IEA Annex 40. Commissioning tools for improved energy performance, Results of IEA ECBCS Annex 40. Executive Committee of the *International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems (ECBCS)* 2004.
- [19] D. E. Claridge and M. Liu. Using Whole Building Simulation Models in Commissioning. (2002) A40-D2-M4-US-TAMU-02.
- [20] O. Baumann. Enhanced Building Operation Using "Operation Diagnostics" - A Case Study. Report presented at the International Conference for Enhanced Building Operations (ICEBO), Pittsburgh, PA, USA, 11-13 October 2005.

- [21] D. E. Claridge. The cost effectiveness of continuous commissioning over the past ten years. In: J. L.M. Hensen, R. Lamberts, editors. *Building performance simulation for design and operation*. (2011) p 365-401, Spon Press.
- [22] Y. Yu, D. Woradechjumroen, D. Yu. A review of fault detection and diagnosis methodologies on air-handling units. *Energy and Buildings* 82 (2014) 550–562.
- [23] M. Bonvini, M. D. Sohn, J. Granderson, M. Wetter, M. A. Piette. Robust on-line fault detection diagnosis for HVAC components based on nonlinear state estimation techniques. *Applied Energy* 124 (2014) 156–166.
- [24] S. Katipamula and M.R. Brambley. Fault Detection, Diagnostics and Prognostics for Building Systems – A Review Part 2. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* 11(2005) 169-187.
- [25] M. Taheri, M. Schuss, A. Fail, A. Mahdavi. A performance assessment of an office space with displacement, personal, and natural ventilation systems. *Building Simulation* 9 (2016) 89-100.
- [26] A. Wagner, E. Gossauer, C. Moosmann, T. Gropp, R. Leonhart. Thermal Comfort and Workplace Occupant Satisfaction—Results of Field Studies in German Low Energy Office Buildings. *Energy and Buildings* 39 (2007) 758- 769.
- [27] H. Kim and J. Haberl. Exploring Methods to Analyze and Display continuously Measured Time-series IEQ Performance Data. *Indoor Air Conference*, 2014.
- [28] ASHRAE. ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, USA, 2010.
- [29] W. S. Dols, A.K. Persily, S. J. Nabhger. Indoor Air Quality Commissioning of a New Office Building. Proceedings of the 3rd National Conference on Building Commissioning, Milwaukee, WI, USA, 1-5 May 1995.
- [30] EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization, Brussels, Belgium, 2007.
- [31] L. Jagemar and D. Olsson. The EPBD and Continuous Commissioning. CIT Energy Management AB. Göteborg, October 2007.
- [32] P. Andre, C. Hannay, J. Hannay, J. Lebrun, V. Lemort, I. Teodorese. A contribution to the audit of an air-conditioning system: modelling, simulation and benchmarking. *Building Services Engineering Research & Technology* 29 (2008) 85-98.
- [33] IEA Annex 47. Cost Effective Commissioning of Existing and Low Energy Buildings. Executive Committee of the *International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems (ECBCS)*, 2005.
- [34] EN 15603:2008 Energy performance of buildings. Overall energy use and definition of energy ratings. European Committee for Standardization, Brussels, Belgium, 2008.
- [35] P. Andre, C. Cuevas, P. Lacote, J. Lebrun. Re-Commissioning of the CAMET HVAC system: A Successful Case Study. Report presented at the International Conference for Enhanced Building Operations (ICEBO), Berkeley, CA, USA, 13-15 October 2013.
- [36] M.R. Braun, H. Altan, S.B.M. Beck. Using regression analysis to predict the future energy consumption of a supermarket in the UK. *Applied Energy* 130 (2014) 305–313.
- [37] P. Isakson and J. Eriksson. Vision of a visualization tool for commissioning. Proceedings of the Fourth International Conference for Enhanced Building Operations (ICEBO), Paris, France, 18-19 October 2004.
- [38] Europe 2020 A European strategy for smart, sustainable and inclusive growth. (2010) European Commission, Brussels, Belgium
- [39] S. Carlucci and L. Pagliano. A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings. *Energy and Buildings* 53 (2012) 194–205.
- [40] B. L. Capehart and M. R. Brambley. *Automated Diagnostics and Analytics for Buildings*. (2014) Fairmont Press.
- [41] Clements-Croome, D. (ed) 2006. *Creating the Productive Workplace*, E&FN Spon, Taylor & Francis Group, London/New York, Second edition.