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Advanced Control Solutions for Building Systems

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Abstract: The path of an innovative technology from the research stage to the validation in real test beds and subsequent commercialization and wider deployment may not always be straightforward. Multiple domain-specific constraints need to be considered and properly addressed. In case of the advanced control solutions for building's Heating Ventilation and Air Conditioning (HVAC) systems, one needs to keep in mind limitations given by the legacy control hardware, typical instrumentation levels, and overall cost-to-benefit ratio. The paper is written from the corporate R&D perspective and discusses methodological and practical aspects of design, validation and implementation of advanced control solutions in the application domain of commercial buildings. All issues are illustrated based on experience from the development of two different technologies: an embedded solution for control performance monitoring and a cloud-based supervisory control for HVAC systems.

1. INTRODUCTION

Today's Building Management Systems provides monitoring and control capability for multiple sub-systems including HVAC, electrical systems, fire systems, security systems and others. They play an essential role in realization of an "intelligent building", which can be defined from many different perspectives: for instance this can be a building that provides the most convenient environment to its occupants, offers a high level of automation, delivers top energy and environmental performance, provides high availability of managed spaces, or everything together. The recent technology trends in the area of building automation enable the development of new types of advanced solutions. The main trends can be generally characterized as follows:

Cloud computing enables the retention of more detailed data about the facility as well as integration of the automation data with other business data (Everett et al., 2013). This in turn enables more powerful building analytics, which can be further improved through Big Data technologies to better inform end users and decision-makers responsible for the operation of the building.

Embedded Intelligence. More computational power and intelligence residing directly in building automation devices will enable an extensive set of self-commissioning, self-tuning, self-diagnostic and correction, and even self-configuring features (Hartman, 2012).

Interoperability. The demand for interoperability between various solutions is driving many industry standards, including Building Information Model (BIM), Haystack, gbXML and similar standards for energy management, and additional protocols and standards for Asset Management (Hamil, 2012).

End-user experience. There is a growing focus on human factors and end-user experience that is driving innovative concepts relying on an active occupants' engagement, such as the Social Building (Irwin, 2013) or the Collaborative Energy Management and Control (Lu et al., 2012).

Development of new control and optimization capabilities for building systems is reflecting the above trends at a continually increasing extent, but at the same time, any new designs have to take into account all traditional barriers and challenges for deployment of these solutions, from which we would like to highlight the following three (Marik et al., 2011).

Legacy automation systems may cause problems in several aspects. Firstly, serious interoperability issues arising from the wide variety of proprietary protocols can make integration of multiple systems from different companies a challenge. Then also control strategies for legacy controllers are often coded in programming languages that do not allow easy modularization of the code, and therefore do not support easy reuse from one application to another.

Instrumentation level in a typical building is not always sufficient for implementation of advanced control solution. Flow sensors - for both air flow and water flow measurement – are typically not available, which makes it difficult to setup models based on enthalpy balances. Similarly, the lack of meters and sub-meters for electricity and gas can severely limit the calculation of energy costs and objective functions used by the optimizers.

Cost-to-benefit ratio remains one of the major limitations. Total cost associated with implementation of an advanced monitoring or control solution includes setup and configuration cost, maintenance cost, cost of additional sensors, and cost of potential hardware retrofits. Desire for an attractive return of investment usually disqualifies complex solutions requiring significant engineering effort to configure and install the solution, as well as to maintain it in long-term.

The paper discusses two innovative solutions – one in the category of embedded intelligence, the other related to cloud-based building automation – while emphasizing important methodological and practical aspects of the solution design, validation, and transition into commercial environment. The text is structured in a way that the Sections 2 and 3 first summarize technical concepts of the control performance monitoring and cloud-based supervisory control solutions. This is then followed by the methodological overview in Section 4, which provides insights into main aspects of the development process.

2. CONTROL PERFORMANCE MONITORING

2.1 Problem Description

A typical HVAC control project requires installation and tuning of multiple PI controllers. Usually there is a little time for manual tuning and also the installers often do not have a rigorous control engineering background. As the result, the control loops are often not properly tuned. In addition, the commissioning during one season leaves loops operating in another season, non-linear HVAC behavior causes poor control at some operating points, and the disturbances are significant. Due to these reasons even the good control quality can deteriorate in time - the comfort is then often violated, the energy is wasted or the actuators are worn out.

Because of that there is a need to monitor the control performance after the installation and identify the poor behavior of loops to prevent those negative effects. There are hundreds of control loops in a building, so the preferred solution is to perform monitoring on the lower level and on-line, without need of data transfer, storage and off-line evaluation.

Existing solutions represent offline analysis of the data in order to classify the performance of loops. Those tools focus more on deeper engineering analysis, and they often do not provide quick reference needed by field engineers. Existing online analysis tools focus on particular aspects of poor controller tuning (e.g. oscillatory or sluggish control), not presenting generalized performance indicator nor wider diagnosis.

2.2 Concept and Requirements

The main idea of performance monitoring of HVAC controllers is to assess and diagnose the behavior of wide variety of control loops to provide information, alert or prioritization in cases when the control quality has deteriorated or the actuators do not behave in a standard way due to valve stiction, backlash, or other faults. The diagnosis is done directly in the controller in order to trigger the loop tuning mechanism, which re-tunes the controller if the cause of poor behavior can be addressed by proper tuning. The status information can also be collected by a higher level monitoring software, which can provide status reports with aggregated statistics.

Based on this description the main requirements of the solution can be summarized as follows. The algorithm should have low memory requirements (recursive algorithms are preferred), it should not provide false alarms, and it should be applicable to a variety of loops in a building. From the user interaction perspective, the solution should be easy to set-up and capable to provide results in an intuitive way, while suggesting or invoking the correct action.

2.3 Methods Used

To meet the solution requirements the performance indices and oscillation detection methods were employed and further augmented by diagnostics, whose results were then merged to form aggregated performance measures. All indices were designed to be computed recursively.

The predictability index, based on minimum variance index (Harris et al., 1999, Horsch et al., 1999), reflects how well the controller error is predictable. In an ideal case the controller error should be white noise, because any model of it can be used for improving the control. For that purpose the auto-regressive model of the controller error is formed, and compared in terms of lower prediction error variance to the better of two elementary models – naive predictor and error variance. The predictability index is defined as

$$PI_{pred} = 1 - \frac{\sigma_{mv}^2}{\min(\sigma_{NP}^2, \sigma_{error}^2)}, \tag{1}$$

where σ_{mv}^2 is the prediction error variance of the model of controller error, σ_{NP}^2 is the prediction error variance of the naive predictor, and σ_{error}^2 is the variance of the controller error. The value of index close to one represents the poor loop performance. The same numerical logic applies to other indices as well.

The fluctuation index is designed to detect high frequency quasi-periodic behavior with low amplitudes in controller output, which causes extensive wear of the actuators (e.g. heating and cooling valves), and it is defined as

$$PI_{fluct} = 1 - \frac{\sigma_{error}^2}{\sigma_{NP}^2}, \tag{2}$$

where σ_{NP}^2 is the prediction error variance of the naive predictor, and σ_{error}^2 is the variance of the controller error.

The offset index detects offset in controller error based on (Rhinehart, 1995), defined as

$$PI_{off} = 1 - \frac{\sigma_{NP}^2}{MSE}, \tag{3}$$

where σ_{NP}^2 is the prediction error variance of naive predictor, and *MSE* is mean square error of controller error.

In order to distinguish acceptable behavior from non-acceptable behavior, the distribution cumulative functions for each index are estimated using quantile regression (Koenker 2001, Chen 2005), with threshold being e.g. 95th percentile.

Oscillation detection is based on recursive Fourier Transform, monitoring the norm of the Fourier coefficients of specified range of frequencies over a time window of pre-specified size. The diagnosis for both performance indices and oscillation detection is based on monitoring the disturbance variable and controller output. In addition, oscillation diagnosis uses controller gain reduction test and monitoring of subsequent changes in oscillation period to conclude whether the cause of oscillation is hardware malfunction or poor controller tuning.

The indices' actual values are normalized to their thresholds and the loop performance measure is obtained selecting the maximum of normalized indices values or oscillation diagnosis results. See the overall scheme in Fig. 1. The controller performance measure is formed using the same logic, but taking into account only cases, where the diagnosis concludes the cause is poor controller tuning – if this measure shows undesired behavior for significant amount of time (derived from estimate of process time constant), the loop tuning procedure is triggered. Both performance measures can be used for benchmarking of the loops (or controllers).

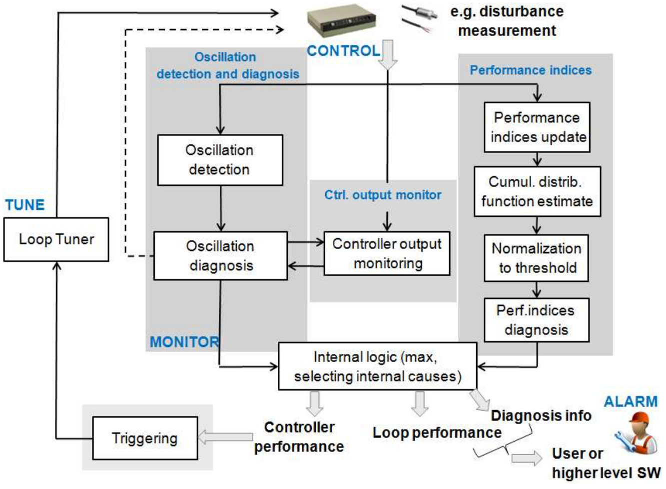
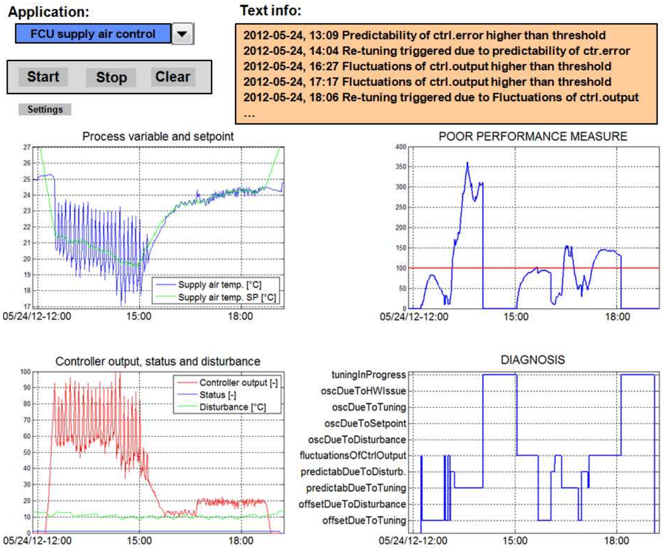


Fig. 1. Scheme of the Control Performance Monitoring

2.4 Implementation and Example

The methods described were implemented in a recursive way, using exponential forgetting for variances update. The control performance monitoring solution was written in C, to be part of controller firmware. In addition, it was implemented as applet in a software application used by field engineers to set up and maintain the control strategies in buildings or access data from controllers.

For the second scenario, the user interface was developed, as shown in Fig. 2. On the left-hand side there are inputs for the algorithm, on right-hand side there are its outputs – time trends of loop performance measure and diagnosis enumerator, and text log. In the applet window the user specifies the application, which selects pre-defined values of time constant estimate (for setting correct sampling time and triggering of re-tuning mechanism) and acceptable error (for oscillation detection and offset index), which then can be adjusted in separate settings window. The diagnosis enumerator was selected as a "full" list of diagnosable items for initial testing. Next step is to merge the items into more generic categories, e.g. poor tuning, loop disturbed, hardware issue, and tuning in progress.



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2012-05-24, 13:09 Predictability of ctrl.error higher than threshold
2012-05-24, 14:04 Re-tuning triggered due to predictability of ctr.error
2012-05-24, 16:27 Fluctuations of ctrl.output higher than threshold
2012-05-24, 17:17 Fluctuations of ctrl.output higher than threshold
2012-05-24, 18:06 Re-tuning triggered due to Fluctuations of ctrl.output
...
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Fig. 2. User interface for the engineering tool

On time trends in Fig. 2 it can be seen an example situation from supply air temperature cooling loop in fan coil unit in a test office building, using one minute sampled data. There the supply air temperature shows a high predictability between times 13:00 and 15:00. This predictability is higher than predictability of disturbance (in this case chilled water temperature, whose values are available at the controller), so poor tuning is considered to be the cause of this undesired behavior. That is why the re-tuning is triggered at time 14:04 (the simulation is on off-line data in this case, so the real tuning did not take place, and during 20 min placeholder for re-tuning the loop performance was not evaluated). From time 17:00 there are significant fluctuations in both process variable and controller output, which is properly reflected in value of fluctuation index exceeding the threshold, and leads to re-tuning triggering at time 18:06.

The solution presented enhances the state-of-the-art by wider diagnosis used in monitoring part at the controller level, while keeping simple set up and easily interpretable outputs. The modular fashion of the solution allows easy enhancements by other diagnoses, e.g. overshoot monitoring, or other performance indices.

3. CLOUD-BASED SUPERVISORY CONTROL

3.1 Problem Description

There has always been opportunity in HVAC control applications to save energy costs using a properly designed reset strategy for important HVAC setpoints, including chilled water temperature, hot water temperature, water pumps speeds, or air handlers fan speeds. But in many installations these variables are either kept constant or adjusted based on a simple rule-based reset strategy, such as the ambient temperature compensation for hot or chilled water temperature. In these cases the common disadvantage is the trade-off between performance and robustness. HVAC control service engineer is usually too busy to tune it properly and keep the configuration regularly updated. Then the natural inclination is to choose a robust solution that will ensure occupants comfort for a wide range of conditions. But the HVAC system, which is controlled this way, usually consumes more energy. An attractive possibility how to address these limitations of HVAC control practice is represented by the model-based supervisory control, which can dynamically adjust all main HVAC setpoints based on actual weather and occupancy conditions.

3.2 Solution Requirements

The primary goal of any HVAC control system is to maintain predefined comfort levels in zones, while minimizing the overall operating costs, usually reduced to the costs of primary energy sources (Marik et al., 2011). From the business point of view there are several critical requirements that must be met for a successful deployment in the field.

Wide applicability. The control solution must be generic enough to be applicable to a large variety of HVAC systems, including fan coil systems, variable air volume (VAV) systems, hydronic heating systems, and others.

Setup costs. Easy setup is one of the most critical requirements since the solution should not require a skilled advanced control expert as is a norm in the industrial domain. HVAC field engineers prefer simple plug & play configuration, ideally, it should be possible to interface the solution with existing control system without requiring significant investments into new sensors, actuators or meters.

Maintenance costs. The solution needs to be able to dynamically adapt to common system changes and drifts, such as the changed occupancy pattern, pump or fan replacement, sensor miscalibration, or performance degradation of HVAC equipment.

3.3 Implementation and Example

The cloud-based supervisory controller was implemented following the solution architecture depicted in Fig. 3 where the existing Building Management System (BMS) is connected with the HVAC supervisory controller via BMS-specific connector. This connector is responsible for the reading of measured sensor data and the resetting of main HVAC set-points. The supervisory controller is initialized every 15 minutes by a timer. The controller contains a data storage, which is used as a long-term memory. New data is regularly processed by components responsible for modeling of energy consumption and occupants comfort, and the resulting models are employed by the optimization engine to determine the cost optimal resets of all setpoints while maintaining comfort within predefined levels.

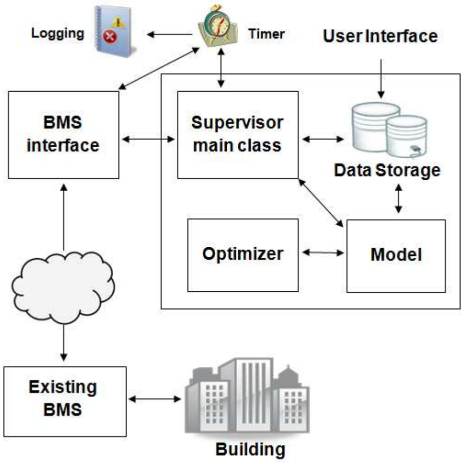

Fig. 3. Cloud-based HVAC supervisory control architecture

The developed solution encompasses two data processing loops as illustrated in Fig. 4. The upper loop is executed at each solution step and consists of (a) reading the most recent sensor values, (b) writing the data into cache, (c) estimating parameters of the pre-defined model structure in order to determine both energy and comfort models, and (d) setpoint optimization using the previously fitted models. The solution step is configurable and typically set to 10 or 15 minutes, and the optimization horizon is several steps ahead.

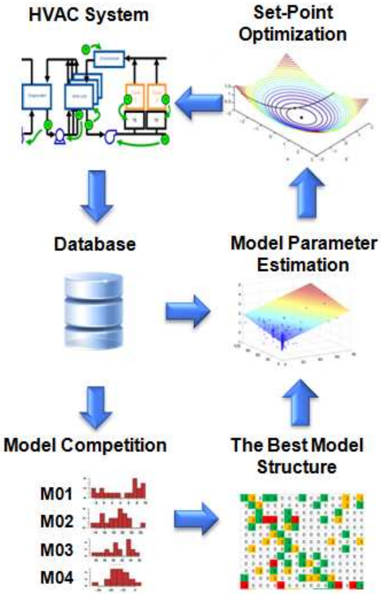

Fig. 4. High-level data flow diagram

Typically the optimization engine produces a 1-hour ahead schedule but only the first step is applied to the plant controllers, following the principle of receding horizon control. The benefit of the on-the-fly parameter estimation is a built-in adaptation mechanism, which is capable to accommodate various HVAC system changes by always using the most recent data to fit the models.

The upper loop is executed just within few seconds, and after that, several minutes are reserved for execution of the model management loop. Its goal is to provide a suitable model structure that will correctly represent relations between optimized set-points and estimated energy and comfort variables. This helps with both the easy solution setup and the model maintenance. Execution of the HVAC supervisory controller can start with a low-quality model whose structure will be continually improved with every execution cycle. This reduces the need for engagement of a control or optimization expert during the solution setup and maintenance. The model structure optimization utilizes model forecast error and penalizes model complexity.

The benefit of described supervisory control solution is 10 to 40% reduction of purchased energy costs. The savings from this range were observed at recent four supervisory control application pilots in United Kingdom and comply with results published in literature (e.g. Lu et al., 2012). The methodology for savings evaluation is described in (Macek, 2012).

4. DESIGN AND VALIDATION METHODOLOGY

Technology development within a global corporation needs to follow well-defined processes to ensure the resulting prototypes can be ported into a production environment and deployed as part of the commercial portfolio of products and services in given field. In this section we first discuss typical challenges related to transition of prototypes from the research to production environment, then we outline overall process and its stages, and finally, we discuss specific approach related to validation of building control strategies.

4.1 Challenges of Corporate Technology Development

The transition of a research prototype into production environment for a subsequent commercial use is usually more difficult than the development itself. This is primarily because the transition requires a successful connection between two different worlds: research and business. On one hand, corporate research teams are expected to operate with a technology vision at least three years ahead and while they are focusing on interesting technologies, they are sometimes lacking a detailed understanding of requirements but also constraints within given application domain. On the other hand, introduction of a new commercial product has to be done by respective business units, which are used to operate and make decisions within a shorter horizon of one or two years while using financial metrics – such as revenues or operating margins – as the key decision criteria. This might sometimes cause a limited understanding of the importance of invention and its advantages in longer-term. This is why a structured process with a proactive participation from both sides plays an essential role.

4.2 Technology Development Process

Development of a new innovative technology follows a path defined by a standardized development process, which is usually adopted across the corporation. The level of detail may differ, but in principle, the following stages are always present.

Research definition is the initial stage when a previously identified opportunity for a new technology needs to be clearly formulated. This typically involves a precise statement of the technical problem to be solved including functional and non-functional requirements, initial analysis of the associated business case, and review of existing alternatives and solutions documented in the public literature.

Concept development stage ends-up with a clear technical concept that solves given problem, minimizes associated scientific risks and does not violate any existing intellectual property. Engagement of the people from business units helps to formulate a clear business model that will be followed during future commercialization.

Prototype development may be executed in several cycles until all solution requirements are fully met, which may also require to make changes in the concept. Before moving to the next stage, the prototype has to be properly validated initially using simulated data sets, then on real data but still in an off-line mode, and finally in the real environment.

Technology transfer closes a successful technology development. Its objective is to transfer the advanced technology to the engineering team of respective business unit in order to productize it and integrate into existing portfolio of commercial products and services.

4.3 Assessment of Building Control Solutions

As part of validation of a new HVAC control solution, it is usually necessary to compare two or more alternative control strategies where one of them is already in use and represents a baseline solution. The objective is to quantitatively assess performance improvements of a new strategy in comparison with the original. These strategies usually differ in how they manipulate with important HVAC setpoints, such as the supply air temperature, supply hot water temperature, fan speed, etc. Given that the operational patterns of any building follow regular daily cycles, a typical scenario is to change the control strategies on a day-by-day basis. Consequently, also the results are assessed over the respective 24 hours intervals.

Two commonly used performance measures associated with HVAC control include the comfort satisfaction and operating costs but the requirements on occupants’ comfort are usually so stringent that they have to be met by any control strategy, so performance assessment then reduces to the comparison of costs. A rigorous framework for comfort conditions assessment was elaborated by (Aswani et al., 2012).

When two different control solutions are running at different days, it is important to consider the different operating conditions, which are primarily characterized by the occupancy pattern and weather conditions. In some cases it might be reasonable to omit the information about the occupancy (e.g. an administrative building with stable occupancy patterns during working days when the individual control strategies are validated just on these days). But in general, the occupancy is an important parameter for the comfort control (Oldewurtel et al., 2013) and should be used wherever it is possible to quantify it. Regarding the weather conditions, the most influencing factor for the energy consumption is the ambient temperature. Fig. 5 illustrates results of a comparison of two different strategies, conditioned by ambient temperature only. Intensity of color is inversely proportional to data age so the recently measured days are the most visible. Lines are results of local regression smoothing using linear temperature-consumption model and Gaussian kernel (σ = 3K). Empty circles at the bottom of plots are weekend or holiday consumptions which are not considered for savings evaluation.

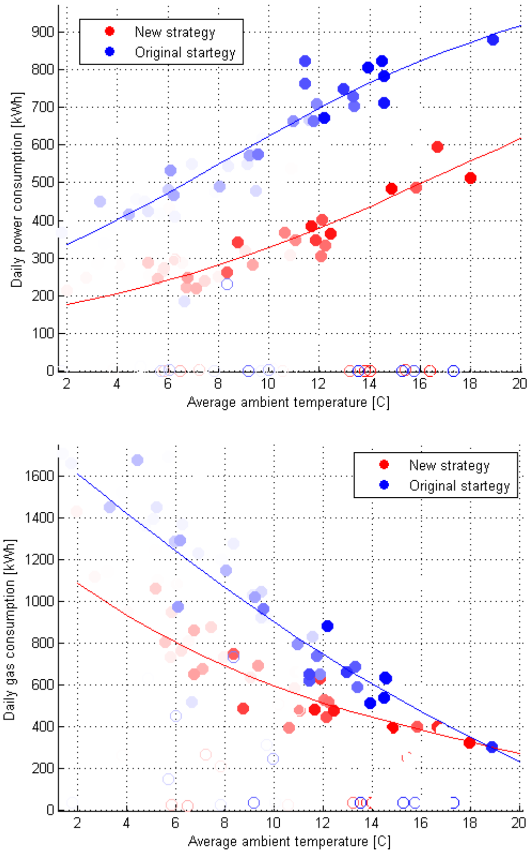

Fig. 5. Daily power and gas consumptions conditioned by average ambient temperature.

5. CONCLUSIONS

The paper presented two innovative technologies for control performance monitoring and cloud-based supervisory control, which follow different deployment scenarios: the former to be embedded in controllers as part of the standard firmware, the other to run in a cloud environment while being remotely connected to HVAC systems in multiple locations. In both cases the main requirement was to develop solutions that would comply with the numerous constraints of the building domain where the most important one is represented by the cost-to-benefit ratio, which includes solution setup and maintenance costs as the two main contributors. That is why the control performance monitoring concept is heading towards an automated loop diagnostics and tuning, which will certainly reduce the time a field engineer has to spend on the fixing of low-level problems. Similarly also the supervisory control solution takes advantage of an automated model adaptation and thanks to its deployment in a remote application center it will allow relatively few specialists to maintain a larger number of advanced control solutions.

REFERENCES

Aswani, A., Master, N., Taneja, J., Krioukov, A., Culler, D., Tomlin, C. (2012) Quantitative methods for comparing different HVAC control schemes, in *Proc. 2012 Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS)*, pp.326-332, Oct 9-12, 2012.

Chen, C. (2005) An Introduction to Quantile Regression and the QUANTREG Procedure, in: *SUGI 30 Proceedings, paper 213-30,* Philadelphia, Pennsylvania, April 10-13, 2005

Chowdhary, G., Srinivasan, S., Johnson, E. (2011), Frequency Domain Method for Real-Time Detection of Oscillations, *AIAA Journal of Aerospace Computing, Information and Communication, 42-52*

Everett, P., Jenkins, N., Rhodes, W., Grinter, S., Liu, R. (2013) Trends is Intelligent Buildings – 2013, www.imsresearch.com

Hamil, S. (2012) Building Information Modeling and Interoperability, National Building Specification, www.thenbs.com

Harris, T. J., Seppala, C. T., Desborough, L. D.: (1999) A Review of Performance Monitoring and Assessment Techniques for Univariate and Multivariate Control Systems. *Journal of Process Control 9 1-17.*

Hartman, T. (2012) The Two Futures of HVAC Controls, HPAC Engineering, www.hpac.com

Horsch, A., Isaksson, A. J. (1999) A Modified Index for Control Performance Assessment, in: *Journal of Process Control 9 475-483*, Stockholm, Sweden.

Irwin, C. (2013) The 'Social Building': Using Social Media to Save Energy, www.breakingenergy.com

Koenker, R., Hallock, K. F. (2001) Quantile regression, in: *Journal of Economic Perspectives—Volume 15, Number 4—Fall 2001—Pages 143–156.*

Lu, Y., Song, Z., Loftness, V., Ji, K., Zheng, S., Lasternas, B., Marion, F., Yu, Y. (2012) Advanced Integrated Control for Building Operations to Achieve 40% Energy Saving, Final Report, US DoE grant DE-EE0003843.

Marik K., Rojicek J., Stluka P. and Vass J. (2011) Advanced HVAC control: Theory vs. reality. Proceedings of 18th IFAC World Congress, pages 3108–3113

Macek, K., Marik, K. (2012) A methodology for quantitative comparison of control solutions and its application to HVAC (heating, ventilation and air conditioning) systems, *Energy*, vol. 44, no. 1, pp. 117-125, Aug. 2012.

Oldewurtel, F., Sturzenegger, D., Morari, M. (2013) Importance of occupancy information for building climate control, *Applied Energy*, vol. 101, pp. 521-532, Jan 2013

Rhinehart, R. (1995) A Watchdog For Controller Performance Monitoring, in: *Proceedings of American Control Conference,* June 1995.