

Whole Building Energy Performance Anomaly Detection at TU/e

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ABSTRACT

Existing buildings account for the majority of energy consumption in the building sector. Surveys of existing buildings have found an estimated 10-20% reduction in energy consumption may be feasible. Research at the Eindhoven University of Technology (TU/e) is seeking to realize this potential in Europe and specifically in The Netherlands. Past research utilized a whole building level anomaly detection and diagnostics tool to demonstrate the effectiveness and potential of the concept when applied to typical European building systems. An ongoing project seeks to develop a benchmarking tool on the basis of an advanced data gathering and monitoring tool which will relate perceived comfort and measured comfort. Additionally, another project will also incorporate expert knowledge to couple energy analysis with analysis regarding system maintenance and failure risk. Proposed research will seek to develop an advanced retro-commissioning analysis methodology to assist with the initial assessment and ongoing assessment of existing buildings.

INTRODUCTION

Worldwide buildings account for 32% of final energy consumed annually (IEA, 2012). In more developed regions this percentage increases to 40% or more (EIA, 2012). Much of the current and past research in the area of building energy efficiency has focused on methods, materials and systems that seek to reduce the energy consumption of new buildings. Additionally, the EU's Energy Performance of Building Directive (EPBD) mandates that new buildings in all member states be near zero energy by 2020 and that new public buildings must meet this goal by 2018 (EU, 2010). The directive also mandates that existing buildings which undergo a major retrofit must also meet a similar performance target. While this focus on new buildings will aid in reducing energy consumption in the long term future, in Europe on an annual basis new buildings account for less than 1% of the total building stock and the renovation rate of existing buildings is 1-2% per year (BPIE, 2011; Kraus, 2011). As a result, the existing

building stock accounts for the majority of the energy consumption in both the residential and commercial building sectors. Surveys of the potential for reduced consumption in the building sector in both Europe and the United States have found that an estimated 10-20% reduction in the consumption of existing buildings may be feasible using a combination of methods and technologies (Bynum et al, 2008; Claridge et al, 2000; Mills, 2009; Klobut and Tuominen, 2010). If the means and methods already exist, the logical question is why this reduction has not already been realized or achieved. The primary reasons are both economic and the lack of sufficient methods for the application of the existing technology to the problem at hand (i.e. energy efficiency of existing buildings). The main barrier is the relative magnitude of energy costs on the overall balance sheet of many building occupants (WBCSD, 2006). For instance, when compared to labor costs the energy costs can seem too insignificant to warrant the investment required for a 10-20% reduction; however, when the impact of improved occupant comfort and productivity is considered the economics improve greatly. For many commercial buildings the energy costs account for less than 5% of annual operating costs with labor accounting for the largest portion of the total cost. Despite these barriers, a recent report from Navigant Consulting Group estimates that the worldwide building commissioning market will double in value from 2012 to 2020 with North America being the primary market (Navigant, 2013). The growth in the application of building commissioning will likely be due to increased understanding among building owners and operators as well as the influence of high-performance building standards.

The energy consumption in the built environment is approximately 35% of the total energy consumption in the Netherlands and is responsible for 30% of CO₂ emissions. A nationwide survey of 40 buildings found that 70% of them were not operating properly causing excessive energy use and comfort issues (ANNEX 47, 2010a). Some large building owners are beginning to utilize performance contracting for operations and maintenance of their buildings but the adoption is not

wide spread. Experience with a bottom-up commissioning approach in the Netherlands led the researchers to conclude that the most owners and users are unwilling to invest in ongoing commissioning (i.e. ongoing system monitoring and optimization) (ANNEX 47, 2010b). To promote the application of building commissioning in the Netherlands, TVVL (Dutch Society for Building Services) founded the Dutch Building Commissioning Association (DBCA) in the fall of 2012. For several years TVVL has also offered courses on commissioning utilizing documents and guidelines published by ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineering), PECL, BCA (Building Commissioning Association) and NIBS (National Institute of Building Sciences). Given the developing state of the commissioning market in the Netherlands, one of the main barriers at present is the ability to make the business case for the services to potential customers. While this challenge exists in other markets, given the lack of familiarity with the service in the Netherlands this barrier is quite large.

RESEARCH QUESTION

As previously noted, several studies of building energy consumption have shown that the potential for a 10-20% decrease in the energy consumption of existing buildings exists. One large study conducted in the United States on the benefits of commissioning utilized a database of 561 existing buildings in 21 states consisting of over 8.3 million m² to analyze the average benefits of commissioning and found the median whole building annual energy savings to be 16% (Mills, 2009). The author stated that these savings could be realized on a large scale without significant capital investment if the methods and tools required were further developed. The need for further development of such methods and tools was also identified in a recently published review of performance assessment methods for existing buildings (Wang et al, 2012). Currently, the analysis of new and existing buildings is often done on an ad hoc basis which relies heavily on the experience of the engineer or consultant. The current practice demonstrates the need for methods which can allow for a systematic, rapid assessment of building energy performance.

For buildings, efficiency gains realized during the design phase are most effective but then the gains must be realized during operating phase. This is done first with initial commissioning (Cx) to ensure that the system is installed and operated as intended, but experience has shown performance typically degrades over time during the occupancy phase. Given this

degradation, there is a need to ensure continued efficient operation. One remedy for this is the application of the retro-commissioning (RCx) process; however, the performance of buildings often degrades once again in the post-RCx period. One study consisted of a survey of ten university buildings and showed an average increase in whole building heating and cooling energy consumption of 12.1% over a two year post-commissioning period (Turner et al, 2001). A larger persistence study (Toole and Claridge, 2006) found a rule of thumb for savings persistence of 25% degradation of savings every four years after commissioning implementation. A larger commissioning study which did not address persistence in detail noted from the limited persistence information collected that savings tend to remain about steady during the first 3-5 years after commissioning (Mills, 2009). In all of these studies, the need for methods that will aid the building operators in assessing the post-commissioning performance of the buildings, identifying operational problems, and diagnosing the cause of problems identified was recognized. The current practice demonstrates the need for a methodology which can assist engineers and/or operators in easily assessing a building's energy performance. Several such methods and tools have been developed but none have been widely adopted due to the limitations of the tools or the proprietary nature of the tools. Other tools have sought to use detailed simulations for real time anomaly detection (Pang et al, 2012; Djuric, 2008) but have seen limited application given the complex nature of the systems and high cost of application. This is perhaps possible for new buildings where a detailed simulation already exists, but for existing buildings, the cost and time associated with producing the detailed simulation makes it impractical and uneconomical. Additionally, some methods and tools provide only a snapshot of the energy performance and are not intended for continued application and analysis.

Another factor that operators must consider is the comfort of the occupants. Given the relationship between indoor environmental quality in general and occupant productivity, comfort can easily be considered an even more important factor, economically speaking, than building energy consumption. In the operating budget of an office building, energy costs can account for less than 5% of total operating costs while labor accounts for the largest portion of the total cost [WBCSD, 2006]. With this in mind, research at TU/e also seeks to address ways to monitor, improve and maintain occupant comfort in buildings through several projects described below.

RESEARCH PHILOSOPHY

Experience has shown there is commonly a gap between the predictions of building performance and measured building performance. This gap is due to three primary factors: prediction errors such as model shortcomings as well as imperfect assumptions of model inputs; equipment failure in the building; and sub-optimal control strategies. The difference between predictions and measurements can be reduced or eliminated by seeking to reduce the contribution of both prediction errors and operational factors although the relative magnitude of the contribution of these two factors is not exactly known. Figure 1 below demonstrates the current relationship between predicted and measured performance in regards to energy consumption where the measured consumption is commonly greater than that predicted. The predicted consumption is represented by a range of values which is found using uncertainty analysis. For the measured consumption, the greatest value represents the current measured consumption. Two different levels of consumption could be realized if first the equipment failures were remedied and second if the sub-optimal strategies were altered to improve performance. Ideally, the predictions could be used to identify the consumption when equipment failures are eliminated and then again when the effects of the sub-optimal controls are eliminated. In other words, the predictions could be used to estimate the performance improvements due to both factors. This is represented by the two consumption ranges shown for the predictions. Prediction errors would also have to be eliminated in order to accurately predict the consumption as shown by the difference between the current and ideal predictions. The goal of the proposed research is the development of methods for reducing the difference so that the predicted values can capture the real measured performance within their range of uncertainty. The following is a description of the past, current and proposed research at Eindhoven University of Technology (TU/e) which is intended to accomplish this goal via improved operational performance of buildings.

PAST RESEARCH

Introduction to ABCAT

As noted above, a major item of concern in the commissioning of new and existing buildings is the persistence of the energy savings attributed to the commissioning process. Numerous studies of retro-commissioning savings persistence (Claridge et al, 2000; Turner et al, 2001; Toole and Claridge, 2006; Bourassa et al, 2004) have demonstrated the need for methods and tools that will aid the building operators in assessing the post-commissioning performance of

the buildings, identifying operational problems, and diagnosing the cause of problems identified. One such tool known as the Automated Building Commissioning Analysis Tool (ABCAT) developed by Texas A&M University is intended to meet this need. ABCAT is a Microsoft Excel based tool, with multiple worksheets, chart sheets, and unique macros. A detailed description of ABCAT can be found in the thesis by Curtin (Curtin, 2007).

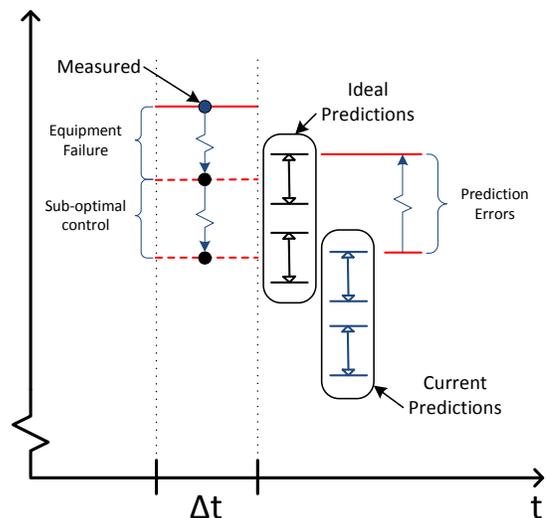


Figure 1. Building performance operations and predictions comparative diagram

ABCAT utilizes a calibrated, simplified, first principles based mathematical model, a “white box” method, to predict the energy consumption under given weather conditions at the whole building level. The merits of a whole building level anomaly detection methodology have led to the development of a number of such tools. Three tools in particular have seen significant development and testing: Performance And Continuous Recommissioning Analysis Tool (PACRAT) developed by Facility Dynamics Engineering, the Whole Building Diagnostician (WBD) developed under the guidance of the Pacific Northwest National Laboratory, and ABCAT. Both PACRAT and the WBD use a multiple variable bin method to predict energy consumption via a “black box”, data driven method. Both PACRAT and WBD also provide real time monitoring of whole building energy performance through an automated process along with comparisons between predicted and measured consumption. Recently, a methodology was developed for utilizing design phase detailed simulations along with measured data from the building to identify faults in a subject building (Maile et al, 2012). This approach is similar to that used in

ABCAT except, most notably, for the detailed level of the simulation and the level of knowledge required for the user to alter the simulation.

The whole building ABCAT tool requires the use of only three sensors (some actually consist of multiple pieces of equipment but are referred to as one sensor for clarity) which are already available in some buildings and are inexpensive and simple to install if necessary: whole building electricity, whole building heating, and whole building cooling. A diagram of the measurement methodology of ABCAT is shown in Figure 2. The low number of sensors helps achieve the tool's goals of being a cost effective and simplified alternative to the more complex systems. The predicted energy consumption is compared to the measured consumption and anomalies are detected based on statistically significant deviations between the two data sets (Lee et al, 2007). The focus of ABCAT is on detecting anomalies that have a significant impact if they persist for a long period of time; therefore, the anomaly detection methodology focuses on the cumulative effects of anomalies. Once an anomaly is detected, the simulated and measured energy consumption is presented in numerous graphical forms that are instrumental in diagnosis. An overview of the development and testing of the ABCAT tool was published in 2012 (Bynum et al, 2012).

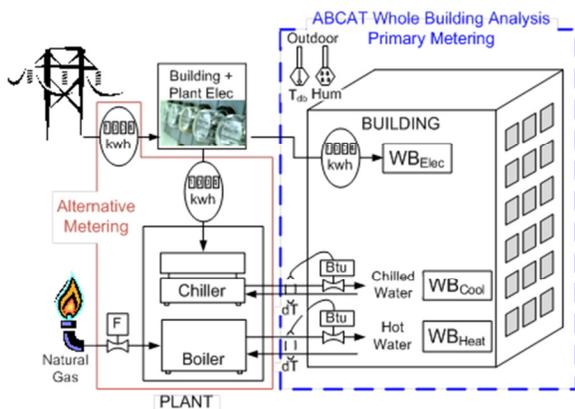


Figure 2. Measurement methodology of ABCAT (adapted from Curtin, 2007)

Original Vertigo application

Following the initial testing of ABCAT, testing was undertaken to determine how the tool performs when applied to a variety of building types and system types. To this end, the Vertigo Building which is the home of the Department of the Built Environment at TU/e was chosen as a test case. The building consists of 26,000 m² with a total of 12 floors. It was constructed in 1965 and underwent a major renovation in 2002 followed by testing and balancing

in 2006. The top four floors consist of office space while the remaining floors are a mixture of classrooms, offices, and laboratories and the below ground floors house most of the mechanical systems. The Vertigo building is generally occupied from 08:00 till 18:00 on weekdays and is vacant on weekends. The primary mechanical system consists of a heat pump located in the basement and two hot water natural gas boilers located on the roof. Heating and cooling is also provided by a district aquifer thermal energy storage (ATES) system. The space conditioning is performed by a combination of four air handling units providing ventilation air, convective radiators along the perimeter of the building, a four pipe climate ceiling in the office spaces and ten fan coil units in unique spaces with high internal gains. All four air handlers are constant volume and consist of a supply fan, return fan, heat recovery wheel, cooling coil and heating coil.

The original data set available for analysis spanned from 1 January 2006 through 24 September 2009. The energy consumption data was taken from the building's management system, while the weather data was obtained from a weather station in Eindhoven. The ABCAT simulation was calibrated to the baseline consumption period of 1 January 2007–31 December 2007 since testing and balancing conducted in 2006 resulted in a significant change in the consumption pattern for that year. The results of calibrated simulation are shown together with the measured consumption for 2007 in Figure 3.

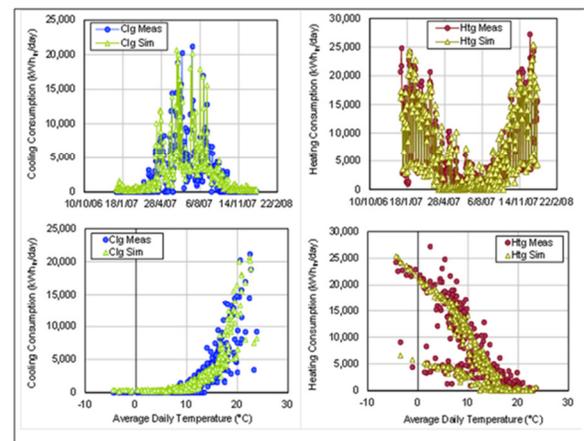


Figure 3. 2007 calibrated ABCAT results for Vertigo building

When the calibrated simulation was applied to the measured data from 2008 and 2009, an increase in weekend heating consumption was identified in the later part of 2008 and 2009. For 2009, two simulated consumption patterns are apparent but now there is no distinct weekend measured consumption pattern

except at very low ambient temperatures as seen in Figure 4.

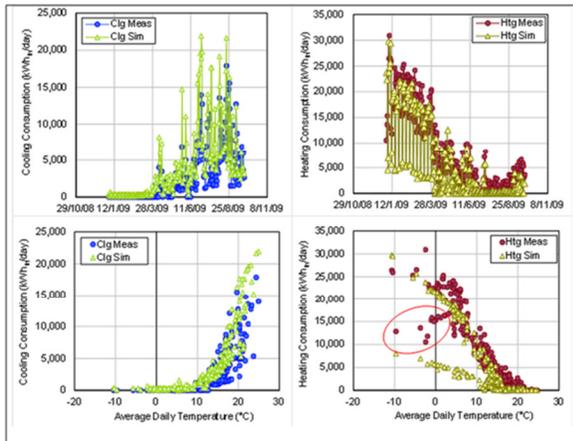


Figure 4. 2009 ABCAT results for Vertigo building

In addition, the weekend consumption pattern (circled in red in Figure 4) has changed slope showing a decrease in measured consumption as ambient temperature decreases. When the weekends of January and February are removed, there is no longer a distinct weekend measured consumption pattern. When the average hourly measured data for 2008 and 2009 are shown together a transition from the original weekend levels of consumption to the consumption pattern of March–September 2009 is apparent as shown in Figure 5. Thus, the change was not immediate but gradually occurred to the point where the weekend and weekday consumption levels are no longer distinguishable from one another. The lack of a distinct weekend measured consumption pattern in 2009 is a clear difference from the simulation results which still show a separate weekend consumption pattern.

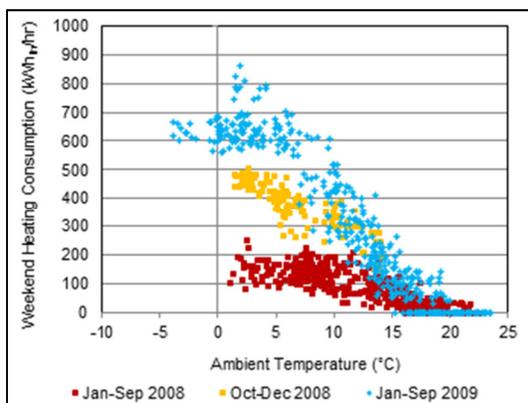


Figure 5. Weekend consumption for Vertigo building in 2008 and 2009

After this anomaly was identified, the starting point for diagnosis was to determine if any changes were made to the control sequence near this time. The building operator identified changes that were made at some point during 2008 or 2009 but was not certain of the exact date. The most common issue addressed was low space temperatures on Monday mornings. The changes included raising the space temperature set point 1°C during occupied and unoccupied hours and implementing a varying start time algorithm for the radiators which is based on the heating needs during the previous days. The first change, believed to have been implemented in early 2009, would result in an increase in measured heating consumption across the board. A review of the 2009 ABCAT results does show that measured heating consumption was consistently greater than the simulated consumption. The second change, believed to have been implemented in late 2008, was seeking to eliminate Monday morning comfort complaints by allowing the radiators to start early in order to have the space temperature at the desired level when occupants arrive. Given that there is no limit to when the early start time may occur, it is possible that this control change may account for the increased measured weekend heating consumption. For further diagnosis, changes were made to the ABCAT simulation to see what input changes would produce similar changes in simulated consumption over the periods in question. The operating hours of the system were increased for weekends and weekdays and the resulting simulated consumption pattern is closer to the measured consumption pattern than the original calibrated simulation. This result was expected given the description of the control changes provided by the building operator. The magnitude of the identified increase in heating consumption is approximately 18% of the annual total for a cost difference of € 23,900 (US\$32,400 at US\$1.3552/€ 1) assuming a cost of € 10.64/GJ for natural gas with the assumed boiler efficiency of 85%. This represents 2.8% of the annual operating budget for the Vertigo building which is estimated to be € 8.4 million of which labor accounts for greater than 90%.

Continued applications at TU/e

Recently, the ABCAT tool has been applied once again to the Vertigo building on the TU/e campus. Testing is also being conducted on other campus buildings however to date the focus has been on the Vertigo building given the past experience with the building and natural interest in the performance of the Vertigo building since it houses the Department of the Built Environment. Energy consumption data from the end of the initial testing period at the end of 2009 to the end of 2012 has been obtained and processed.

While some data quality issues were encountered and identified through the use of the energy balance method (Shao and Claridge, 2006), in general the quality of the data is sufficient to easily continue analysis of the building. As was discovered in the initial analysis, in 2009 a change in the consumption pattern occurred where separate weekend and weekday patterns were no longer easily identifiable. This trend continued throughout the period from 2010 through 2012 as well and is likely due to the same control change which was identified in the initial testing. The model in ABCAT was recalibrated to account for this change in consumption pattern before comparing the measured and simulated consumption for anomaly detection. The analysis is still underway but to date no anomalies have been identified using the updated simulations.

Opportunities for development of methodology

The methodology utilized in ABCAT has shown to be a viable and capable approach to the operational analysis of buildings. Specifically, ABCAT has been implemented in numerous buildings covering over 20 building years of energy consumption data. Initial testing showed the value of the whole building level top down approach to anomaly detection used in ABCAT is found in detecting anomalies over the long term (i.e. weeks or months) as opposed to days or weeks. Detection can be accomplished visually or automatically using the persistence and magnitude of the deviations between measured and simulated consumption. Testing also indicated that the ease of use of the simplified simulation methodology employed in ABCAT is very beneficial when it comes to diagnosis. The Vertigo application shows the robustness of the ABCAT tool specifically and the simulation based anomaly detection method in general. The experience also indicates further development of ABCAT is necessary to make the detection portion of the process more automated and less dependent on the experience and knowledge of the user. Work in this area has recently been conducted at Texas A&M University. In addition to the original goals of tracking and ensuring energy optimization in commissioned buildings, several other added benefits or alternative functional approaches were identified. These include the use of this methodology as a commissioning savings tracking tool; a simple whole building energy analysis tool (even without the simulated consumption); and providing verification of, or use in filling missing metered or billing data, both important for customers of district utility providers, and the providers themselves. At TU/e, the future development of the methodology will focus on the use of more detailed models and the use of design models to implement

the methodology. Identifying the most important inputs and including more temperature independent variables in the model are also important factors. In assessing more detailed models, the scalability of the method must be considered so that the benefits of the greater detail are balanced with usability which can be a major impediment to adoption by the target audience. Other areas of research include the implementation of automatic recalibration of the building model as well as identification of the optimal epoch of analysis and analysis time step. These last two items are discussed in greater detail below.

Epoch of analysis – what is most appropriate?

The detection methods of the ABCAT tool are better at detecting anomalies that have occurred over longer periods of time (weeks, months, or sometimes years). Therefore, conducting analysis of the building using ABCAT more frequently (daily) may not be beneficial. New detection techniques recommend using a shorter time period to detect anomalies than that recommended in the original ABCAT documentation; however, this new estimate is described as conservative and in need of further investigation. In both cases, the ABCAT tool uses a daily simulation model for comparison to daily measured consumption data meaning that analysis in periods shorter than a day is not possible. Given the natural variability of building energy consumption, daily whole building level analysis lends itself to the detection of a change in the trend of the consumption, not a change from one day to the next. Metering problems that result in unrealistic values (e.g. measured consumption that abruptly increases by an order of magnitude) being an obvious exception. There is a need to balance the capabilities of the methodology and the cost of utilizing it with the cost of the energy or productivity that may result from poorly operating equipment or systems. With this in mind, a shorter period would be beneficial assuming the methodology does not require a lot of effort from the user to upload and process the data. If the process is automated well enough than data could be imported nightly, weekly or bi-weekly and be available for regular review weekly (or bi-weekly) depending on available resources. A weekly application was suggested by third party users during initial testing of ABCAT (Curtin, 2007). It is unlikely that many anomalies would be detected the same week they occur; however, more frequent review would allow for a detectable anomaly to be identified as early as possible instead of allowing it to persist undetected for a month or more.

Another option is to alter the tool so that analysis is possible on a smaller time scale, for instance on an

hourly basis. While this may seem attractive in theory given the availability of simulation tools capable of simulating buildings using hourly (or smaller) time intervals, in practice this can be difficult to implement. For instance, with such a large amount of data trends are sometimes harder to identify given the amount of natural variability in the measured energy consumption due to a variety of factors (e.g. user behavior). Also, the sheer volume of data can make processing more difficult without producing appreciably better results given the top-down, whole building level nature of the tool.

COMFORT BENCHMARKING, MONITORING AND DIAGNOSTIC TOOL DEVELOPMENT

As mentioned in the introduction, research at TU/e is also focused on monitoring comfort in existing buildings. Often a discrepancy exists between designed, measured and perceived comfort. In the design phase, for a lot of parameters the values are still unclear, or are overestimated for the sake of finding an optimum in the design. This uncertainty can lead to prediction errors which when combined with system anomalies can cause the difference between the predicted and operational comfort level in the building. Also merely measuring comfort indicators like temperature, relative humidity, air flow etc. and testing them against guideline values does not guarantee a certain level of comfort, since the perception and preferences of each user are different. Furthermore the measured values for these parameters do not always correspond with the actual values at the workspace of the user.

Research in the field of perceived comfort, mainly by post-occupancy evaluation (POE), has already led to several adaptations in comfort guidelines, for instance adaptive temperature limits. A Dutch consulting engineering firm has developed a commissioning tool which is used to monitor and visualize building performance based on data received from the building management system. The system monitors the building performance in four areas: comfort, energy, process and component failure. For each area it indicates the performance as green (good), orange (potential malfunction) or red (malfunction). The system also sends feedback to the building manager when one of the monitored fields shows a (potential) malfunction, so the building management can immediately respond to the situation.

The goal of this project is to research to what degree the comfort indicated by the tool really represents the perceived comfort of the building occupants, and to what degree the measured comfort corresponds to the design comfort levels. Additionally, another goal is

to develop a benchmarking application for the tool. The consultant also wants to integrate the possibility to predict the performance of a building, based on a limited set of measured data (a data driven model). This model would be used to decide in the early stages of the monitoring process what adjustments to the building or the system would improve the building energy and/or comfort performance. On this topic, one goal is to determine the feasibility of incorporating more extensive guidelines for comfort in the tool.

MODELING AND EXPERT KNOWLEDGE TOOL FOR RISK ASSESSMENT

The majority of commercial buildings are equipped with climate control systems. These systems are, together with the lighting, the largest energy consumers in the built environment. Most buildings also have access control, intrusion detection, fire detection and other energy demanding systems. All these systems hardly ever operate as intended in terms of energy consumption and asset consumption. Also the lifetime of these complete systems is much lower than the lifetime of the individual components. Besides the fact that this results in high costs for the building owner, this also often decreases occupant comfort. In addition, malfunctioning systems result in more failures and therefore increased maintenance and higher costs. The existing systems make potential savings possible but in practice this potential is almost never utilized due to lack of knowledge and effective tools.

For most construction projects, the design phase energy simulations are not fully utilized during the operational phase of the building life cycle despite the ability of the simulations to describe the behavior of the building systems under different operating conditions and scenarios. Additional information regarding the system behavior during the operational phase can be very helpful to building operators in assessing the needs of different stakeholders and managing risk associated with system operation and maintenance. This information could be particularly helpful in mission critical applications such as data centers and hospitals where the risk of system errors and malfunctions must be kept low given the needs of the building occupants. One goal of this research will be to develop a methodology for the use of design phase building simulations for new buildings and alternative simulations for existing buildings to aid in predicting and managing the risks associated with the building operations as well as a method for balancing the effects of system operations on occupant productivity, energy consumption and maintenance costs as they relate to different stakeholders.

To relate the effects of system operation to productivity, the project will utilize previously developed and well published methodologies that relate indoor environmental quality to occupant comfort and productivity. This project will not seek to develop new relationships between environment and productivity but will instead apply existing knowledge in a unique way. To relate the effects of system operation to energy, the project will use building simulations to assess the system energy performance under different operation scenarios in order to determine the optimal operations sequence when all relevant factors are considered. To relate the effects of the system operation to maintenance costs, the project will rely on an existing expert-knowledge based database of information. The database was designed to provide detailed maintenance cost and risk information to operators for specific equipment in order to assist them in managing both factors. The risk of failure will also be assessed by the incorporation of anomaly detection methods which are based on expert rules. The calculated risk will be an important factor in the methodology for determining the optimal operations for a given building or site on a case by case basis. For instance, for a typical office building the most important parameter for the building occupants may be employee productivity (followed closely by energy efficiency) given the high cost of labor as compared to other related operating costs; however, in a data center the primary parameter may be the minimization of the risk of system failure given the needs of the occupant. These two different priorities may lead to different solutions during both the design and operation of a building. Specifically, the methodology could also be useful in the design phase when risk and first cost are being weighed in order to provide the best value to the relevant stakeholders.

The main goal of this proposed project is the development of a Technical Management At Distance (TMAD) system that provides the continuous optimization of energy and asset performance of building-related systems while considering comfort as an equally important factor. The purpose of TMAD is that the building systems are automatically adjusted. TMAD will contribute in different ways to achieve the asset and energy-savings, including: error detection and tracing errors during the operation of systems; addressing these errors and increasing the efficiency of these systems; making the functioning of the systems dependent on the usage of buildings and their function; developing and implementing energy-saving and asset adjustments with a profitable payback period; and more efficient and less

maintenance and service through dynamic maintenance.

METHODS FOR VERIFYING OPERATIONAL PERFORMANCE IN BUILDINGS

As previously described, pre-commissioning energy assessments of existing buildings are often done on a case-by-case basis using the experience of the consultant, tools developed by the individual consultant and/or simple benchmarking. Assessment of building performance post-commissioning is often left to the operations staff due to the limits of the engineer's/consultant's scope of work. In many cases, the energy performance improvements are often not fully realized in subsequent years due to limited resources on the part of the operations team and the lack of support given to the operators. There is the need for both a systematic initial assessment method for possible subject buildings that goes beyond basic benchmarking as well as the need for a method to assist with the continued assessment of energy performance. While these needs may be met if the involvement of a proficient consultant is comprehensive, open source methods available to all building owners have the potential to provide a greater impact across the entire building stock.

A proposed project at TU/e will focus on the development of a simple initial assessment methodology as well as a methodology for the continued operational optimization of the building systems. The main objective of the project is to create a methodology that will assist in the increased application and savings persistence of RCx. The first objective will be accomplished by creating an easy to use method which can allow an engineer to quickly assess the performance of a subject building. The second objective will be accomplished via the development of a method for the ongoing assessment of a building's energy performance in the period following the completion of RCx. The final aim is to reduce the energy consumption of existing buildings in order to realize as much of the previously identified efficiency increases as possible.

The initial assessment method will be based on a combined surrogate model developed from a detailed model and a simplified model. A surrogate model is a data driven model which emulates the behaviour of a more detailed model as closely as possible but is much easier to implement (Qian et al, 2006). In this black box method, the inner workings of the model are not based on first-principles, but instead on statistical analysis of simulation results. Surrogate models can be assembled using only detailed simulations or using a combination of detailed and

simplified models. Given the availability of simplified building energy models, the second method will be used in this project. The process of building a combined surrogate model is shown in Figure 6 below. Using both model types allows the developer to use more simulations to develop the surrogate model which will presumably improve the robustness of the final model. Methods for developing surrogate models include response surface modeling and kriging. Determining the optimal method for this application will be an early part of the research.

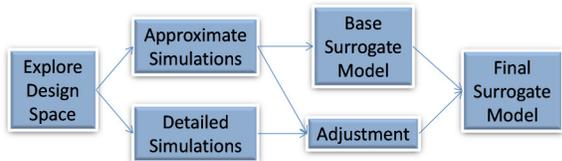


Figure 2. Outline of combined surrogate model development (adapted from Qian et al, 2006)

The operational optimization methodology will utilize simulation as well as data based techniques to present the current status of the building performance to the operational personnel. Commonly, the limited resources available for RCx do not make it possible for the use of detailed simulations that require a lot of time and money to develop. Therefore, in order to increase the level of utilization throughout the existing building stock, the method will be based on a simplified model that can be run at low cost. The development of this model will be aided by the use of the detailed model for inter-model comparisons to assess the accuracy and applicability of the simpler model. Thus, the simpler model will be verified in a select number of cases before being applied on a larger selection of buildings. Following verification the model will be available for use by building owners, operators and consulting firms who seek such methods to monitor and analyze the performance of the buildings for which they are responsible. The features will include data importation, data screening, data visualization, data analysis and a simplified first-principles model. For instance, the data analysis may include the automatic generation of change point models that describe the behavior of the building under different operating conditions (Kissock et al, 2001). The results of these data driven models and the simulation model will be statistically compared to the measured data to identify significant deviations in the behavior of the building. In addition to statistical analysis, the method will include selected visualization techniques that will assist the operators in identifying and diagnosing the cause of performance deviations such as simple time series

line plots, carpet plots, scatter plots, histograms, and etc. which have been previously investigated (Baumann, 2004).

The focus of the project will be on institutional buildings. Using institutional buildings will increase the usage types for which the method is developed as well as the range of building sizes for which the method is developed. Furthermore, if a single large institution is chosen that is in close enough proximity to the university campus, then the educational benefits of the project can be extended to undergraduate and master's students who can assist with onsite investigations, measurements and interviews as a part of their learning experience. Introducing more students to the RCx process at earlier point in their education will help educate further engineers on the importance of operational analysis and assessment of existing buildings. The results of this project will be open source and applicable to as large a portion of the existing building stock as possible. Given the time and cost constraints of the RCx process, the new method will seek to combine accuracy with ease of implementation as well as the capability for simple continued analysis during the building lifetime in the post-RCx period. The deliverables will include a working example application of the methodology as well as documentation describing the development and testing of the methodology for the application of RCx. The main goal of the project will be to provide a well-documented, inexpensive and simple to use methodology for assisting with the initial assessment and subsequent operations of existing buildings. Both methods will be implemented in such a way that expensive third party software licenses are not required for their use. A description of the operations stage analysis methodology (outlined in blue) is shown in Figure 7 below.

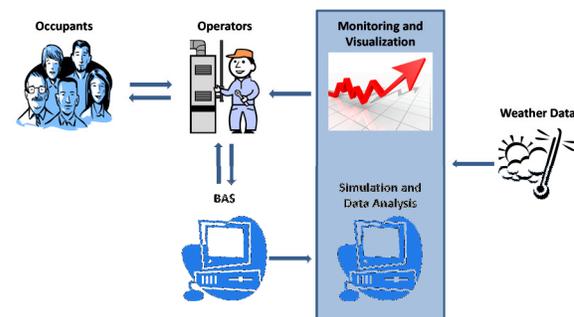


Figure 7. Operations stage analysis methodology information flow diagram

CONCLUSION

Operational performance of buildings is an important area of interest at TU/e as shown by the numerous

projects outlined here which focus on occupant comfort and energy consumption of existing buildings. Past and current research at TU/e utilizing the ABCAT tool has shown the potential of this methodology. The tool successfully identified a change in the energy consumption pattern of the Vertigo building which was the result of control changes implemented by the building managers. This experience has led to the proposal of a project for the development of a pre and post commissioning methodology for the assessment of savings potential and ongoing monitoring of existing buildings. The importance of occupant comfort to the operations of existing buildings led to an ongoing project which is intended to assess the effectiveness of an existing monitoring tool. Another proposed project seeks to utilize expert knowledge systems to develop a risk management methodology for building management companies.

REFERENCES

- Annex 47. 2010a. "Commissioning Overview, a Report of Cost-Effective Commissioning of Existing and Low Energy Buildings", Energy Conservation in Buildings and Community Systems (ECBCS) Program, International Energy Agency.
- Annex 47. 2010b. "Commissioning Tools for Existing and Low Energy Buildings. A Report of Cost-Effective Commissioning of Existing and Low Energy Buildings", Energy Conservation in Buildings and Community Systems (ECBCS) Program, International Energy Agency.
- Baumann, O. 2004. "Operation Diagnostics – Use of operations patterns to verify and optimize building and system operation", Proceedings of the Fourth International Conference on Enhanced Building Operations, Paris, France. October 18-19.
- Bourassa, N.J., Piette, M.A. and Motegi, N., "Evaluation of Retrocommissioning Persistence in Large Commercial Buildings", 12th National Conference on Building Commissioning, May 18–20, 2004.
- BPIE, 2011, "Europe's Buildings Under the Microscope - A country-by-country review of the energy performance of buildings", Buildings Performance Institute Europe (BPIE), ISBN: 9789491143014, http://www.bpie.eu/documents/BPIE/LR_%20CbC_study.pdf.
- Bynum, J.D., Claridge, D.E., Turner, W.D., Deng, S. and Wei, G. 2008. "The Cost-Effectiveness of Continuous Commissioning Over the Past Ten Years", The 8th International Conference for Enhanced Building Operations (ICEBO 2008), October 20-22, Berlin, Germany.
- Bynum, J.D., Claridge, D.E., and Curtin, J.M. 2012. "Development and testing of an Automated Building Commissioning Analysis Tool (ABCAT)," *Energy and Buildings*, 55, pp. 607-617.
- Claridge, D. E., Culp, C. H., Liu, M., Deng, S., Turner, W. D. and Haberl, J. S., 2000, "Campus-wide Continuous Commissioning of university buildings," *Proceedings ACEEE Summer Study on Energy Efficiency in Buildings*, 3(1), pp. 3.101-3.112.
- Curtin, J. 2007. Development and testing of an Automated Building Commissioning Analysis Tool (ABCAT), Master's Thesis, Texas A&M University, College Station, TX.
- Djuric, N. 2008. Real-time supervision of building HVAC system performance. PhD Thesis. Norwegian University of Science and Technology. Trondheim, Norway.
- EIA. 2012. "Annual Energy Review 2011", United States Energy Information Administration, Washington, DC, USA. DOE/EIA-0384(2011).
- EU. 2010. DIRECTIVE 2010/31/EU. Official Journal of the European Union.
- IEA. 2012. "Energy Technology Perspectives 2012", International Energy Agency. Paris, France. ISBN: 978-92-64-17488-7.
- Kissock, K., Haberl, J. and Claridge, D., 2001. Development of a Toolkit for Calculating Linear, Change-point Linear and Multiple-Linear Inverse Building Energy Analysis Models: Final Report, submitted to ASHRAE under Research Project 1050-RP, University of Dayton and Energy Systems Laboratory (December).
- Klobut, K. and Tuominen, P. 2010. "Energy Savings Potential in the Building Stock of nine Member States of European Union", Proceedings of the CLIMA 2010 Congress, Antalya, Turkey. 9-12 May.
- Kraus, F. 2011. "Pilot Project – 'Efficient Homes'", SBN Workshop, Paris, France. 2 February. http://esci-ksp.org/wp/wp-content/uploads/2012/02/SBN05_Kraus.pdf

Lee, S.U., Painter, F. and Claridge, D.E. 2007. "Whole building commercial HVAC systems simulation for use in energy consumption fault detection", ASHRAE Transactions, 113 (1), pp. 52–61.

Maile, T., Bazjanac, V. and Fischer, M., 2012. "A method to compare simulated and measured data to assess building energy performance", Energy and Environment, 56, pp. 241–251.

Mills, E., 2009, "Building Commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse-gas Emissions," Technical Report, <http://cx.lbl.gov/2009-assessment.html>.

Navigant. 2013. "Building Optimization and Commissioning Services - Commissioning, Recommissioning, Retrocommissioning, and Continuous Commissioning Services: Market Analysis and Forecasts", Navigant Consulting, Boulder, CO, USA. <http://www.navigantresearch.com/>.

Qian, Z., Seepersad, C.C., Joseph, V.R., Allen, J.K. and Wu, C.F.J. 2006. "Building Surrogate Models Based on Detailed and Approximate Simulations", ASME Journal of Mechanical Design, 128(4), pp. 668-677.

Shao, X. and Claridge, D.E. 2006. "Use of firstlaw energy balance as a screening tool for building energy data, part I -methodology", ASHRAE Transactions 2006, Vol. 112, Pt. 2, pp. 717-731.

Toole, C. and Claridge, D.E., 2006, "Review on Persistence of Commissioning Benefits in New and Existing Buildings," Proceedings. of 7th International Conference for Enhanced Building Operations – Maximizing Building Energy Efficiency and Comfort, Part II, Paper VI-4-4, Shenzhen, China, November 6-8, 2006, 15 pp.

Turner, W. D., Claridge, D.E., Deng, S., Cho, S., Liu, M., Hagge, T., Darnell, C.J. and Bruner, H.J., 2001, "Persistence of Savings Obtained from Continuous Commissioning," Proceedings of the 9th National Conference on Building Commissioning, Cherry Hill, NJ.

WBCSD. 2006. "Energy Efficiency in Buildings – Business realities and opportunities – Facts & Trends Summary Report", World Business Council for Sustainable Development, Geneva, Switzerland.