USING SIMULATION MODELS FOR BUILDING COMMISSIONING

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Summary The International Energy Agency ECBCS Annex 40 "Commissioning of Buildings and HVAC Systems for Improved Energy Performance" task investigating Use of Whole Building Simulation in Commissioning has identified the following applications of whole simulation in the commissioning process: 1) during the design process; 2) in post-construction commissioning of new buildings; 3) design simulation for on-going commissioning; 4) calibrated simulation for retro commissioning; 5) calibrated simulation for on-going commissioning; and 6) simulation to evaluate new control code. These applications are discussed and examples of each of these applications are provided. The only one of these which has been applied in routine commissioning projects is the use of calibrated simulation for retro commissioning. The other examples have been applied in a research setting, and costs must be lowered for routine application, but there appears to be potential for significant application of simulation in the commissioning process.

Keywords: commissioning, simulation, retro-commissioning, on-going commissioning

INTRODUCTION

Whole-building models are routinely used in the design of building HVAC systems but are not widely used for commissioning. Various models or simulations are sometimes used during the pre-design phase. These models generally simplify the input process with numerous default inputs to speed their use to enable rapid feedback on the significance of major envelope or system configuration options early in the design process. More detailed models are customarily used to size the heating and cooling equipment during design phase, and a detailed simulation model such as DOE-2, TRNSYS, EnergyPlus, etc. may be used to explore the implications of a limited number of design options on annual energy use. While the continuous use of simulation throughout the life cycle of a building has been contemplated for the last two decades (e.g. Selkowitz, et al., 1992), at least, it has never yet been implemented.

When the Annex began, commissioning had rarely used simulation as part of the process. It had apparently only been used for isolated retrocommissioning projects (e.g. Liu and Claridge 1995, Liu et al. 1999). Simulation is also sometimes used during the design process in a way that may be viewed as part of "commissioning" the design. However, participants believed there are significant other opportunities to utilize simulations to improve the commissioning process. This is particularly true when simulation models have already been used as part of the design process, as part of a savings determination process (e.g. Option D of the *International Performance Measurement and Verification Protocol*) or for diagnostics in the building.

IMPORTANT FACTORS IN WHOLE BUILDING SIMULATION FOR COMMISSIONING

Use of whole building simulation in commissioning is likely to be most practical in cases where a simulation has already been performed as part of the design process or as part of a retrofit evaluation. The input deck for the design simulation will then become a direct expression of the design intent. The simulation can then be used to predict building performance and deviations would indicate the need for commissioning measures to bring the building to design intent. However, the specific comparisons that can be performed will be dictated in part by the capabilities of the simulation model and in part by the performance data available for comparison with the simulation. In most cases, EMCS data will be used for comparison with the simulation, necessitating appropriate energy consumption sensors on the EMCS.

The simulation will generally be used to evaluate what we will term "passive testing" or "active testing." The term passive testing will refer to use of data collected during normal operation of the building, without any intervention to extend the range of operating variables implemented during any particular time interval. In contrast active testing will entail use of specified control sequences to determine response to an extended range of operating variables, or a particular dynamic sequence of operating variables.

Passive testing

Passive testing for commissioning as used in the past has generally involved examination of simulated data and of measured consumption data. These comparisons are sometimes performed with time series data, but often with plots of heating/cooling consumption plotted as functions of outside air temperature. If the simulation is an idealized simulation, then significant differences between the simulated and measured consumption are taken as indications that the system is not performing optimally or as designed.

An illustrative sequence of passive tests is described below. This sequence is not exhaustive. Many more tests are used and many others will be developed and used.

    a. <u>Check room temperatures and humidity levels</u>. Trend logs of the temperature and humidity in every zone can be tracked over one or more days. As long as these values stay within the set points (and any control undershoot, overshoot or throttling range), temperature and humidity control are deemed acceptable. If not, diagnostics (that may or may not involve simulation) are needed to diagnose reasons for the excursions observed. If this test is passed,

    b. <u>Compare energy use with predictions</u> over a period of at least a few days. If measured consumption is within an acceptable range of predicted consumption, this test is passed. However, it is non-trivial to develop practical "passing" criteria for this type of test. If "pass" criteria are narrowly missed, this may indicate a need to change inputs and

    c. <u>Extrapolate performance from limited trend data to design conditions</u>. It is certainly necessary to determine whether equipment capacity is adequate.

Depending on the capability of the simulation and the sensors available on the EMCS, it is desirable to verify a wide range of operating parameters such as airflows and supply temperatures to individual zones, waterside system parameters, and primary system performance.

Active Testing

Active testing involves specific active tests implemented for diagnostic purposes; these may be triggered in response to failure of one or more passive tests. Active testing may also include functional tests devised to explore the comfort control capabilities of the system and its dynamic response over a wide range of operating conditions. Active tests normally provide some empirically determined input variables to be used in the simulation program being used.

Active testing will normally control an input variable with a major impact on building comfort and energy performance through a specified sequence of values. It may include the cycling of a known lighting load or other major load on/off on a specific cycle devised to test response of the HVAC system and test system performance. Likewise, it may involve variation of space temperature set points in a way that will test system capacity and control.

A range of tests is needed to test system response to a range of loads in the spaces and to determine the efficiency with which the primary and secondary systems are working with the control system to meet the space loads.

While simulation has been used in a number of specific commissioning applications, a wide range of questions remain to be addressed more generally by both active tests and passive testing techniques. General questions include:

- What capabilities are required in a simulation model to be used for commissioning in specific types of applications?
- How do the necessary simulation capabilities depend on the building type and system type?
- Should tests be devised for a specific model or a group of models?
- Should the model be designed to handle a necessary test suite?
- How should energy balance be used with simulation in the commissioning process?
- To what degree should the experiments be used to tune inputs to the model?
- How much time will be required for simulation?
- How much time can be spent for simulation?

More specific questions to be addressed include:
- How can the capability of the equipment to meet peak loads be most easily determined?
- What about oversizing? Undersizing?
- How can the efficiency of the equipment to meet building needs under normal operating conditions best be determined?

- User behavior impacts performance – particularly in terms of windows, lights and thermostat settings – what are the key parameters that will characterize this behavior?
- The envelope performance is generally more important in Europe and Asia than in North America. What are the most important envelope characteristics for commissioning? E.g. what is the importance of different shapes vs. W/k/m^2-floor area, or window area/m^2 floor, the use of operable widows, window tightness, etc.

DIFFERENT APPLICATIONS OF BUILDING-LEVEL MODELS FOR COMMISSIONING

Annex participants have identified and defined six different applications of whole building models for use in different types of commissioning. These are:

1. <u>Use During the Design Process</u>. Models may be used during the pre-design phase at the beginning of the design process – to assist in "commissioning" the design. Typically, models configured for rapid use, such as TRNSYS Light, Enerwin, etc. are used for this purpose. They may or may not be used for energy simulation. This modelling is not used during the commissioning after construction. The use of detailed simulation models later in the design phase may also be considered to be part of "commissioning" the design.

2. <u>Use in Post-Construction Commissioning of New Buildings</u>. A design simulation of the building may be used to predict heating and cooling performance and the predictions may be compared with measured use – significant deviations then serve as clues to identify problems in the building. The design simulation should have the occupancy schedules changed if necessary to reflect the actual occupancy of the building. Simulation may also be used at this stage to refine and optimise controls strategy. Relatively complex simulations are used for this purpose.

3. <u>Use of a Design Simulation for On-Going Commissioning</u>. The same simulation developed in the design process may then be run at specified intervals, e.g. weekly, monthly, etc. and the model predictions compared with the measured energy consumption. Deviations may serve to trigger an alarm when building performance degrades. Diagnostics for the probable causes of such deviations need to be developed. These simulations will probably be run off-line, but may be run on-line if the control system can accommodate the simulation.

4. <u>Use of Calibrated Simulation for Retro Commissioning</u>. A rapidly calibrated simulation may be used as a diagnostic aid and to predict the savings that will be achieved from implementing proposed commissioning measures.

5. <u>Use of Calibrated Simulation for On-Going Commissioning</u>. The calibrated simulation developed in the retro-Cx process may then be run at specified intervals, e.g. weekly, monthly, etc. and the model predictions compared with the measured energy consumption. Deviations may serve to trigger an alarm when building performance degrades. Diagnostics for the probable causes of such deviations need to be developed. These simulations may be run off-line or on-line if the control system can accommodate the simulation.

6. <u>Use of Simulation to Evaluate New Control Code</u>. Either the design simulation or a calibrated simulation may be used to test the energy impact of proposed changes in control code before implementation. This will generally be done off-line.

EXAMPLES OF USE SIMULATION MODELS AT THE BUILDING LEVEL

Each different application of whole building models in commissioning will be described in this section in the context of one or more specific applications.

Use During the Design Process

Holst (2003) used simulation in conjunction with the generic optimization program GenOpt (Wetter 2001) to develop an optimized set of design parameters for a small 461-m^2 school building in Trondheim, Norway. The optimization program was used to select parameter variations on 14 input variables used in the simulation program EnergyPlus (LBL 2001). The following quantities were optimized: window area and U-value for each of the four sides of the building; thermal mass, exterior wall insulation thickness, roof insulation thickness, floor insulation thickness, shading device transmission, and the night setback temperature. Each parameter was assigned a starting value corresponding to the value used in the school as built. GenOpt then determined the minimum combined heating, cooling and lighting consumption for the building by varying these parameters within set bounds using specified step values for each parameter. The optimization process reduced the simulated consumption of the building by 22.5% after performing 122 simulations from the 2.9x10^{10} combinations permitted by the input variables.

Baumann (2004) will be reporting on the use of simulation to optimize the design of a school building in Germany later this year.

Use in Post-Construction Commissioning of New Buildings

Keranen and Kalema (2003 and 2004) have utilized simulations of the 9500 m^2 IT-Dynamo Building in the commissioning process. This building, which houses the Department of Information Technology at Jyvaskyla Polytechnic in Jyvaskyla, Finland, was completed in May 2003 and placed in service in August 2003. The building has been simulated using the programs IDA-ICE (IDA 2002) and RIUSKA (RIUSKA 2003) based on DOE-2. The heating and electricity use of the building are monitored and the electricity used for HVAC is separately monitored. Indoor conditions including numerous temperatures and CO2 levels are monitored and stored for two days on the building automation system. During commissioning, these variables have been transferred to memory for longer terms.

Comparison of the simulated and measured heating consumption showed measured heating consumption almost twice the simulated consumption during the first three months of operation. Investigation revealed that heating and cooling thermostat dead bands were too narrow in about 20% of the building area, resulting in continuous operation of either the heating or the cooling at maximum values in these areas. Correction of this problem reduced the difference between measured and simulated heating consumption to less than 10% in each of the next three months.

Attention has now shifted to comparisons that show electricity consumption for cooling and ventilation to be much higher than simulated. The reasons for this discrepancy are being investigated and will be reported later this year. Other commissioning activities are investigating reasons for poor temperature control in a number of rooms, and discrepancies between simulated and measured exhaust air temperatures.

Carling et al. (2003a, 2003b, 2004) have tested the use of whole building simulation in the commissioning of an office building in Katsan, Sweden. This building utilizes multiple innovative HVAC systems. They used the IDA simulation environment to assess these untested HVAC-solutions and for dimensioning. During the initial commissioning they evaluated the performance using extensive measurements from the BEMS. Five-minute values for about 200 signals were collected during a full year following the initial occupancy of the tenants. A detailed whole-building simulation model was calibrated with adjusted internal loads based on measured electrical power and measured weather inputs. To determine whether the HVAC-systems performed as intended, the results of the calibrated model were compared with measurements of the whole-building energy use as well as with some important temperatures and control signals.

Comparison between the extensive measurements and the calibrated model were made and use of the different residuals for evaluation of the HVAC-system performance and on-going commissioning are presented. At least five problems with control set point and/or operation were detected and corrected as a result of this process.

Carling and Isakson (2004) found the cost of the procedure to be too high for routine application for several reasons: generating the detailed model took several weeks; model run times were long; additional sensors (at additional cost) would have improved model contribution to commissioning; and dealing with poor data was time consuming. They conclude that the approach has a large potential to support better design and commissioning of buildings <u>provided</u> that the costs can be decreased to an acceptable level.

Nakahara et al. (2004) have examined the performance of five simulation programs HASP/ACSS, EnergyPlus, DOE-2, Dest and HVACSIM+ for use in post-construction commissioning as well as design commissioning and on-going commissioning. Despite extensive efforts to accurately simulate the same building using all five programs, the highest annual cooling load was 1.77 times the lowest (310 MWh vs. 175 MWh) and the highest estimate of annual energy consumption for heating and cooling was 1.40 times the lowest (173 MWh vs. 123 MWh). This suggests that great care will be necessary to ensure that a program used for commissioning can adequately simulate a building and that it is properly used.

Use of a Design Simulation for On-Going Commissioning

Adam et al. (2004) will be reporting on the use of the design simulation for the on-going commissioning of the CA-MET Building at this meeting. Holst et al. (2004) will also be reporting on the use of design simulation for on-going commissioning.

Use of Calibrated Simulation for Retro Commissioning

Simulation at the building level may be used as a tool in conjunction with data on the demands and needs of the building to determine the potential for energy savings in the building. This application is particularly apt when commissioning an older building. For older buildings, utility billing history is generally available. The increasing

use of interval metering means that hourly or 15-minute data is more frequently available at the whole building level. The decreasing cost of metering and recording such data means that it will also increasingly be available on the building EMCS for additional end uses such as heating and cooling, though this is not yet common.

Such data can be used to calibrate a simulation program to the measured consumption data from the building. When this is done, the simulation can readily be used to accurately explore the impact of a wide range of building changes, ranging from operational changes that may be implemented as part of a commissioning program to evaluation of thorough energy efficiency retrofit measures, and demand reduction measures. The simulation can also be used to investigate the comfort impact of certain measures before they are implemented.

Claridge et al. (2004a) have developed an approach to calibration of a cooling and heating energy simulation for a building to measured heating and cooling consumption data that addresses some of the time/cost constraints reported by Carling and Isakson (2004). They present a methodology for the rapid calibration of cooling and heating energy consumption simulations for commercial buildings based on the use of "calibration signatures", that characterize the difference between measured and simulated performance. The method is described and then its use is demonstrated in two illustrative examples and two case studies. The report contains characteristic calibration signatures suitable for use in calibrating energy simulations of large buildings with four different system types: single-duct variable-volume, single-duct constant-volume, dual-duct variable-volume and dual-duct constant-volume. Separate sets of calibration signatures are presented for each system type for the climates typified by Pasadena, Sacramento and Oakland, California.

Liu et al (2002a) emphasizes the use of simulation for on-going commissioning, but also contains two case studies in which the AirModel simulation was used to identify and diagnose system problems at the whole building level. These case studies illustrate the value of calibrated whole building simulation for retro-commissioning. The first case study conducted a calibrated simulation of a 28,000 m^2 hospital in Galveston, Texas as part of a retro-commissioning project. The calibration process lead to identification of 2°C – 4°C differences between pre-cooling, cold deck and hot deck temperatures and their respective set points. The simulation was subsequently used to develop optimum schedules for these quantities. In the second case study, simulation was performed on an 11,400 m^2 medical laboratory building in Houston, Texas. The calibration process indicated a probable error in the chilled water metering and serious lack of control in the chilled water valves. Subsequent field inspections revealed that the chilled water meter was reading only 50% of the correct consumption due to an open bypass valve and found that leaks in the pneumatic control lines had caused the chilled water valves to operate in the full open position much of the time.

The simulation effectively identified HVAC component problems and was used to develop optimized HVAC operation and control schedules in the hospital. Likewise, it identified the metering and valve leakage problems successfully in the laboratory building. Re-heat valve leakage problems and excessive airflow problems were identified after fixing the leaking chilled water valve. The simulation indicated that building thermal energy consumption would be reduced by 23% or $191,200/yr by using the optimized operating schedules in the hospital. The measured energy savings were consistent with the simulated savings.

Ginestet and Marchio (2003) have developed a simulation tool that has several features that will be particularly useful for retro-commissioning and on-going commissioning. The simulation utilizes typical weather and building thermal parameters, but also incorporates a number of flow parameters and control parameters that are not used in many building simulation tools. These parameters enable the program to be used to evaluate indoor air quality in individual zones and evaluate different ventilation strategies. It is also able to simulate a number of air handler faults since it models duct pressure drops, fan operation, and sensor problems related to location, bad connections, bad set points, etc. Plans call for addition of a filter model, detailed heating coil model, valve models, and damper models.

Andre et al. (2003a, 2003b) describe the retro commissioning of a relatively new building. The use of building level simulation in this project will be described in a forth-coming paper.

Additional investigators performing relevant calibrated simulation investigations include Adam et al. (2004), Baumann (2004b), Carling, et al. (2004), Holst (2004b) and Masy et al (2004).

Use of Calibrated Simulation for On-Going Commissioning

A simulation calibrated to a building after commissioning is performed may be used to check the measured consumption on an on-going basis. Comparison once a month or once a quarter is probably adequate. Significant increases can then serve as an alarm to indicate when additional commissioning follow-up is justified. Building operators generally don't get very interested in following up on an alarm that does not directly impact comfort and create occupant complaints unless it has a rather substantial cost impact. Hence, there is little need for this

information on an hourly or even a daily basis when tracking whole building consumption. This type of tracking may also be performed with simple regression models of consumption, as well as with more detailed physical models. If the simulation is coupled to a diagnostic system that can indicate probable causes of deviations, this will increase its value.

The need for this type of tracking has been explored by Turner et al. (2001), and findings in two specific buildings have been investigated and reported by Chen et al. (2002) and Liu et al. (2002b).

On-Line Simulation as a Commissioning Follow-up Tool

A design simulation or a calibrated simulation may be embedded in the EMCS. It can serve as an alarm any time consumption deviates beyond an alarm limit. It may also be used to evaluate the impact of any control changes implemented – comparison of measured performance with simulation results would show whether performance has improved or degraded as a result of the changes.

Liu et al. (2002a) presents the results of a study of the potential for using simulation programs for on-line fault detection, problem diagnosis, and operational schedule optimization for large commercial buildings with built-up HVAC systems. Within the Annex 40 context of subtask D2, it examines the potential for the use of calibrated whole building simulation for retro-commissioning and for on-going commissioning.

This study reviewed over a dozen simulation programs and determined that AirModel and EnergyPlus were most suitable for initial use in the on-line simulation applications that were the focus of the study. These programs cover both ends of a spectrum from a relatively simple program that can be used quickly and embedded in an EMCS for on-line simulation to one of the more detailed and flexible simulation program available.

Tsubota and Kawashima (2003) developed detailed load and HVAC system simulation program for a 28,481 m^2 building that consists of an 11-story office wing and a 3-floor conference wing. The building uses double bundle heat pump chillers with heat recovery, an ice storage tank and hot water storage tanks. The simulation was carefully calibrated to measured consumption from the building. The error in cooling load for a week shown was 2.2%, with an expected annual discrepancy of 5.7%. The discrepancy between measured and simulated electric consumption was only 1.4% on an annual basis. The program has been operated online using data from the building so the operators can view hourly comparisons between target (or simulated) consumption and measured consumption. Operators can also view 8-day "weekly" plots of the hourly data comparisons that permit examination of a week's performance and with the same day of the previous week. Similar "weekly" plots of daily total target and measured consumption are also available.

Others performing investigations of on-line simulation include Carling et al. (2004), Claridge et al. (2004b), Holst (2004a), and Masy et al. 2004.

Use of Simulation to Evaluate New Control Code

New control code can be tested by simulation before actually putting it into the system and activating the new or modified mode of control. Baumann has used this approach to optimize the control of the water supply temperature for heating and cooling in a new school. Wang has developed a new simulation tool particularly intended to permit rapid evaluation of the dynamic performance of a building at short time steps so it is suitable for evaluation of control code.

Baumann (2003) has used a TRNSYS simulation in conjunction with the GenOpt program to develop an optimal control strategy for the heating and cooling water supply temperatures in a 10,000 m^2 vocational school in Biberach, Germany. This school will be completed in the summer of 2004 and incorporates an embedded hydronic heating and cooling (EHHC) system consisting of flexible tubes embedded in the massive concrete ceilings. Water heated by a heat pump or cool ground water is supplied to the EHHC system, depending on whether heating or cooling is required in the building.

The massive ceiling has a very long time constant, so controlling the temperature of the water supplied to the system is critical to minimize the number of occupied hours when the space temperatures are either too hot or too cold. The control scheme adopted uses the median temperature values for the last 3 days (with the most recent day double-weighted) to define the "median" outdoor temperature that determines the temperature of the supply water. The supply water temperature varies between a maximum value of 28°C and a neutral value of 21°C as the "median" outdoor temperature varies between values of $T_{o,heat,max}$ and $T_{o,heat,min}$. The supply temperature is maintained at 21°C until the "median" outside temperature increases to $T_{o,cool,min}$ where the supply temperature starts to decrease linearly toward 18°C at a temperature of $T_{o,cool,max}$. The supply temperature is held constant at 18°C for temperatures above $T_{o,cool,max}$ and is held constant at 28°C for temperatures below $T_{o,heat,max}$.

The simulation was used to optimize the values of $T_{o,heat,max}$, $T_{o,heat,min}$, $T_{o,cool,min}$, and $T_{o,cool,max}$ to minimize heating and cooling energy subject to the constraints that the room temperature never go below 21°C and go above

26°C for only a small number of hours. It was found that the optimum heating consumption was only half the maximum value that produced equivalent comfort.

Wang (2003) has developed a hybrid model suitable for rapid short time-step simulation of the dynamic performance of buildings - hence suitable for control simulation and optimization. This hybrid model uses a 3-resistor, 2-capacitor (3R2C) model of the building envelope, with the sum of the three resistances constrained by the total resistance of the envelope and the total capacitance constrained by the total thermal capacitance of the envelope. Wang uses a genetic algorithm to choose optimum values for the resistances and capacitances so the frequency response and phase lag of the 3R2C model closely approximates that of the theoretical model for the walls at all but the highest frequencies. The same technique is used to develop optimal parameters for a 2R2C model of the interior mass in the building by searching in the time domain.

This model was developed in part to determine optimal control strategies for night ventilation and off-peak pre-cooling to take advantage of a Time of Use Rate that was implemented in Hong Kong in 2001.

CONCLUSIONS

The following uses of whole building simulation in commissioning have been defined:

- during the design process
- in post-construction commissioning of new buildings
- design simulation for on-going commissioning
- calibrated simulation for retro commissioning
- calibrated simulation for on-going commissioning
- simulation to evaluate new control code

Examples of each of these applications are provided. The only application cited where simulation has been applied in routine commissioning projects is the use of calibrated simulation for retro commissioning. The other examples have been applied in a research setting, and costs must be lowered for routine application, but there appears to be potential for significant application of simulation in the commissioning process.

ACKNOWLEDGEMENTS

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