Using Whole Building Simulation Models in Commissioning
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The commissioning process has seldom used simulation as part of the commissioning process to date. It has been used for isolated retrocommissioning projects (e.g. Liu and Claridge 1995, Liu et al. 1999). However, there appears to be significant opportunity to utilize simulations as part of the commissioning process, particularly when simulation models are used as (1) part of the design process, (2) part of the savings determination (e.g. Option D of the International Performance Measurement and Verification Protocol) process or (3) for diagnostics following commissioning.

Conceptual descriptions of three major applications of simulation as part of the commissioning process follow:

1. Use in the standard commissioning of buildings. A design simulation of a new building could be used to predict heating and cooling performance and the predictions could then be compared with measured use – significant deviations would be used as clues to identify problems in the building. Likewise, a calibrated simulation can be used similarly in the retrocommissioning process.

2. Develop calibrated simulation of the building after Commissioning (new or retro-) and compare predicted consumption with measured consumption at some interval such as quarterly or annually – deviations could serve as an alarm for changes in building performance. Diagnostic techniques using the simulation and measured data to identify probable causes of such deviations should be developed.

3. On-line simulation. 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. Alternatively, new control code could be tested by the simulation before actually putting it into the system and activating this mode of control.

Implications of each of these modes of use will be explored and described in more detail.

Use of Whole Building Simulation in the Commissioning of Buildings

This is likely to be most practical in cases where a whole building simulation has been performed as part of the design process or as part of a retrofit evaluation. The input deck for the design simulation would then become a direct expression of the design intent. The simulation could then be used to predict building performance and deviations would indicate the need for commissioning measures to restore 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 would be used for...
comparison with the simulation, necessitating appropriate energy consumption sensors on the EMCS.

The simulation would 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
The passive tests described are simply illustrative. Many more will certainly be developed and used.

a. Check room temperatures and humidity levels. Trend logs of the temperature and humidity in every zone could 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 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. Compare energy use with predictions 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 will be 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. Extrapolate performance from limited trend data to design conditions. It is certainly necessary to determine whether equipment capacity is adequate.

Depending on the capability of the simulation and the sensors on the EMCS, it will be desirable to verify a wide range of operating parameters such as air flows and supply temperatures to individual zones, water-side system parameters, and primary system performance

Active Testing
Active testing may involve specific active tests implemented for diagnostic purposes and triggered in response to failure of one or more passive tests. It may also involve a set of 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 will normally be expected to result in empirically determined input variables to be used in the simulation program being used.

Active testing will normally vary an input variable with a major impact on building comfort and energy performance. It could include the cycling of a known lighting load or other major load on/off on a specific cycle devised to test response of HVAC system and test system performance. It may involve variation of space temperature set points in a way that will test system capacity and control.
A range of tests will be 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.

A wide range of questions need to be addressed in developing both active tests and passive testing techniques. Questions to be addressed include:

General questions:
- What capabilities are required in a simulation model to be used for commissioning?
- 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. What are the most important envelope characteristics for commissioning?
- E.g. Importance of different shapes vs. $W/km^2$-floor area, or window area/m² floor, the use of operable widows, window tightness, etc.

**Whole Building Simulation for Older Buildings**

Simulation at the building level may be used as a tool in conjunction with data on the demands and needs of the building, and an energy balance to get the potential for energy savings in the building. This latter application is particularly apt when commissioning an older building. For older buildings, utility billing history will generally be available. The increasing use of interval metering means that hourly or 15-minute data will increasingly be 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.

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.

**Calibrated Simulation After Commissioning as a Commissioning Follow-up Tool**

Calibrate a simulation to the building after commissioning is performed and compare simulation results with consumption on an on-going basis. Comparison once a month or once a quarter is probably adequate. Significant deviations may then serve as an alarm for changes. The deviations that are considered significant will depend on the accuracy of the simulation and the stability of the building operation. 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. Our experience suggests that the minimum setting for such an alarm should be an increase of 5-10% in heating or cooling. 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. (2002).

**On-Line Simulation as a Commissioning Follow-up Tool**

As noted in the introduction, 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. Alternatively, new control code could be tested by the simulation before actually putting it into the system and activating this mode of control. The discussion for the potential applications of such simulations that follows is excerpted from Liu, Claridge and Haves (2002).

There is an increasing realization that many buildings do not perform as intended by their designers. Reasons include faulty construction, malfunctioning equipment, incorrectly configured control systems and inappropriate operating procedures. Changes in the use or configuration of buildings without corresponding changes in systems or operating practices often contribute to these problems. Occasionally the problems are caused or compounded by design errors.

The first step in detecting and diagnosing such problems is the evaluation of building performance. A quantitative evaluation of performance requires a baseline or reference, against which to compare the actual performance. Possible sources of such a baseline include:
1. The previous performance of comparable buildings
2. The current performance of comparable buildings
3. The previous performance of the building in question
4. The intended performance of the building in question

In the first case, the performance of the building in question is compared to that of similar buildings using a database of the actual performance of a statistically selected sample of comparable buildings. The comparison is usually made in terms of whole building electricity and fuel consumption. This ‘benchmarking’ process can provide an approximate assessment of relative performance from very modest input data, typically building type, floor area and geographical location. Benchmarking is a useful screening tool, allowing attention to be focused on those buildings that appear to be performing poorly.

In the second case, campuses or chains of comparable buildings with suitable monitoring capabilities may be compared on the time-scale of an hour to a week to detect the onset of operational changes or malfunctions that have a significant effect at the whole building level. This quasi-real-time form of benchmarking provides a relatively simple method of detecting significant degradations in performance before the cumulative effects of that degradation become severe.

In both the first and second cases, simple regression models are typically used to correct for differences between the conditions under which the actual performance is observed and the conditions for the baseline. However, simulation models are starting to be used as interpolation tools for more sophisticated benchmarking where more information about the buildings and their energy systems is available.

In the third case, the previous performance can be represented using a ‘calibrated simulation’, in which the parameters of the model are adjusted to minimize the difference between the predicted and measured performance over a selected period. The model can either be a detailed first principles model, such as EnergyPlus (Crawley et al. 2000), DOE-2 (LBNL 1982) or ESP (ESRU 2000), a simplified first principles model, such as AIRMODEL (Liu and Claridge 1998), or an empirical model, such as an artificial neural network (Kreider and Haberl 1994). In addition to providing a baseline for future performance, first principles models can also be used to identify more efficient operating strategies. Detailed first principles models tend to be over-parameterized for the measurements that are available in practice, suggesting that simplified first principles models may be more appropriate. This approach is discussed in a later section.

In the fourth case, use of a whole building simulation program is the natural method of representing intended performance. Comparison of actual and intended performance can be made either during commissioning or during routine operation. In the second, third and fourth cases, comparisons of energy use, peak demand and comfort conditions can be made on time-scales ranging from hours to weeks. In general, a longer time-scale results in greater accuracy of the prediction but less information that may be useful in diagnosing the nature of any faults or problems.

The second step is to identify the faults in a building by comparing the intended performance with the actual performance. This requires that the actual energy consumption (such as whole building electricity, heating, and cooling energy
consumption) be measured along with weather and room conditions. These measurements are compared with the baseline performance and any differences analyzed to determine the faults.

The third step is to diagnose the problems if the measured performance differs from the expected or predicted performance. This can be accomplished by using one or more of the following approaches:

1. Inspect building and measure major building operational and control parameters, such as system operation schedules, supply water temperatures, supply air temperatures, etc. to identify faults
2. Conduct numerous short term measurements with dedicated meters. Input measured parameters to a specialized system model(s) or component model(s) to identify possible problems.
3. Calibrate baseline model(s) to match the simulation output to current measured energy performance data by adjusting input and operational parameters.

The first approach can identify major mechanical and electrical problems, such as broken VFDs, and damaged valves or dampers. If engineers conduct the field inspection, the control sequence may be checked as well. However, it is often hard to identify problems that only occur under different operating conditions. For example, it is hard to identify a leaking hot water valve if the inspection is conducted during winter when the valve is controlled open or it will be hard to detect chilled water hunting if the inspection is conducted during summer when the system is not hunting.

The second approach is useful for identifying problems with a particular component or set of components. This approach will be developed and integrated into Building Automation Systems (BAS) as the declining cost of sensors makes it practical.

The third approach requires that building energy consumption be measured. The building energy consumption can be measured using dedicated meters or meters installed as part of the BAS. The operational schedules, control parameters, envelope parameters, and or occupancy schedules are adjusted as physically appropriate in the input section of the baseline model. The baseline model results are then compared with measured consumption. If there are significant differences, building parameters and schedules are adjusted to match the simulation output with measured performance.

If the operational schedules in the original baseline model are changed to match the simulation with measured performance (energy consumption and room conditions), the deviation of the changed operation and control schedules from the original schedules is the cause of the poor performance. The fault or faults are diagnosed. This approach can be implemented from remote locations or on site. This approach can effectively locate the faulty devices and the nature of the problem(s). It can also identify historical problems and problems that occur under other weather and occupancy conditions, providing comprehensive system diagnosis capabilities.

The exact mechanical problems may not be identified explicitly. For example, this approach may identify a leaking control valve. But it may not determine whether the leakage is due to an excessive pressure difference or a stuck valve core. On-line simulation cannot entirely replace field inspection. A field visit should be performed to
identify the problem and repair should be performed accordingly. Using simulation to assist in fault detection and diagnosis can maintain high building performance with minimum cost.

**Case Study**

The following case study illustrates the use of off-line simulation in the process of commissioning an existing building. However, it also serves to illustrate the diagnostic capability of simulation, whether used off line or on-line. It is taken from Liu and Claridge (2002).

**Building and HVAC Systems**

The Basic Research Building (BRB) at M. D. Anderson (MDA) Cancer Center is a seven-story building with 123,000 ft² gross floor area, which includes 93,000 ft² for the laboratory and office section, 20,000 ft² for a library, and 10,000 ft² for mechanical rooms and other purposes. The HVAC systems operate 24 hours per day.

Four single duct constant volume air handling units (AHUs) provide cooling and heating to the laboratory and office section. The design airflow rate is 150,000 cfm with 100% outside air. Figure 1 presents the schematic diagram of a typical AHU. The pre-heat deck set point is 55°F. If the outside air temperature is below 55°F, the pre-heat coil warms the air temperature to 55°F. If the outside air temperature is higher than 55°F, the pre-heat valve is closed. The cold deck temperature is set at 55°F. The room temperature is controlled using reheat. If the room temperature is below the set point, which varies from 72°F to 75°F from room to room, the reheat coil is turned on to maintain the room temperature.

In addition to the single duct system that serves most of the building, there is one dual duct constant volume air handling unit, which provides cooling and heating to the library.
section. The design airflow is 27,000 cfm with 50% outside air intake. Figure 2 presents the schematic diagram of the dual duct air handling unit for the library section. The cold deck set point is 55°F. The hot deck set point varies from 85°F to 110°F as the outside air temperature decreases from 85°F to 40°F.

![Schematic Diagram of Dual Duct Air Handling Unit for Library Section](image)

**Figure 2: Schematic Diagram of Dual Duct Air Handling Unit for Library Section**

Three single duct air handling units provide heating and cooling to mechanical rooms and other spaces. The design airflow is 14,000 cfm with 100% return air. Figure 3 presents the schematic diagram of these systems. The cold deck set point is 55°F. If the room temperature is satisfied, the AHUs will be turned off.

![Schematic Diagram of Single Duct Air Handling Units for Mechanical Rooms](image)

**Figure 3: Schematic Diagram of Single Duct Air Handling Units for Mechanical Rooms**

The building heating and cooling energy consumption are measured and recorded using a dedicated logger. The heating and cooling signals are split from utility meters. Figure 4 presents the measured hourly heating and cooling energy consumption versus the ambient temperature.
Figure 4: Measured Hourly Heating and Cooling Energy Consumption Versus the Ambient Temperature

Baseline Development

AirModel was used to simulate the building heating and cooling energy consumption using simplified building and system models. The building was divided into two parts: the laboratory section, which uses 100% outside air and the library section, which uses 50% outside air. Each part was simplified to two zones: interior and exterior. The design operational schedules were used in the simulation.

Figure 5 compares the measured heating and cooling with baseline heating and cooling energy consumption. The baseline energy consumption was simulated using actual Houston weather but not the weather data corresponding to the measured energy consumption period. The measured dew point temperature was missing for the measured energy consumption period. The baseline heating is significantly less than the measured heating while the baseline cooling is significantly higher than the measured cooling.

Figure 5a: Comparison of Baseline and Measured Cooling Energy Consumption
Fault Detection and Diagnosis

The baseline cooling is approximately twice as high as the measured values during the peak summer period while the baseline heating is slightly lower than the measured values during winter. This indicates that a fault may exist in the cooling energy metering system. Since the measured value is approximately 50% of the baseline, it was suggested that the scaling factor or the engineering conversion was set incorrectly. The measured cooling energy consumption is adjusted by a factor of 2. Figure 6 presents the corrected heating and cooling energy consumption.

Figure 6: Measured Heating and Cooling Energy Consumption After Meter Correction

The difference between the measured and simulated cooling energy consumption decreases as the ambient temperature increases from 55°F to 95°F. The difference
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decreases when the ambient temperature decreases from 55°F to 30°F. This indicates a leaking chilled water valve. The leaking chilled water valve over-cooled the air. The terminal reheat-coils reheated the air to maintain room temperature, causing significant waste of heating and cooling energy.

Leaking chilled water flow can arise for a number of reasons. A recommendation was given to inspect the control valves.

**Field Inspection**
A field inspection was conducted and found that: (1) all control valves were less than 3 months old; (2) existing pneumatic lines were used when the valves were replaced; (3) all chilled water valves are normally open with a range of 3 to 8 psig; and (4) the maximum control pressure to the valves was 5 psig due to old, leaking pneumatic lines. As a result, it was not possible to close the valves fully.

This confirmed that the leaking chilled water control valves were the primary cause of the poor performance. Fixing the leaking pneumatic lines was expected to reduce the heating and cooling energy consumption to the baseline level.

**Operational Optimization**

It was suggested to reset the supply air temperature from 57°F to 59°F as the outside air temperature decreases 100°F to 59°F. This will decrease simultaneous heating and cooling significantly with a moderate room humidity level increase.

**Implementation**
The implementation included replacing the pneumatic lines and programming the reset schedule into the BAS system. These changes were made at the same time.

Figure 7 compares the measured chilled water consumption before fault detection and diagnosis, the chilled water consumption after fixing the pneumatic lines and implementing the optimized schedule, and the simulated optimal consumption. Figure 8 provides the same comparisons for heating water.

The measured annual cooling energy savings are 28,900 MMBtu/yr, and heating energy savings are 16,162 MMBtu/yr. The total annual cost savings are $369,000/yr, which includes heating savings of $129,000 and cooling savings of $240,000.

When the ambient temperature is lower than 50°F, the measured energy consumption agrees with the simulated energy consumption. When the ambient temperature is higher than 50°F, the measured energy consumption is somewhat higher than the simulated energy consumption. It appears that the building has other problems such as leaking reheat valves and excessive airflow.
Figure 7: Comparison of Measured Cooling Energy Consumption Before and After Repair of Leaky Pneumatic Lines and Implementation of Optimal Reset Schedule

Figure 8: Comparison of Measured Heating Energy Consumption Before and After Repair of Leaky Pneumatic Lines and Implementation of Optimal Reset Schedule
Summary

The simulation effectively identified the metering and valve leakage problems successfully in the this case. Re-heat valve leakage problems and excessive airflow problems were identified after fixing the leaking chilled water valve. This suggests that on-line fault detection should be an on-going process.

The simulation effectively identified HVAC component problems and was used to develop optimized HVAC operation and control schedules in another available case study. It further indicated that building thermal energy consumption would be reduced by 23%, or $191,200/yr by using the optimized operating schedules in this building. The measured energy savings after implementing the optimized schedules were consistent with the simulated savings.

These results, coupled with similar experience in other buildings strongly support the value of simulation in the commissioning process, both for off-line and on-line applications as a diagnostic and optimization tool for building operation.

References


ESRU, 2000. The ESP-r System for Building Energy Simulation, ESRU Manual U00/1, Energy Simulation Research Unit, University of Strathclyde, UK


