Control System Commissioning for Enhanced Building Operations

Timothy I. Salsbury[1] Ashish Singhal
Timothy.I.Salsbury@jci.com Ashish.Singhal@jci.com
Controls Research Group, Johnson Controls, Inc.
507 E. Michigan St., Milwaukee, WI 53202

ABSTRACT

This paper highlights the import role control systems play in the operation of modern buildings and describes ways to improve the final stage of commissioning. We also describe practical issues associated with modern IT-oriented control systems that can impact a commissioning exercise.

INTRODUCTION

Commissioning is primarily a quality assurance process that should include comprehensive testing of building systems to verify that they operate according to defined criteria (ASHRAE 1995, 1999). Commissioning can also involve balancing of air and water circuits, calibration, tuning of controllers, and setting of controller attributes such as setpoints and operational schedules.

In order to carry out a successful commissioning exercise, it is important to plan the activity carefully and make sure all objectives are clear and that procedures are documented properly (Lawson, 1991; Choat, 1993). Certification programs such as LEED have helped promote commissioning and have their own particular criteria (Tseng et al., 2002). Some buildings may require formal validation procedures and there may be legal requirements imposed because of proposed usage.

Subcontractors will normally carry out some kind of commissioning on their part of the building system whether in an ad-hoc way or according to an overall commissioning plan (Tyler, 1994; Underwood, 1993). Sub-elements of a building and its systems thus get commissioned as construction proceeds. However, having individual parts of a system work properly does not necessarily mean that the system as a whole will work as intended.

Modern communication infrastructures allow disparate building systems to be operated in a more coordinated manner. Supervisory controllers are examples of higher-level control that take advantage of networked devices. Although control applications that fully capitalize on the existence of a network are still in their infancy, research activity in this area is increasing (Larsson and Skogestad, 2000). A consequence of more coordinated control is greater interaction between different parts of a building and its systems (Chapman, 1990). Therefore, it is now becoming more important than ever for commissioning to consider these interactions and not just focus on individual elements in isolation (Mills, 1995).

The only way to properly commission the operation of individual subsystems that are interacting is to evaluate performance through the building control system (Tseng, 1994; Shadpour, 2001). This type of performance evaluation should take place after each of the individual subsystems has been separately commissioned. Currently, this kind of commissioning is not normally carried out in a very systematic way. A common approach is to switch on all systems and controllers and manually observe behavior over a prescribed *witnessing* period. Thus, there is a significant potential for improving current practice given the advances that have been made in control system technology.

This emphasizes the importance of control systems in the overall operation of buildings and argues that current approaches to the final stage of commissioning miss an opportunity for a more systematic evaluation of performance.

CONTROL SYSTEM COMMISSIONING

Control is an enabling technology that is often treated as secondary in importance to the devices being controlled. This situation is common in buildings where the control system is traditionally viewed as an added feature to the installation and not central to its operation. The legacy of manual operation in the buildings area has also limited expectations of what role control systems should play. The reality today is that the way buildings

[1] Corresponding author, Phone: +1 (414) 524 4660, Fax: +1 (414) 524 5810

operate is increasingly determined by the control system (Kohl, 2001). There is a general rise in the number of elements in a building that are under some form of automatic control. Moreover, new types of interactions between different elements are being introduced that are governed by applications running in the control system. Typical functions performed by modern control systems include:

- Scheduling of equipment operation
- Local control of devices by regulating variables to setpoint
- Safety functions, such as freeze protection, fire protection
- Supervisory control and coordination of local control loops
- Integration and presentation of system data to building operators

In addition to the integration of different systems such as HVAC, fire, access and security, lighting, etc, new features that are beginning to appear in building control systems are:

- Adaptive and self-tuning controllers – ensures more consistent control performance over time
- Optimization strategies – coordination of different control loops to optimize something such as energy use
- Fault detection and diagnosis – allows problems in the plant or controllers to be detected and diagnosed
- Fault tolerant control – maintains some level of control in the face of a partial system failure

Further advances in networking and communication technology are also making it easier to set up building control systems. For example interoperability, standard communication protocols, and ad-hoc networking concepts are making the idea of plug-and-play a reality for control devices. Gaining access to information on a controls network is also becoming much easier with Internet and wireless connectivity.

At the current time, the development of technology that forms the infrastructure of a building control system has outpaced the development of ways in which to use the additional information that is available. A common problem faced by operators is therefore that of *data* overload. The distinction between *information* and *data* is important since the challenge now facing the controls industry is to develop technology for converting the vast amounts of data available on building control system networks to meaningful information and/or control actions that serve useful purposes.

Communication protocols, access portals, data transmission rates, sensor accuracy, etc., are very important aspects of a control system, but these do not require the controlled plant to be in place in order to verify that they are operating properly. There is therefore a large part of commissioning that will involve testing separate parts of a control system in isolation. Some of these tests may be carried out in the factory before delivery to a building and some may be carried out in-situ. The same situation applies to the plant; for example, a packaged air-handling unit may have already been through some quality assurance tests in the factory but it will also need to be tested once the water, air, and electric supplies have been connected on site.

The distribution of commissioning testing throughout the production and installation cycle of a particular plant or controller item will depend to what extent the item has to be customized for the building and the level of interaction with other systems. A chronological list of typical commissioning/quality assurance tasks for a particular item in a building is listed below.

- Factory-level tests on mass-produced components
- Tests on custom-built components/features
- Installation tests of connectivity such as piping, wiring, ducting, etc
- Interaction tests to ensure that an item is properly integrated in the overall system architecture

As control systems become more complex they are also becoming increasingly modularized. There is a trend toward the encapsulation of functionality within self-contained components that only expose interface information. Complex systems are then constructed by combining different standardized components and linking their respective interfaces. This component-based architecture applies to both software and hardware in a control system. The plug-and-play idea is an example of hardware componentization while object-oriented programming exemplifies its use in software. From a commissioning and quality assurance perspective, modularization helps move some of the onus on testing to the factory and component vendor. A valid expectation is therefore for components, whether hardware or software, to have been tested before arriving at a building for installation.

Hardware or software that is custom-built for a particular building will also normally be tested in some form by the vendor before being shipped. Consider a control strategy for a particular building. The overall control strategy could be built from a library of pre-tested objects and also combinations of objects that form sub-strategies. These sub-strategies may also have been pre-tested. However, because of the diverse nature of building projects, it is likely that the particular strategy that is put together will be unique and will not have been tested in its entirety before. Currently, verification of a control strategy normally consists of checks on such things as data types, causality, logic resolvability, etc. There is little testing of the functional performance of the control logic with the custom interactions set up for the required strategy. However, the development and maturity of simulation technology in the buildings area is creating new opportunities for improving the verification of custom-built control strategies without having to use the real plant/building (Augenbroe, 2002).

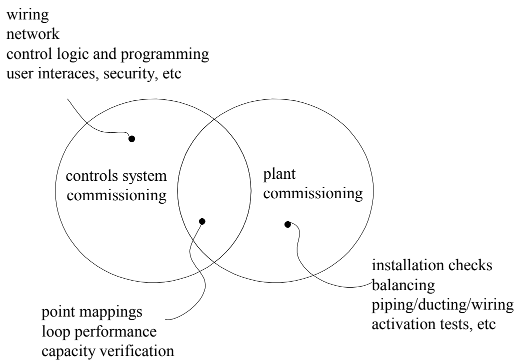

Figure 1: Installation commissioning tasks

The degree of control system modularization and the amount of testing already carried out on different components will determine the extent of commissioning required during the installation process. Of course, the most important aspects to verify and commission on-site will be those that have been affected by the installation process itself. For example, checking wiring and panel connections is very important as is verifying that any on-site software downloads and/or configurations have been successful. Although, pre-calibrated sensors are reducing the need for wide-scale sensor validation, a very important commissioning task is to check whether points have been correctly mapped into the control logic, i.e., are the appropriate actuators being controlled using the correct sensors? Although technology is now available to automate some of the decision-making involved in configuring a control system (e.g., Clapp and Blackmun, 1992) there are still significant opportunities for mistakes to occur.

Tests on the controlled system (plant) may have taken place before installation of the control system or in parallel to it. Figure 1 lists some of the commissioning tasks performed as part of the installation process. As shown in Figure 1, an overlap between the plant and controls occurs at some point in the commissioning process. Even if all the composite plant and control system components have been thoroughly commissioned, there is still a need to check that both pieces operate together as intended.

PRACTICAL CONSTRAINTS

Ideally, an overall commissioning plan should be formulated that minimizes the amount of testing required on the plant and controllers operating together. This can be achieved through good design and selection of pre-tested components, and by performing comprehensive testing on the custom-built parts of the system as they are being put together. There are several reasons to avoid too much testing of the controllers and plant operating together:

- Lack of time
- Difficult to test safety features or performance at extreme conditions
- Requires very broad knowledge of multiple system and controller types to carry out tests and interpret results

Once all systems and controllers are in place and seem to be operable there is normally overwhelming pressure for hand-over to occur quickly so that building owners can realize profit from their investments. Delays that are commonplace in construction projects compound this pressure so that it becomes very difficult to allocate any significant time to the final stage of commissioning. Moreover, the dynamic response times of many building systems are slow making it hard to properly evaluate performance over short periods.

Another problem of assessing performance over short periods and at one time of a year is that not all parts of the system and its safety features can be tested (DuBose, 1993). For example, cooling systems cannot be properly tested in the middle of a cold winter. Also, realistic testing of safety features might require that the plant be put in jeopardy, which would normally be considered an unnecessary risk to take. Finally, the way in which plant and controller items operate together and interact with the building is very complex to understand and analyze. There might therefore be problems finding appropriately skilled persons to perform the commissioning and analyze results.

In practice, commissioning is often performed inadequately during the construction process and the only remaining opportunity to verify performance is with all systems and controllers running together. It is therefore important to make the best possible use of the time available in order to make up for any shortfalls in preliminary commissioning tasks. Trying to verify performance of individual components when all systems are operating and interacting can be viewed as a top-down approach to commissioning. Performing progressive commissioning, as construction proceeds would be a bottom-up approach and this would be the preferred quality assurance option. Choosing a top-down approach is riskier, but can pay off if only few problems happen to exist. In summary, there are several constraints that are likely to be faced when implementing commissioning of the plant and controllers operating together:

- The time available is usually short, typically ranging from 24 hours to 2 weeks.
- Weather and load conditions prevalent at the time of the tests cannot be controlled and restrict the range of achievable operating points
- Preliminary commissioning of individual components may not have been carried out properly and faults may exist
- There is likely to be limited availability of skilled personnel to carry out the tests and analyze results

The constraints outlined above help define the criteria for putting together a methodology for the final stage of commissioning. For example, test procedures should be as extensive and as efficient as possible in order to maximize the usefulness of tests carried out within the short period available. Ways should be devised to evaluate the performance of the system outside of the restricted range available at the prevalent weather and load conditions. The exercise should be conceptualized as a top-down approach to commissioning and therefore should have the ability to detect and diagnose, as best as possible, root causes of problems in individual components and subsystems. Automation should be used as much as possible to minimize the human resources required to both carry out the tests and analyze results (Piette et al., 2000). The following section describes some approaches that could be adopted to test both the controller and plant in unison.

COMMISSIONING METHODOLOGIES

Today, the normal procedure for commissioning the plant and controllers operating together in the period before building hand-over consists of manually witnessing operation over some nominal period. In some cases, the system may be interrogated through an operator's user interface to check whether certain important loops are controlling to setpoint. Typically, the inspection of individual loop performance occurs over small snap-shots of time and might not occur when loops have to reject disturbances. Another common approach is to just leave the system under normal operation for 24 hours, or more, and check whether any alarms have been generated. This latter approach will only be able to reveal quite serious problems in the system since alarming in building control systems is normally set up to detect out of range signals.

System Decomposition

The first thing to do before attempting to formulate a commissioning methodology is to identify modular elements in the system that can be treated similarly. The main purpose of an automatic control system is to make sure designated variables are maintained at setpoints (where, in some instances, the setpoints themselves can be controlled variables). A very general way to decompose a building control system is therefore to consider it as an amalgamation of multiple control loops. A loop comprises control logic, the plant item under control, and the sensor and actuator interfaces to the physical world. Hybrid control concepts are also used in modern control systems. Hybrid control refers to the case where event-based logic interacts with local loops. Sequencing logic, safety provisions, scheduling, etc, are all examples of event-based logic that provide mode changes and override signals when certain events occur.

In terms of trying to develop a generically applicable commissioning methodology, the best approach is to focus on the control loops rather than the event-based logic routines. One reason for this is that the objectives of control loops are well defined in a very general sense. Every loop will use a control algorithm or logic routine to manipulate a plant item via a physical interface (such as an actuator) to control a variable to a setpoint through another interface (typically a sensor). Furthermore, control loops in buildings nearly always use a feedback loop and a PI(D) controller (the D term is rarely used), which considerably simplifies their assessment. In contrast, event-based control routines do not have a standard objective such as trying to control to a setpoint and the objective can be whatever the designer wants it to be. Although it may be possible to group together certain classes of event-based logic, such as sequencing routines, there is a lack of standardization in the way control is performed. An obvious future direction for the industry would be to standardize some of the common event-based control functions to simplify testing and commissioning.

Since event-based control routines are often coupled to control loops as part of a hybrid strategy, it is sometimes possible to adopt a loop-centric approach to testing and still implicitly evaluate elements of the event logic. For example, sequencing logic is normally used to switch control between different pieces of equipment so that a control loop can maintain a setpoint when capacity requirements change. Evaluation of the ability of a control loop to maintain setpoints as conditions change across switching points is therefore one way to assess the whole hybrid control strategy.

Passive Tests

The term *passive testing* has been used in the commissioning community to describe an approach to performance evaluation that is based on observing operation under normal conditions. The current practice of an ad-hoc witnessing period is thus a form of passive test. However, passive testing is meant to include more systematic approaches to the following key elements:

- Selection of variables to observe
- Trending and archiving of selected data points
- Analysis, visualization, and report generation

An obvious choice is to designate the variables that are expected to control to setpoints as the most important data points to observe. It would also be useful to record the setpoints associated with each of the chosen variables, especially if setpoints are likely to change. It might also be useful to include driving variables that have a large impact on system operation, such as outside air temperature, time of day, etc.

Rather than just observe instantaneous values of the selected data points it is very beneficial to set up trend logs and organize the archiving of the data points. In order to be able to establish whether the loops are controlling properly data points have to be sampled at the appropriate frequency and with the proper treatment (as explained in more detail in the next section).

Another important aspect to plan carefully is the analysis of the archived data and the way in which it will be converted into information that will have value. Large buildings can have hundreds, if not, thousands of control loops and a manual analysis of all data trends would not be practical. Some form of automatic processing would thus be required to make the exercise viable. Statistical methods probably hold the most promise for processing large sets of data and some possible techniques are listed below:

- Peer comparisons – this technique can be very powerful in buildings that contain multiple similar systems. For example, in a building with a number of VAV boxes, statistical techniques can be used to identify those boxes that are substantially different from the rest. Methods such as clustering and outlier detection can be used in these kinds of approaches.
- Comparisons with generic expectations or those derived from design information – if a large group of similar items does not exist then another approach is to compare observed behavior with a design expectation or an expectation established from experience or laws of physics.
- Change detection – another possibility is to look for changes in variables over time. This approach is particularly useful if some of the key driving variables are changing to such an extent that new operating points are being explored.
- Correlation analysis – the dependence between different variables can be investigated in order to uncover certain classes of control problems. For example, loops that are unintentionally coupled can end up wasting energy and controller effort through unnecessary interactions.
- Spectral analysis – analyzing the frequency properties of signals could be considered as a form for autocorrelation analysis and these kinds of techniques can reveal such problems as poor tuning and excessive noise.

In the buildings area, the use of advanced analysis techniques for commissioning is not widespread and there are therefore significant opportunities for wider application. Other industries, such as manufacturing and process engineering, have been using statistical techniques for monitoring control performance for many years, i.e., SPC (statistical process control). Recently, interest has increased in using statistical techniques for periodical performance assessment exercises with large-scale practical applications now in use (Paulonis and Cox. 2003). These periodical assessments focus on loop performance and are being called *control loop audits*. There is an obvious synergy between control loop audits and the type of passive tests discussed in this paper and many of the techniques being applied to the process industries would have direct applicability to building systems.

Active Tests

Another way to assess performance is to carry out what is often referred to as *active tests*. These tests differ from their passive counterparts in that normal operation of the systems is disturbed in some artificial way. The purpose of applying artificial disturbances is to elicit responses from plant and controllers to establish performance. Active tests are more powerful than passive tests since behavior can be probed to obtain the kind of information needed to assess performance in the shortest time. Also, some of the constraints imposed by prevalent weather and load conditions can be overcome by forcing plant items to be exercised at different operating points. For example, the operation of cooling coils could be assessed in cold conditions by forcing other devices to generate artificial cooling loads.

A commissioning exercise that incorporates active testing requires a set of test protocols to be designed. The protocols could either be in the form of a manual procedure or could be programmed into the control system. There would be two main types of test that could be carried out through the control system:

1. Open loop test – this kind of test would involve putting a control loop into manual mode and making changes to the manipulated variable. A typical test would be to stroke an actuator from one extreme to another and observe the response from the plant. This kind of test could be used to verify that the plant is controllable and to determine settings for the control logic. It would also be possible to characterize the plant from an open loop test and compare observed behavior with some expectation. Design specifications, past empirical data, experience, or physical laws could be used to derive an expectation.

2. Closed loop test – a closed loop test would involve applying a disturbance such as a step change to the plant input or setpoint. The difference between this test and the open loop test is that the controller and plant are assessed together. Closed loop tests can also be designed to characterize the plant, but they also allow the suitability of the control law and tuning to be ascertained simultaneously.

Closed loop tests are more of a top-down approach to commissioning since they lump together the controller and the plant. In contrast, open loop tests allow a more thorough assessment of plant behavior. Although it is theoretically possible to decouple plant and controller performance from a closed loop test, it is more difficult to properly analyze plant behavior than with open loop tests. In addition to being able to assess the controller and plant together, closed loop tests will normally take less time and be less disruptive to the system since control modes do not need to be changed to manual. In practice, the main factor that will decide whether to carry out open- or closed-loop tests will be the time and resources available. When time is limited, a practical approach would be to first carry out closed loop tests and only carry out open loop tests if problems are found. Figure 2 shows a flow chart for a possible decision process.

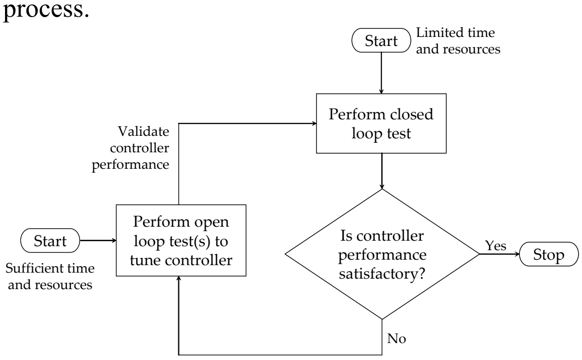

Figure 2: Open versus closed loop tests

Although actives tests are a more powerful way to assess performance than passive tests they also have a number of practical disadvantages:

- Requires engineering effort to set up and perform the tests – the costs involved in carrying out manual tests would most likely be too high for typical building projects. Although tests could be automated, there would be costs involved in programming the test sequences into the control system.

- Reluctance to perform tests – the fact that active tests involve making changes to the system once it is finally up and running can be perceived as a risk. Furthermore, there will probably be reluctance to probe the system to search for problems that are not apparent when the system is up and running properly in its nominal state.

Another issue that can affect the viability of active testing is the degree to which the test sequences would need to be customized for each particular system. Ideally, an active test procedure that is carried out through the control system should not require too much information about the types of system being controlled and the general design. Although, control loops could be treated as generic classes in an active test plan, some information about the interaction between loops would need to be known. A parallel testing approach could be carried out on loops that operate independently, but a sequential approach may have to be adopted for interacting loops. The overall organization of an active testing plan would therefore require information about the design of the control strategy. Unless, this information could be inferred automatically, the engineering requirements of an active test plan might be cost-prohibitive in many cases.

IMPLEMENTATION ISSUES

The commissioning approaches that make use of the building control system to evaluate plant and controller performance are all data-driven. The control system is used to make measurements of variables over a prescribed test period and these measurements form a data set that is analyzed to evaluate performance. The ultimate aim is to ensure that the building and all its constituent systems operate satisfactorily in terms of comfort conditions, and energy use, among other things. All the ultimate measures of performance relate to the physical and continuous world. Use of the control system to obtain a view of real behavior thus involves some level of distortion because control systems operate in a discrete and digital way.

It is important to be aware of the distortions that a digital view of the world can impose as some of these can be severe enough to cause false diagnoses to be made. Some of the most important distortions that occur in building control systems are described below.

Sampling – a digital control system makes measurements of a variable at instants in time. Everything that happens between consecutive sample instants is lost. Discretization of continuous variables by means of sampling is therefore a process of information removal. The important thing is to make sure that sampling occurs fast enough to capture the pertinent features in the signals needed to characterize behavior of the considered systems. To evaluate control loop performance, sampling rates should be selected based on the combined dynamics of the plant and controller. A slow loop could therefore be sampled at a slower rate than a fast loop and still reveal the same amount of relevant information.

Sampling theory dictates that sampling should occur more than twice as fast as the fastest frequency of interest in a periodic signal. If the signal is not periodic, there should be on the order of ten samples within each time constant. In buildings, some control loops should therefore be sampled much faster than others. For example, a static pressure loop should really be sampled faster than once a second, while a room temperature controller could be sampled every minute. It is important to emphasize that no meaningful information about controller and plant performance can be established if sampling is too slow. Data from a static pressure loop sampled every minute is little more than useless in being able to properly establish performance.

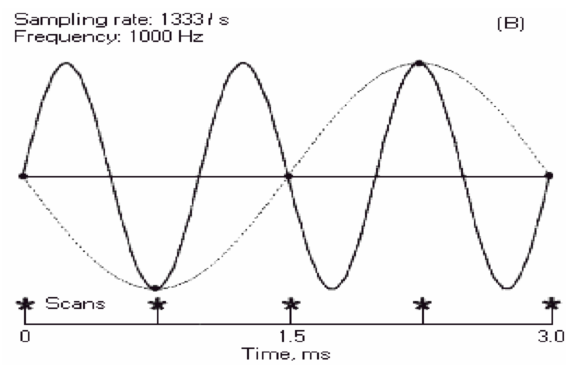

Figure 3: Aliasing of a signal

Anti-aliasing filters – when a signal is sampled by a control system, frequencies that are faster than half the sampling frequency will be aliased. Aliasing means that the original frequency can no longer be determined and slower frequency components will instead appear in the sampled signal (see Figure 3). High frequency noise, caused by such things as power line interference can thus lead to slower frequency (aliased) components appearing on the sampled signal. These aliases can cause excessive controller effort and interfere with subsequent performance evaluation. Control systems should therefore be equipped with analog anti-aliasing filters that remove high frequency signals before they enter the digital domain. Also, digital anti-aliasing filters should be used before any down sampling takes place. A failure to observe this latter requirement will may lead to problems when trying to analyze the down sampled data.

Deadbands and other non-linear elements – many "tricks of the trade" that are programmed into controllers are non-linear in nature and end up causing more problems than they solve. Dead-bands are one example of inherently non-linear elements that are common in building control systems that can result in instability. Rather than making a loop more non-linear, a better approach is to properly design and tune the controller (Bialkowski, 1992).

Signal quantization – sampling discretizes a signal in the time domain but the use of analog to digital converters also discretizes the signal in the amplitude range. Signal values thus get rounded or quantized to a degree depending on the number of bits being used. Furthermore, the problem is significantly compounded by the use of *change of value* (COV) routines popular in building control systems. These COV routines are designed to only report a new signal value if it has changed by a certain amount, sometimes specified as a percentage of the signal value itself. The result is that quantization is not only made worse, but that its effect varies depending on signal amplitude. The combined effect of severe quantization and poor sampling can make data virtually unusable for performance evaluation.

Archiving and data compression – although data archiving infrastructures are still in their infancy in the buildings area, other industries such as process control have made major progress in building the technology for handling large data sets. Indeed, businesses are being built around the data archiving idea suggesting that there are profits to be made. Data archiving and databases are driven by software technology and control theory or dynamics rarely play a role in the design of the systems. A consequence of this is that the emphasis has been on developing software-based methods to compress data sets as much as possible to reduce storage and transmission costs.

Data compression can be considered like sampling and it involves throwing away some information. Although, data compression techniques are designed to be able to re-construct the original data set with minimal information loss, the control viewpoint is often not considered and features can be lost or distorted that would influence control performance assessment (Thornhill *et al.*, 1999).

Control systems in buildings and in other applications are becoming more a part of the general IT (information technology) picture, which is a good thing in many respects since it allows significant leveraging of technology and a lowering of costs. However, the downside is that the control system industry is becoming dominated by IT-oriented viewpoints on design and implementation and there is a danger that sight will be lost of the application itself. In addition to the points above, the design of control applications need to be made with an understanding of control theory and also an appreciation of how practical constraints impact behavior. A priority for the industry should be to make sure that education programs include the fundamentals of control theory (Santos, 2001).

CONCLUSIONS

Commissioning is a quality assurance process that is applied to buildings to ensure satisfactory comfort conditions, energy use, and operational behavior of systems and services. Automatic control systems now operate more systems in buildings than ever before making the performance of buildings intrinsically linked to that of the controls. The use of advanced control strategies that tie together the operation of many different systems is also making it increasingly difficult to ensure correct operation of the whole building by just testing its constituent parts. The final stage of commissioning involving testing controllers and plant acting together is therefore becoming a critical part of any successful commissioning exercise. This paper has discussed the main objectives of building control systems and the importance of overall, or holistic, commissioning tests. Methodologies for carrying out tests through the control system have been described and practical issues highlighted.

One aim of the paper has been to stress the important role that control systems play in the operation of modern buildings and to emphasize the dangers of adopting an overly IT-oriented view of controls at the expense of observing fundamental control theories and constraints. Finally, commissioning should be recognized as a quality assurance process that can be reapplied at various stages in the building life cycle, and even continuously (Liu, 1999).

REFERENCES

ASHRAE. 1995. “HVAC commissioning process”. ASHRAE Guideline, n 1-1989R, Dec, 1995, 110p.

ASHRAE. 1999. “Building Commissioning”. Published in the ASHRAE Handbook – HVAC Applications – Chapter 41.

Augenbroe, G. 2002. “Trends in building simulation”. Building and Environment, v 37, n 8-9, p 891-902.

Bialkowski, W. L. 1992. “Dreams versus Reality: A View from Both Sides of the Gap”. Proceedings of Control Systems ’92 (Modern Process Control in the Pulp and Paper Industry). Whistler, B.C., Canada.

Chapman, C. M. 1990. “Distributed control for distributed systems”. IEE Colloquium (Digest), n 93, 1990, 5p.

Choat, E. E. 1993. “Implementing the commissioning process”. ASHRAE Transactions, v 99, n pt 1, p 857-862.

Clapp, M. D., G. Blackmun. 1992. “Automatic engineering of building management systems”. GEC Review, v 8, n 1, 1992, p 40-46

DuBose, G. H., J. D. Odom, P. W. Fairey. 1993. “Why HVAC commissioning procedures do not work in humid climates”. ASHRAE Journal, v 35, n 12, 6p.

IEA Annex 40 “Commissioning of Buildings and HVAC Systems for Improved Energy Performance”. Website www.commissioning-hvac.org.

Kohl, R. 2001. “Commissioning HVAC controls systems”. ASHRAE Journal, v 43, n 12, December, 2001, p 27-30.

Larsson, T., S. Skogestad. 2000. “Plantwide control: A review and a new design procedure”. Modeling, Identification and Control. Volume 21. Pages 209-240.

Lawson, C. N. 1991. “Documentation of the commissioning process”. ASHRAE Transactions, n pt 1, 1991, p 765-772.

Liu, M. 1999. “Improving building energy system performance by continuous commissioning”. Energy Engineering: Journal of the Association of Energy Engineering, v 96, n 5, p 46-57.

Mills, E. 1995. “Lighting commissioning - a neglected opportunity”. Strategic Planning for Energy and the Environment, v 15, n 2, p 25-28.

Paulonis, M. A., J. W. Cox. 2003. “A Practical Approach for Large-Scale Controller Performance Assessment, diagnosis, and improvement”. Journal of Process Control. Volume 13. Page 155-168.

Piette, M. A., S. K. Khalsa, P. Haves. 2000. “Use of an information monitoring and diagnostic system to improve building operations”. Proceedings ACEEE

Summer Study on Energy Efficiency in Buildings, v 7, p 7.101-7.112

Santos, J. J. 2001. “Controls education: More critical than ever”. HPAC Heating, Piping, AirConditioning Engineering, n SPEC. ISS, May, p 10+12+14-15.
Shadpour, F., L. E. Willis. 2001. “DDC systems as a tool for commissioning”. ASHRAE Journal, v 43, n 11, November, p 43-45.

Thornhill, N. F., M. Oettinger, P. Fedenczuk. 1999. “Refinery-wide Control Loop Performance Assessment”. Journal of Process Control. Volume 9. Page 109.

Tseng, P. C., D. R. Stanton-Hoyle, W. M. Withers. 1994. “Commissioning through digital controls and an advanced monitoring system - a project perspective”. Source: ASHRAE Transactions, v 100, n 1, p 1382-1392.

Tseng, P. C., K. Stum, H. J. Enck. 2002. “The role of commissioning in LEED certification”.
HPAC Heating, Piping, AirConditioning Engineering, v 74, n 2, p 38-40+43+66.

Tyler, R. J. 1994. “Legal aspects of building commissioning - claim avoidance”. ASHRAE Transactions, v 100, n 2, p 1159-1168.

Underwood, T. D. 1993. “Commissioning process: How it affects the building owner and maintenance contractor”. ASHRAE Transactions, v 99, n pt 1, 1993, p 863-866.