Commissioning of HVAC Systems for Improved Energy Performance: IEA Annex 40 Update

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Synopsis

The Energy Conservation in Building and Community Systems program of the International Energy Agency (IEA) has established Annex 40, a research working group on Commissioning of Building HVAC Systems for Improved Energy Performance. The objective of Annex 40 is to develop, validate and document tools for commissioning buildings and building services. This work includes five tasks: 1) the commissioning process, 2) manual commissioning tools, 3) building energy management system assisted commissioning tools, 4) use of models for commissioning, and 5) commissioning projects.

The Annex research project has completed its working phase and is currently at the middle of the final-year reporting phase. At this point in the project, the commissioning process has been well defined and numerous tools have been developed to facilitate various aspects of commissioning. These tools include standard models of commissioning plans (SMCxPs) for various building types, task lists that can be applied using a cost benefit analysis, and software designed to aid in automation and documentation of tests. Many of these tools have been tested in real building commissioning projects and the results are being documented along with the lessons learned regarding challenges in development and implementation.

This paper, based on the work produced by the different participants of Annex 40, presents the goals of the Annex 40 research project, describes the progress made in each subtask, and gives a snapshot of the results to date. Parts of this document are excepted from the collective documents prepared within the Annex including the draft final report [1,2,3].

About the Author

Natascha Castro is the US team leader for Annex 40. As a Mechanical Engineer in the Mechanical Systems and Controls Group of the NIST Building and Fire Research Laboratory, she has worked on several projects in the areas of commissioning and fault detection and diagnostics. Natascha is currently working on her PhD at the George Washington University in the field of building control.

The Annex 40 Project

Approximately one-third of end-use energy consumption in the International Energy Agency's (IEA) member countries occur in residential, commercial, and public buildings[1]. In the US, buildings represent 70 % (26.45 quads or 7.8 x 10^6 GWh) of peak electricity use and accounted for 38 % of the US carbon emissions, 52 % of sulfur dioxide (SO_2) emissions, and 20 % of nitrous oxide (NO_x) emissions [4]. This presents a major demand on energy resources, congestion on distribution systems and as well as a significant component of total emissions.

Recognizing this, the Energy Conservation in Buildings and Community Systems program of the IEA has supported projects to enhance operation of buildings. In the 1990s, two successive projects were set up to develop fault detection and diagnosis tools and to implement them in real buildings. The implementation of these tools revealed that most of the buildings never worked as intended. This highlighted the need and importance of commissioning buildings to avoid initial faults. In 2000, two international workshops were organized to define the best international approach to make progress in this field. The resulting project, Annex 40 on "Commissioning of Building HVAC Systems for Improved Energy Performance", was launched for the period 2001 to 2004 [5].

Ten countries are involved in the Annex program as full participants:

- Belgium
- Canada
- Finland
- France
- Germany
- Japan
- Norway
- Sweden
- Switzerland
- USA.

Four countries are involved as observers:

- China
- Hungary
- Korea
- The Netherlands

Participants include research institutions, universities, controls manufacturers, equipment manufacturers, design and construction firms, and energy service companies.

The objective of Annex 40 is to develop, validate and document tools for commissioning HVAC systems and their associated control systems. These tools include guidelines on commissioning procedures and recommendations for improving commissioning processes, as well as software that can be implemented in stand-alone tools and/or embedded in building energy management systems (BEMS). The Annex is divided into five tasks:

Task A: The Commissioning Process
Task B: Manual Commissioning Procedures
Task C: BEMS Assisted Commissioning Tools
Task D: Use of Models and Commissioning
Task E: Commissioning Projects

Details of the scope of each of these tasks are located in the Annex 40 work plan [1] and summarized in the next section.

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[1] IEA member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, The Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States

Annex 40 Research Overview

The following section presents the issues addressed in each task and presents the approach taken to aid in the commissioning process. Major products developed to facilitate the commissioning process (i.e., protocol and software tools) are summarized along with results from the draft final report. The material for this section comes primarily from the draft final report of the Annex [2].

Task A: Commissioning Process

One of the first needs of the Annex was to establish a common vocabulary of relevant terms to facilitate discussions. To meet this need, Subtask A1 was organized to write a glossary of terms using existing definitions were used basis for discussions with modifications as required for Annex 40. This became one of the earliest products of the Annex. It has since been adapted as a web-based tool to improve understanding of disseminated documents as well as to improve future implementations of the commissioning process. In Figure A, a screen capture of the on-line glossary tool, shows the definition of commissioning developed by Annex 40 along with foreign translations, relevant terms and links to the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) definition for comparison.

Figure A: Screen capture of the on-line glossary tool

In many countries, commissioning is viewed as a check of functional performance carried out after system assembly and before handover. However, the Annex favors a broader definition which aims to bridge the gaps between four different visions: the owner's vision for the building, the designer's vision for the plan, the contractor's vision for the assembled system, and the facility manager's vision for the system operation. Annex 40's definition of commissioning in Figure A was guided by the ASHRAE definition and that of the Japanese Society of Heating, Air-conditioning and Sanitary Engineers (SHASE). It defines commissioning as a quality-oriented process for achieving, verifying, and documenting that the performance of facility systems and assemblies meet defined objectives and criteria that continues throughout the whole construction project.

Subtask A2 is focused on describing the Commissioning process, beginning at project inception in the pre-design phase and continuing for the life of the facility through the occupancy and operation phase. The aim was to provide a uniform, integrated, and consistent approach for delivering and operating facilities that meet the owner's on-going requirements. This includes:

- clarifying and documenting the owners expectations for the building in the owner's project requirements (OPR) in a way that the owner and designer will both understand and agree upon,
- translating the designer's plans into specifications which can be understood, realized, and verified by the contractor,
- applying functional performance testing procedures which will enable the contractor, the building owner, and the designer to verify that the system is clearly operating as expected,
- producing a system manual which will enable the operator to best take advantage of the ideas of the designers and of the system realized by the contractor to fulfill OPR,
- producing reports at regular intervals which will enable the operator and the building owner to check that the operation continues to fulfill OPR.

It is recognized that in actual practice, only part of the whole commissioning process is applied. As cost is often a major barrier to commissioning, it is necessary to identify the required tasks for the commissioning project based on a cost-benefit analysis. Building owners must first rapidly assess the level of commissioning needed for their project. This assessment is the basis for customizing the commissioning plan which is necessary to reach a good cost-benefit ratio. The flow chart for this assessment is shown in Figure B. From the Owners Program, three key pieces of information are established: Building size, Building complexity, and Risk level. This same process can be used for small size buildings with a simple heating and ventilation system to complex critical buildings. Risk level is identified by evaluating what potential damage could result when aspects of the owner's project requirements are not met. This includes both quantitative and qualitative components. Using this information can be used along with the probability of occurrence to choose the appropriate commissioning level.

Once the commissioning level is known, an appropriate Standard Model Commissioning Plan (SMCxP) can be selected. These plans are a series of models (or examples) defined for different types of building projects by Subtask A2 members. They include generic task lists with a description of the content for each of the tasks. They are not country specific and can be used as the basis to define customized commissioning plans adapted to a given project. This process tool increases understanding of the effort, related expenses, and management needs.

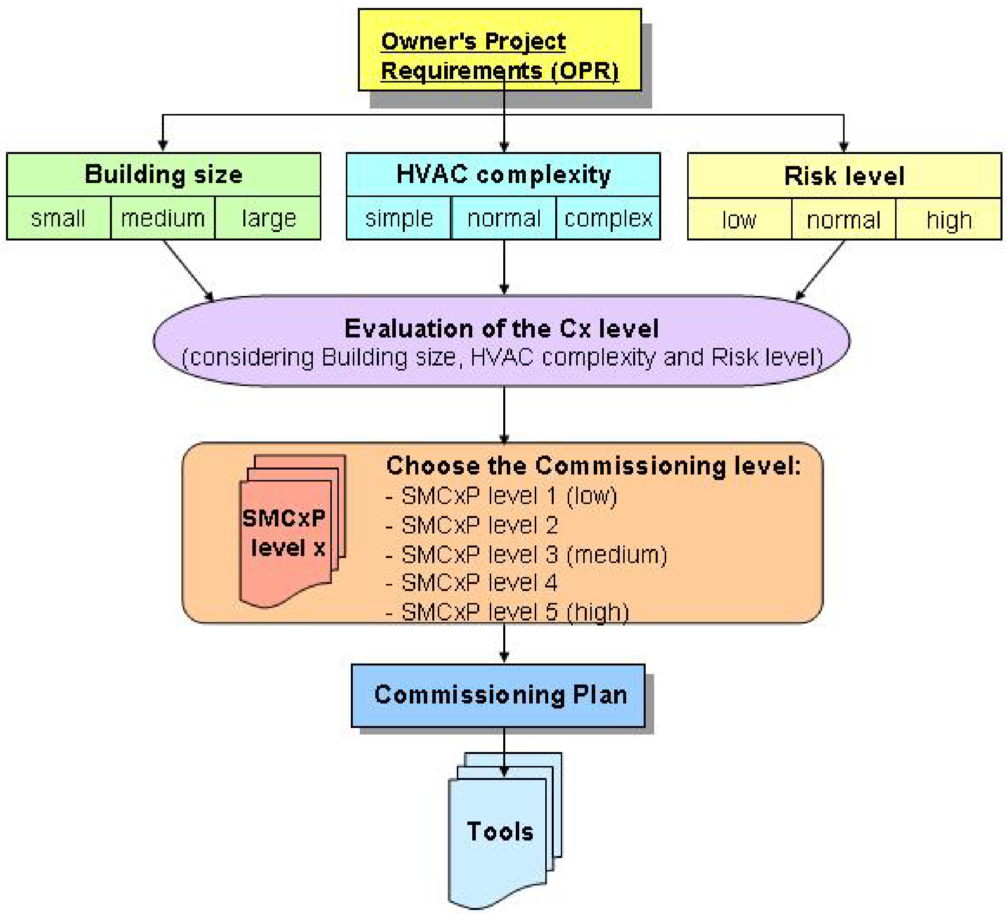

Figure B: Commissioning Flow for Building Type, Risk Analysis, and SMCxP Level

Other process tools that can be applied range in complexity. An example of a simple tool developed by the Annex is a checklist provided for ventilation systems. However, the list of actions required to commission a building can be quite long and therefore must be well structured. For more complex applications, the approach chosen in the Annex is based on a Dutch tool called "Model Quality Control matrix" (MQC)[6]. Model Quality Control is a general model that can be applied for all kinds of processes (building and building services, industrial etc.). Regarding HVAC systems it is possible to elaborate a MQC system for the total ventilation system or for separate elements (i.e.: heating, cooling, ventilation). In the Netherlands the MQC structure is elaborated for heating systems and domestic ventilation systems.

The commissioning matrix show in Figure C consists of columns on the horizontal axis that correspond to project phases: pre-design, design, elaboration, construction and operation and occupancy. On the vertical axis of the matrix, ten quality control aspects are listed, including: 1)task definition, 2)action to be performed, 3)organization to perform the task, 4)tools used to apply the task, 5)purchases and finances needed to apply it, 6)documentation of the results, etc. With this structure a detailed description of tasks can be linked to each matrix cell along with relevant tools. A Screen capture of software developed to facilitate this process is shown below in Figure C [7].

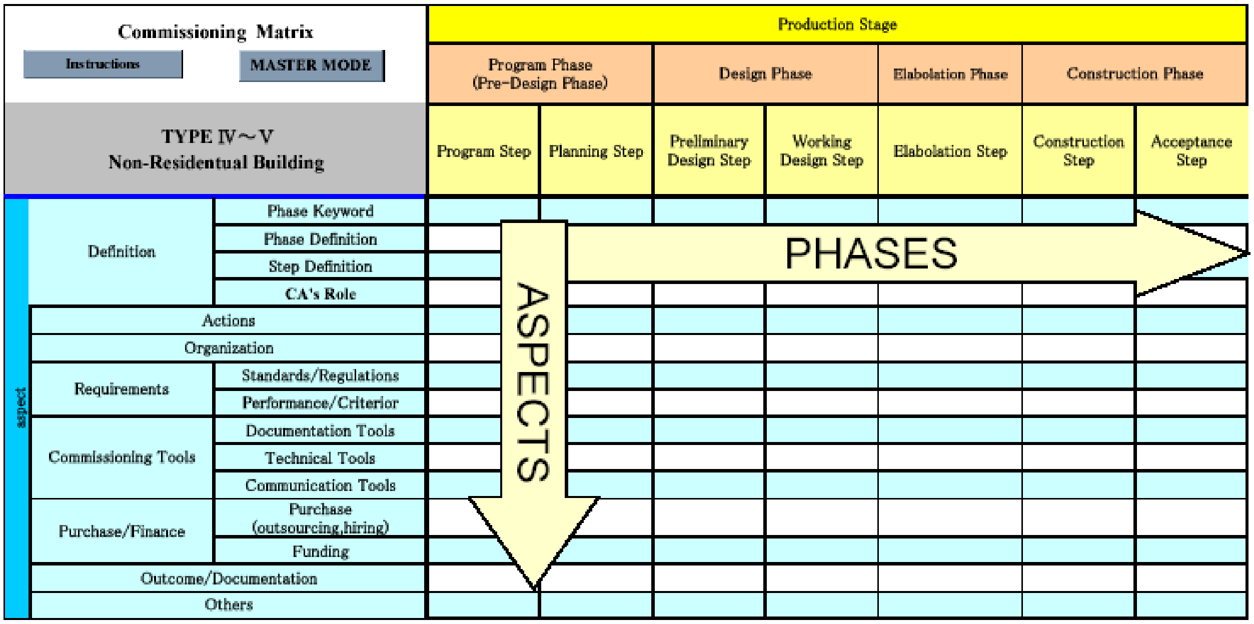

Figure C: Model Quality Control Matrix

An issue related to the commissioning process is the need to identify the best commissioning management organization. The Annex has identified three main organization scenarios without proposing which approach or which combination of approaches is the best adapted to different market situations. Their respective advantages and drawbacks are summarized below.

In the first approach, commissioning tasks are performed by a commissioning authority that reports only to the building owner and is fully independent of the other players in the construction process. This approach assures that an advocate for the owner's interests is looking at all aspects of the project, especially taking into account maintenance issues and the overall process which gives the owner security. The main disadvantages are the extra costs for this new activity and the risk of lower involvement of the other players in quality aspects. In the second approach, commissioning tasks are performed by the usual commissioning related parties: architects, engineers, contractors, etc. This leads to a commissioning process that is much more embedded in the day-to-day practice of their work. The challenge here is to differentiate well the commissioning tasks from the usual design, installation, testing and balancing tasks. It is also a challenge to establish the building owner's confidence that these tasks are really performed above and beyond current practices. This confidence could be obtained through a certification of the players by a third party. The third approach is an intermediate one and consists in having most of the actions performed by the usual players and to have a commissioning authority in charge of verifying that they are effectively performed.[3]

The cost/benefit ratio for commissioning will make commissioning a more common practice. Consequently the number of training and certification programs will increase to meet market demands for commissioning. If the organization of an independent commissioning authority dominates, it is anticipated that a new class of commissioning companies will arise. However, if all major players take on the commissioning tasks, it is anticipated that the commissioning work will be incorporated into their work as a quality control practice.

Task B: Manual Commissioning Procedures

It is recognized that much work has already been performed by different organization throughout the world to develop checklists and performance testing procedures. The main challenge today is to make the best use of existing procedures. The strategy of the task is to define specifications for functional performance tests and to transfer procedures from one country to others, when appropriate, developing new procedures only when necessary.

The target audience of the functional performance tests includes designers of mechanical systems, test designers, those who apply the tests, and building owners who need to be convinced of the benefit of commissioning. Functional performance tests can be carried out at the component, subsystem, as well as at the system level. Primary sources of existing procedures have been located. The easiest access to US procedures is given through the Commissioning Test Protocol Library developed by Pacific Gas & Electric Company and Functional Test Guide developed by Portland Energy Conservation Institute. Regardless of the source, the requirements of the test must be well defined which ties back to the SMCxP task lists and MQC.

The Annex 40 final report will include access to a database containing performance testing procedures developed within the Annex. Because the field of manual commissioning procedures is very broad, different groups in the annex are concentrating on different topics. One group has focused on procedures necessary to apply standard model commissioning plans to simple buildings such as Type 1, 2 and 3 and a second group has focused on more complex, air-conditioned buildings such as Type 4 and Type 5 buildings.[2]

Task C: BEMS Assisted Commissioning Tools

Building Energy Management Systems (BEMS) provide a platform that is powerful and flexible enough to operate various building systems and at the same time offer new opportunities to automate parts of the commissioning process. Task C participants are working to see how the limits of existing commissioning procedures could be extended by using the BEMS as a tool to facilitate commissioning, an application termed “BEMS assisted commissioning”. This involves finding efficient ways to access the necessary data and defining standard data requirements for BEMS assisted commissioning tests. However, because building control is directly dependent on the performance of the control system, it is critical to ensure that the control system is operating as intended. This application of commissioning to the control system and its components is termed “commissioning of the BEMS itself”. Task C is working to develop an integrated set of commissioning tools for these two applications as well as to address implementation issues such as defining the system architecture, where the tool is implemented on the BEMS, communication requirements, and limitations.

BEMS assisted commissioning of HVAC systems is an attractive option. By using the control system to manipulate the energy systems using actuators and switches, it eliminates the need for direct manipulation. Sensors connected to the control system could then log the system responses in a database and the test data could be used on-line or upon request to determine if the system is operating as intended. Various automatic commissioning tools have been developed to target areas in the commissioning process that are labor intensive and therefore expensive. This includes complex analyses that can be facilitated using tools such as simulations as well as simpler checks that are typically only applied to a subset of components due to time or cost limitations (e.g., testing terminal boxes). One limitation is that the BEMS may be operational at too late a stage to be used for much of the initial commissioning process and may therefore be better suited to final or on-going and retro-commissioning. [2]

Two approaches to BEMS assisted commissioning considered in Annex 40 are "passive testing" and "active testing". Passive tests are non-invasive and use the BEMS to monitor the sensor and actuator signals under normal operating conditions. Algorithms are then applied to the data points being monitored to determine if the behavior is correct. This approach requires a low level of expertise over long periods of time. Active tests not only monitor data but also inject test signals to the HVAC system, such as changing setpoints or stopping and starting up plants and opening or closing dampers. These tests can be open loop tests, making specific artificial changes to the system to interrogate behavior, or they can be closed loop tests which continuously adapt to the behavior of the system. The two types of active tests described above are likely more expensive and complicated to implement but can enable much more thorough testing of a controlled system in a shorter period of time than passive tests. Criteria for deciding between passive and active tests are presented in the final report.

For the commissioning of the BEMS itself, an evaluation of user needs and challenges faced by controls manufacturers identified the following potential ways to improve the commissioning of the BEMS via automation: 1) using simulation to test control strategies on a test bench prior to installation, 2) automatically generate reports when checking that all equipment is installed, 3) conducting a range check and auto-calibration of input and output at panels, 4) testing the local controller's self discovery of communication points, 5) closed loop testing of control functions, and 6) for the operator workstation and supervisory controller, set-up a) auto tuning b) test of communication c) check of supervisory strategies through closed loop tests.[2,3]

Tools developed and/or used in the Annex are based on one or a combination of methods to perform or facilitate the analysis of large amounts of data. The methods considered in Annex 40 include cross checks, simulation models, expert rules, graph technology, functional test sequences, and performance indices, many of which were evaluated under Annexes 25 and 34 [8][9] which focused on developing and testing techniques to detect and diagnose faults of HVAC equipment using real time data. Prototype software has been developed to enable the automation or semi-automation of functional performance tests. The prototypes are developed sufficiently to enable testing in real commissioning projects in collaboration with the envisioned users of the tools. The user interfaces for several tools are shown in Figure C. Clockwise from the top, the first interface displays data collected for a period of one week from several air-handling units where multiple faults are color coded, the second interface displays system data and trend logs, and the third interface displays air-handling unit properties.

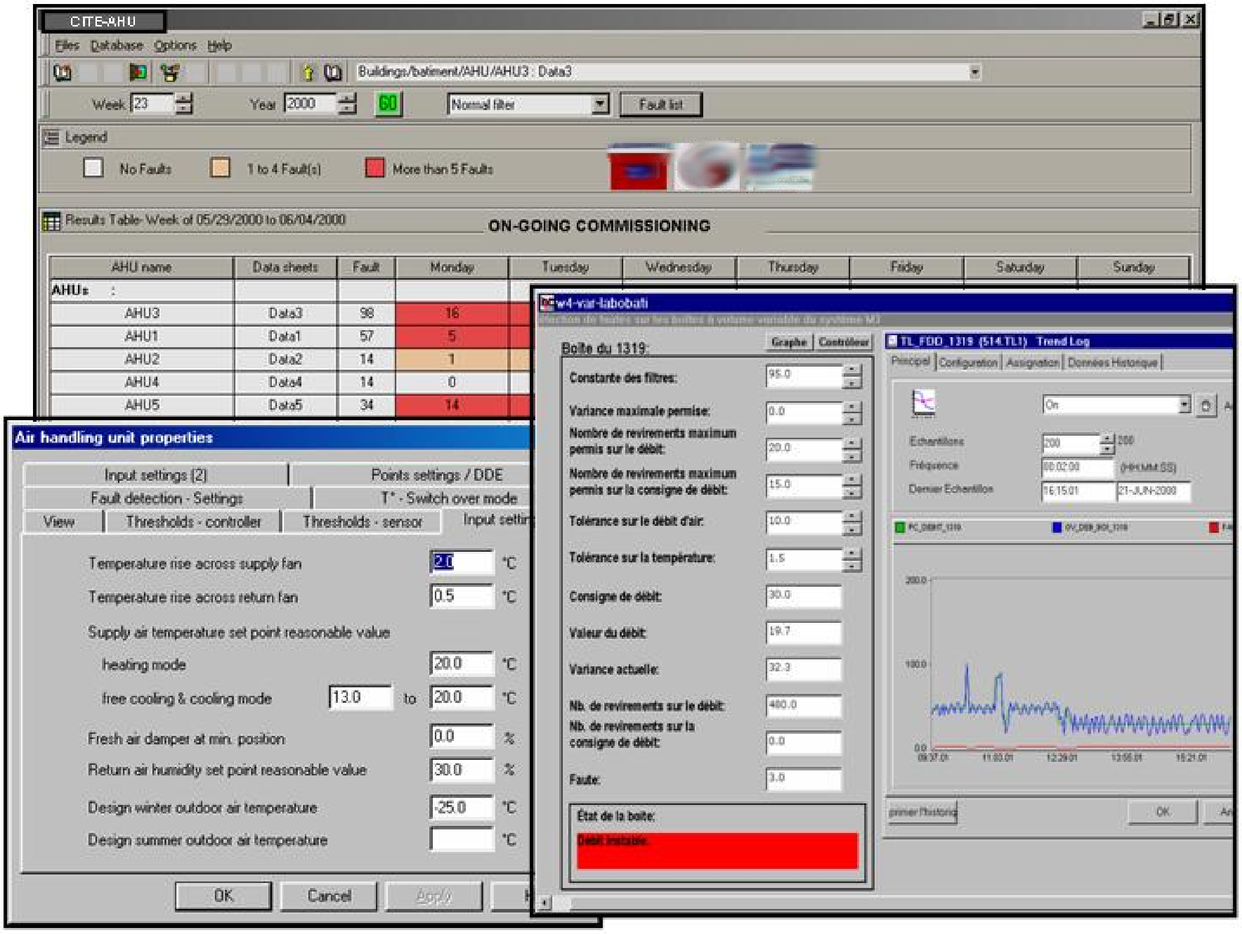

Figure D: Examples of BEMS assisted commissioning tool interfaces

Subtask D: Use of Models and Commissioning

The use of models is becoming more and more widespread. The main objective of Task D is to evaluate the feasibility of using computer simulation, based on models, to verify the performance of components, subsystems, and whole buildings. One of the first activities was to review past and current efforts to use simulation models for commissioning.

Simulation models are applied at two different levels:
- component or subsystem level (addressed in subtask D1)
- whole building level (addressed in subtask D2)

The work in subtask D1 is focused on methods for performance evaluation of air handling units. The goal at the component and subsystem level is to use models of HVAC equipment to represent correct operation. The models are used to prepare functional testing and performance monitoring procedure that are connected to SMCxP. The subtask participants have created a library of component models using the Engineering Equation Solver (EES) software. Models have already been developed for: terminal units, fan coils, components of air-handling units (mixing box, heating and cooling coil), chillers, and a cooling tower. Models are currently being developed for: active cooled beams, chilled ceilings, terminal boxes, free chilling systems, pump and pipe system, ice storage systems, boilers, sensors. In addition, a list of issues to be addressed regarding models was defined. Component models for AHU components and subsystems, multiple variable air volume (VAV) boxes; a heat pump and a cooling tower are being tested off-line using real building data. In addition model based functional test software will be tested online. Figure E shows one type of model that was tested, a simple model that compares the simulated power consumption for normal fan operation to that of the system operation which in this case has a slipping belt.

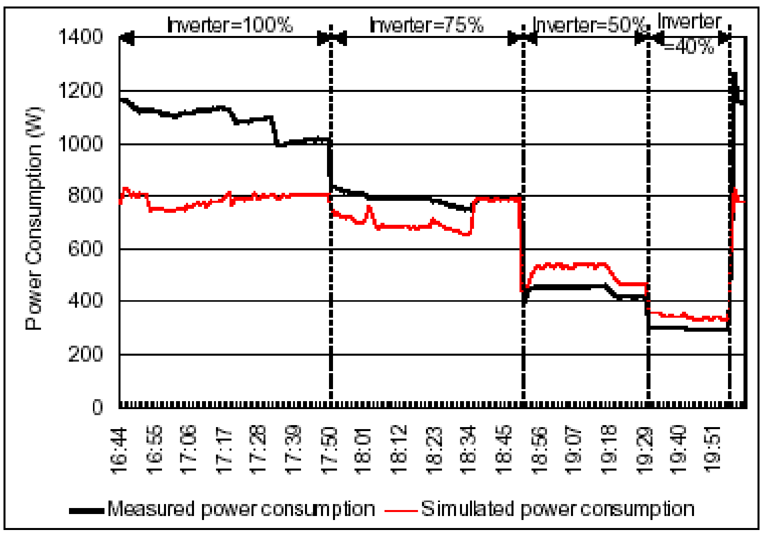

Figure E: Example of a the use of a component model for commissioning

The global vision of the steps to use models at the component or subsystem level is the following[2]:

1. For automated functional testing, the model is configured using manufacturers' performance data and system design information. In general, the model parameters will be determined by a combination of direct calculation and regression.
2. An active test is performed to verify that the performance of the component is acceptably close to the expected performance. This test involves forcing the equipment to operate at a series of selected operating points specifically chosen to verify particular aspects of performance (e.g., capacity, leakage).
3. The test results are analyzed, preferably in real time, to detect and, if possible, diagnose faults.

4. If necessary, the test is performed again to confirm that any faults that resulted in unacceptable performance have been fixed. Once the results of this test are deemed acceptable, they are taken to define correct (i.e., acceptable) operation.
5. The model is re-calibrated using the acceptable test results.
6. The tool is used to monitor performance during on-going operation. This will typically be done in passive mode, though active testing could be performed at particular times, e.g., every weekend, after routine maintenance, after system modifications or retrofit, on change of ownership.

At the whole building level, the subtask members have identified six approaches to using models to perform commissioning tasks that seem promising:

1. Models may be used early in the design process – to assist in "commissioning" the design. Typically, models configured for rapid use are used for this purpose.
2. Use in the standard commissioning of new buildings. A design simulation of the building may be used to predict heating/cooling performance to be compared with measured use and possibly used at this stage to refine controls strategies.
3. Design simulation for on-going commissioning. 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.
4. Use of calibrated simulation for retro-commissioning. 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. Calibrated simulation for on-going commissioning. The calibrated simulation developed in the retro-commissioning process may then be run at specified intervals, e.g. weekly, monthly, etc. and the model predictions compared with the measured energy consumption.
6. Use of simulation to evaluate new control code. 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.

The Annex final report will contain a summary of one or more whole building model applications linked to several of the six approaches listed above. One example of this is shown in Figure E where measured data can be compared to simulation predictions. Other issues that will also be addressed are the importance of building dynamics, the sensitivity of simulations to driving variables and time steps, and the use of simulations with passive and active testing.

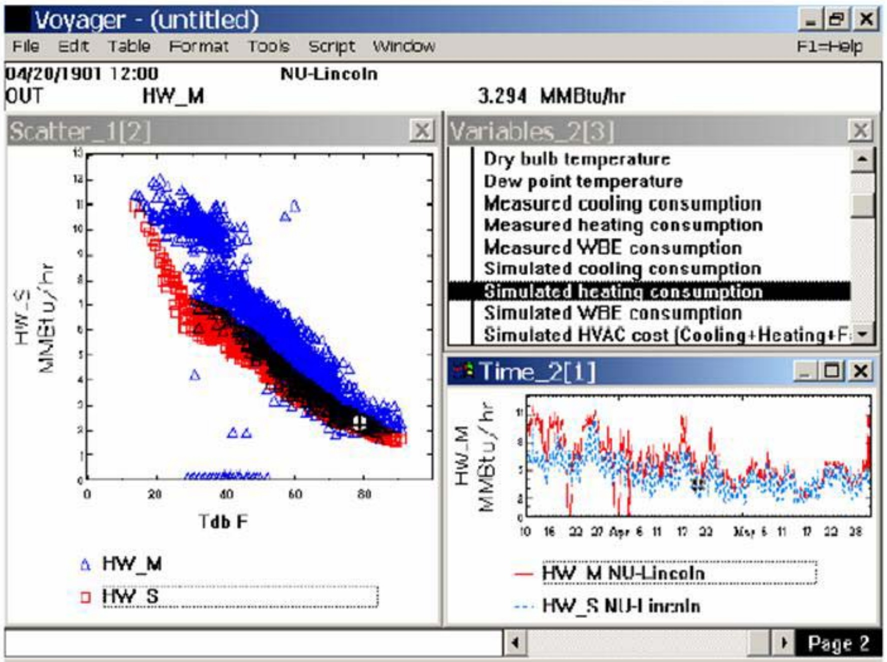

Figure F: A screen shot of the calibration process for a Whole Building Model

Subtask E: Commissioning Projects

The purpose of the commissioning projects is to enable in-depth interactions with potential users of the tools developed within the Annex. Each Annex member is involved in at least one commissioning project and reports on the application of the tools developed within the Annex. These real projects test the tools developed and demonstrate the advantage of commissioning. In effect they are the basis for demonstrating the results of the Annex.

Twenty-five projects have already been selected in North America, Europe, and Japan. They include various building types and include a house, a hotel, a stadium, a train station, and several projects on office buildings, laboratories, schools and shopping centers. A brief description of each of these projects is available on the Annex 40 web site at www.commissioning-hvac.org.

Conclusions

Commissioning is a promising approach to improve the energy performance of HVAC systems, but to do so requires 1) a clear definition of the tasks to be performed, 2) transparency in the roles that individuals have within the commissioning organization, and 3) a practical toolset to help accomplish the task list in a systematic manner.

The Annex 40 research group has collected a tremendous amount of information for both organizational and implementation aspects of commissioning that can aid practitioners as well as design professionals. Process tools, including protocol and software were developed to improve the planning and implementation of the commissioning process for initial, retro- and on-going commissioning. Specific examples have been created for Standard Model Commissioning Plans, Model Quality Control matrices, manual and automated commissioning tools and models. Users will soon be able to draw from this collection of tools or use the structure for developing new ones. The Annex 40 research project is in its final year and has moved from the working phase to the reporting phase. The final report will be publicly available in early 2005.

Acknowledgement

This document is based on the collective documents prepared within the Annex including the draft final report. The author would like to acknowledge the members of Annex 40 for their support in the preparation of this document.

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