International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

Project Summary Report

Commissioning Tools

for Improved Building Energy Performance

Energy Conservation in Buildings & Community Systems Programme

ECBCS Annex 40

Commissioning Tools for Improved Building Energy Performance

ECBCS Annex 40 Project Summary Report

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-eight IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research.

The research and development strategies of the ECBCS Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Building Forum Think Tank Workshop, held in March 2007. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in three focus areas of R&D activities:

Dissemination

Decision-making

Building products and systems

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)

Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Buildings and Communities
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings
Annex 51: Energy Efficient Communities
Annex 52: Towards Net Zero Energy Solar Buildings
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods
Annex 54: Analysis of Micro-Generation & Related Energy Technologies in Buildings
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - Energy Efficient Communities

(*) – Completed

Executive Summary

Space conditioning in buildings represents a significant proportion of the world's energy use and so correctly operating buildings are an important consideration when trying to minimise wasted energy. It has been shown that energy savings of 20% - 30% can be achieved by re-commissioning building HVAC systems such that they operate properly and previous work undertaken in the ECBCS project "Annex 34: Computer-Aided Evaluation of HVAC System Performance", highlighted that many systems in buildings do not work properly.

Building Energy Management Systems (BEMS) are increasingly common in both new buildings and in retro-fitting existing buildings. These systems allow the control of more complex systems and this complexity can cause problems when commissioning. The development of tools that assist the planning and control of commissioning, that can be integrated into BEMS systems and that utilise existing BEMS function, can assist in ensuring that buildings work properly. ECBCS Annex 40 investigated these issues developing approaches to aid commissioning and trialled them in real buildings in a number of different countries.

The project was subdivided into five key tasks:

- **Commissioning process:** deals with the identification of suitable commissioning organisations that are adapted to the complexity and quality expectations of a given project in terms of cost and benefit. Different commissioning organizations are described using a set of 'standard models of commissioning plans.' These plans are customized to describe examples of different national commissioning organizations.
- **Manual commissioning procedures:** includes tools for commissioning without the use of Building energy management systems (BEMS). These have been developed into specifications and trialled in real buildings and across countries.
- **BEMS - assisted commissioning tools:** includes tools to aid the commissioning of BEMS systems and to automate parts of the systems commissioning exploiting current BEMS capabilities. The tools developed are applicable mainly to commercial and institutional buildings. Considered topics were: Use of BEMS today for commissioning; how current limitations of commissioning may be expanded through use of BEMS; BEMS access to data for commissioning; definition of standard data for BEMS augmented commissioning methods; development of prototype automated and semi-automated Functional Performance Testing tools.
- **Use of models and commissioning:** This evaluated the feasibility of using computer simulation based on models to verify the performance of the whole building and its subsystems and components.
- **Commissioning projects:** Demonstration of the tools developed in the Annex on real buildings from all of the participating countries.

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1. Introduction

Building users are demanding better quality of indoor environment while reducing impact on natural resources and minimising energy use. The heating, ventilation and air conditioning (HVAC) industry is addressing these requirements with new products and technologies which is increasing the complexity of installed systems. The resulting systems are not only difficult to design, but difficult to install, set to work and maintain. The process of commissioning can help mitigate these issues.

Commissioning is clarifying building system performance requirements set by the owner; auditing different judgments and actions by the commissioning related parties in order to realize the performance; writing necessary and sufficient documentation; and verifying that the system enables proper operation and maintenance through functional performance testing.

Commissioning should be applied through the whole life of the building and will probably develop in the coming years for three main reasons:

- **Energy and environment -** global warming has increased the pressure to reduce energy use in buildings.
- **Business -** many companies are developing new services to diversify their activities in the building and energy industries and commissioning is a way to offer benefit to their customers.
- **Technological -** building automation systems are now standard in new buildings and are being installed in many older ones and these offer possibilities for innovative commissioning services.

The primary obstacles that hamper the adoption of commissioning as a routine process for all buildings are a lack of awareness, lack of time and excessive cost. Future work should consider how new tools, methods and organizations can address these issues.

1.1. Project Background

The Energy Conservation in Buildings and Community System programme of the International Energy Agency has supported projects to enhance the design and operation of buildings for three decades. In the 90's two successive projects were undertaken to develop fault detection and diagnosis tools and to implement them in real buildings. The goal was to provide building operators with tools to quickly detect faults that occur in building systems. Testing these tools in different buildings throughout the world led to the realisation that most of these buildings never worked properly in the first instance. Commissioning buildings to ensure correct operation is critical to achieving the design performance and the project focused on developing, validating and documenting tools for commissioning of buildings and building services.

The tools developed include guidelines on commissioning procedures and recommendations for improving commissioning processes, as well as prototype software that could be implemented as stand-alone tools and/or embedded in Building Energy Management Systems (BEMS). The Annex focused on the impact that commissioning HVAC systems and their associated control systems had on occupant comfort and building energy use.

1.2. Project Objectives

- To develop tools to facilitate the commissioning of building services;
- to use these tools to verifying and optimising the performance of energy systems within real buildings;
- to develop recommendations and guidelines on commissioning procedures and recommendations for improving commissioning processes;
- to develop these tools for use by;
- contractors and commissioning agents, who will use the tools to ensure that a building satisfies performance requirements at the time of hand-over,
- property owners, who will use the tools to verify the performance of their building and / or to decide whether or not to acquire a building,
- services companies, who will use the tools to improve the operation of a building and to prove that they have achieved this goal,
- BEMS manufacturers, who will implement the tools in their products.

1.3. Achievements

- The development of three tools that address the commissioning process;
- an analysis of the way commissioning is performed in different countries;
- a glossary of terms relating specifically to the field of commissioning;
- four sub types of the conventional term ‘commissioning’ has been identified;
- 12 specifications for functional performance testing were developed;
- a study of the commissioning possibilities using existing BEMS systems;
- a study of the use of models and simulation for commissioning;
- 27 case studies across 12 countries.

2. The Commissioning Process

Commissioning is a quality-oriented process for achieving, verifying and documenting whether the performance of a building's systems and assemblies meet defined objectives and criteria. All too often it is viewed as a task performed after a building is constructed and before it is handed over to the building owner to check operational performance: This leads to deficiencies in performance which can result in excessive energy use.

There are four visions that relate to commissioning a project: The expectations of the building owner; the project of the designer; the assembled system of the contractor and the running system of the operator. Differences in these interests undermine the commissioning process.

These issues could be mitigated by:

- Clarifying the expectation of the building owner to obtain the *owner's project requirements* so that the owner and designer understand one another and are in agreement;
- translating the project of the designer to specifications which can be understood and 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 *system manuals* which will enable the operator to take best profit of the ideas of the designers and of the system realized by the contractor to fulfil owner requirements;
- producing at regular interval report which will enable the operator and the building owner to check that the operation continue to fulfil these requirements.

This broader view of the commissioning process begins at project inception during the pre-design phase and continues for the life of the facility through the occupancy and operation phase. Four types of commissioning have been identified in the project and are depicted in Figure 1:

- **Initial commissioning** is a systematic process applied to production of a new building and/or an installation of new systems;
- **Retro-commissioning** is the first time commissioning is implemented in an existing building in which a documented commissioning process was not previously implemented;
- **Re-commissioning** is a commissioning process implemented after initial commissioning or retro-commissioning when the owner hopes to verify, improve and document the performance of building systems;
- **On-going commissioning** is a commissioning process conducted continually for the purposes of maintaining, improving and optimizing the performance of building systems after initial commissioning or retro-commissioning.

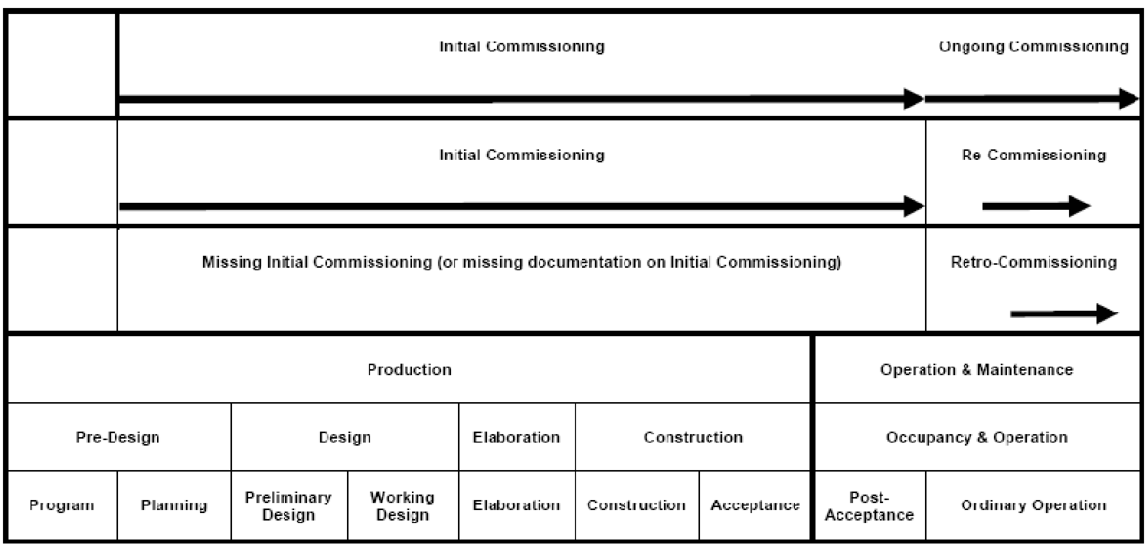

Figure 1: The relationships between building project timeline and commissioning activities.

2.1. An 'Ideal' Approach to Commissioning

The building process from design to operation is described in relation to the (HVAC) commissioning activities. Detailed definitions of the terms used are given in Appendix A.

2.1.1. Pre-Design Phase

The Pre-design phase is the first phase of the Initial Commissioning process, divided into two steps:

Program Step

The *owner's program* is established and the owner generates a *request for proposals* and solicits a *Commissioning Authority*. At this stage the owner can ask for inside and/or outside professionals for advice on technology, finance, business and construction.

Planning Step

The appointment of the Commissioning Authority typically defines the beginning of the planning step. The Commissioning Authority consults the construction manager, facility manager, financial advisor, operation and maintenance staff, occupants, etc., to identify the systems targeted for Commissioning and documents them. In addition, the Commissioning Authority will assist the owner in estimating costs for design, construction, testing, adjusting and balancing, consultants, etc. and investigate the necessary regulations relating to the commissioning. The scope of the work varies widely depending on the project size and owner's requirements for Commissioning. in general, however, for a successful Commissioning Process; the Commissioning Authority develops a commissioning plan and with the owner, formulates the *design requirements*; these requirements in conjunction with the owner's requirements is used to generate the *owner's project requirement* document; this allows a design professional to propose a firm design; consequently, a *Request for Proposal* is generated and used to select a design professional for the project.

2.1.2. Design phase

The design phase begins with drafting schematic planning documents and ends with completion of design documents and their handover to the owner and is divided into two steps:

Preliminary Design Step

Begins with schematic planning documents and ends with the submission of the preliminary design documents. The Commissioning Authority verifies the appropriateness of these documents and clarifies the procedure and schedule of Commissioning. The Commissioning Authority coordinates the commissioning plan with the design intent so that the design professional can state the commissioning specification in the design documents.

Working Design Step

The final design documents are developed. The design professional updates the draft design intent document in the preliminary design documents and completes the final design documents. The Commissioning Authority audits these documents for completeness. The design is the responsibility of the design professional. Inconsistencies with the owner's project requirements, however, should be highlighted to the owner by the Commissioning Authority.

2.1.3. Elaboration Phase

This is the transitional phase between completion of design and commencement of construction. In this period completion of the; construction documents, bid submission, bid assessment and selection of the contractor for the construction are carried out. The Commissioning Authority helps to coordinate the commissioning related parties.

2.1.4. Construction Phase

This includes construction, *testing adjusting balancing*, *functional performance testing* and acceptance, under the guidance of the Commissioning Authority and is described in two steps:

Construction Step

Shop drawings are created from the design documents. The system is installed and Testing Adjusting Balancing is carried out. The Commissioning Authority conveys changes of the Owner's Project Requirements to the commissioning related parties or propose design changes to ensure performance is achieved. The Commissioning Authority audits performance of the construction supervision and control, supervises the Testing Adjusting Balancing work, confirming the maintainability of building systems with the owner

Acceptance Step

Testing Adjusting Balancing work, Building and Energy Management System (BEMS) installation, as-built records and system operation and maintenance manual are completed. The Commissioning Authority verifies the Testing Adjusting Balancing work, the correctness of the as-built records and determines from the Functional Performance Testing results whether the operations of the equipment and systems meet the Owner's Project Requirements. Deficiencies are addressed by the appropriate party. The Commissioning Authority plans and manages the training program.

2.1.5. Occupancy and Operation Phase

This takes place after handover when the building systems are operating acceptably. Some seasonal Functional Performance Testing will still be required with certain systems. There are two steps:

Post-Acceptance Step

Applies to building systems in which the performance is seasonally changed and the *design requirements* demands confirmation of the annual performance (i.e. HVAC systems). This is the final step of The Initial Commissioning process. The role of the Commissioning Authority in this step is to identify the seasonal system performance. This might include (for HVAC systems) determining the system performance for the peak-cooling season, the peak heating season, and the intermediate season when cooling and heating modes are both required. Functional Performance Testing is used in conjunction with the BEMS after faults identified in the acceptance step have been rectified. The term of the post-acceptance step mostly overlaps with the warranty term of the construction and the seasonal Functional Performance Testing mentioned above is considered to be requested in the range of the construction.

Ordinary Operation Step

After post-acceptance step of initial commissioning. If the initial commissioning itself or the post-acceptance step is not applied, this step would be matched with the occupancy and operation phase. In this step, the evaluation work for the re-commissioning and / or On-Going Commissioning to identify the unresolved issues, desired changes, weaknesses identified, desirable improvements identified during Commissioning, warranty action items, etc., may be addressed. The repeated Re-Commissioning could correct faults and the evolution to the on-going commissioning may maintain the building systems in optimal condition through life of the building.

2.2. Organisations for Commissioning

The task of commissioning a building systems can be undertaken by three types of organisation, all with advantages and disadvantages:

- **Commissioning Authority:** Employed by the building owner to oversee the whole process and is independent of the other stakeholders. Offers the most security to the owner but at greater cost;
- **Architects, engineers, installers:** Difficulty in differentiating the commissioning from the usual design, installation and TAB tasks. Owner's confidence that systems are operating correctly may be impaired and may require third party certification;
- **Architects, engineers, installers and the Commissioning Authority:** The third approach would be to use the Architects, Engineers and Installers to carry out the work and have a Commissioning Authority to verify the commissioning.

These approaches drive differing requirements and there is probably no one 'best' solution. To some extent these are driven by national experience, the vision outlined above, however, favours the use of a Commissioning Authority.

2.3. Structuring the Commissioning Process

Whatever organisational approach is chosen, the key challenge to commission a building or system is to follow a well managed process. A central document for that purpose is the commissioning plan which defines the actions to be performed. The commissioning plan is the key tool that gives the stakeholders an understanding of what is meant by commissioning on a specific project, what amount of effort and money will be required and how it will be managed. The commissioning plan can be developed at three levels of detail, described in Table 1

Table 1: Tools used in commissioning plans.

Tool	Description	Level of detail
Standard Models of Commissioning Plans (SMCxP)	A typical description of commissioning actions during a project To be used as a guideline to define the commissioning plan for a given project	Medium
Check lists	Minimum level of definition of a commissioning plan Is specific to a given type of HVAC system	Low
Matrix for Quality Control (MQC)	An extensive tool for the management of the quality of the whole construction project. Includes commissioning plan as well as other elements in a very structured way	High

2.3.1. Standard Models of Commissioning Plans

These are selected in the basis of building size, HVAC system complexity and an accepted risk, offset against cost. Five example standard models were developed in the project:

- Type 1; small size building with simple HVAC system.
- Type 2; medium size building with independent HVAC units.
- Type 3; medium size building with simple HVAC system.
- Type 4; large commercial building with centralised HVAC system.
- Type 5; complex and/or critical building.

- **Check lists:** A simple list of actions and verifications which requires the minimum effort in implementation.
- **Matrix for quality control:** Detailed Microsoft Excel based tool for planning, decision making and data storage. It is designed to be valid for production through to operation.

Details of implementations of standard models of commissioning plans and matrices of quality control in different countries can be found on the project website (www.commissioning-hvac.org).

3. Functional Performance Testing

Functional Performance Testing is required to validate the performance of building systems. Building systems are constructed from many components and malfunction in any of these can compromise the correct behaviour of a subsystem or the whole system. Malfunction maybe due to; design faults, a selection or sizing mistake, manufacturing fault or initial deterioration, installation fault, wrong tuning, control failure, abnormal conditions of use.

Functional performance testing is aimed at detecting these problems and can be realized on the whole system, a subsystem (several interconnected components) or on specific components that are considered as critical. The selection of the appropriate level is made on the basis of risk in relation with the acceptance criteria.

The search for malfunctions can either progress 'top-down' or 'bottom-up':

- **Top-down:** The whole system functional performances are first verified, moving on to subsystems and then onto specific components as malfunctions are found and require investigation. The goal is not to verify if a component is 'good' or 'bad' in itself, but to check if it's correctly integrated in the system considered.

  One problem is the possibility that energy-wasting situations could be missed. For example; a poorly-tuned control may cause an AHU to cycle between heating and cooling. If the zone temperature doesn't vary too much and stays very near to its set point, the problem might not be apparent. Such faults may be found at the system level only, if the waste is great enough to be obvious when compared with expectations.

- **Bottom-up:** Starts by confirming the performance of an elementary component and progressively working up to the whole system. This may be more appropriate for initial commissioning, following construction. It allows a safer identification of local defaults, but it may require excessive effort.

In addition to these basic approaches an 'up-stream' analysis can be useful. This involves working from an observed malfunction back through the hierarchy of systems. For example; a malfunction may be an excessively high zone temperature, the investigation may move towards the 'source' (for example the cooling plant), passing through intermediate subsystems and components (for example the air distribution network and the air handling units). Such a strategy should allow the commissioners to identify the main 'bottlenecks' of the system (for example the reasons why the zone considered is not cooled enough)

It's important that measuring devices and systems and components used as 'measuring devices' are given priority and consequently the BEMS is the first system to have Functional Performance Testing applied to it. Without the verified performance of these, the data collected from them in relation to the measured performance of subsystems cannot be relied upon.

3.1. Integrating FPT into the Commissioning Process

Functional Performance Testing is just one part of the whole Commissioning process and test results should be incorporated into the *As-built Records*. Before Functional Performance Testing can commence, verification checks (also called pre-start checks, start-up checks or pre-functional tests) are necessary to insure safe operation. Typical checks are flushing and static pressure testing of piping systems and verifying:

- Components are actually installed as described in the As-Built records
- Piping and wiring connections
- Calibration and sensor locations
- Safety settings
- Belt tension
- Electrical parameters like voltage and amperage
- Pressure and flow ranges for utility and support systems

In initial commissioning, all component datasheets, containing all operational and maintenance information, have to be delivered before installation and verified against what is installed.

3.2. Pre-Test Preparation

Before testing commences, system information should be collated:

- **Operating principles:** A recall of basic principles (according which the system has been designed), working principles, expected performances, calculation methods and simulation models (used in the design), emergency procedures, interaction with other (sub-)systems and corresponding building service area(s). This information should be made available in the as-built records.
- **Manufacturers' data:** Technical and performance data sheets, including maintenance information for components. Again these sheets should be available in the as-built records.
- **Problems to be considered:** Most relevant malfunctioning cases have to be listed, in relationship with occurrence risks and practical consequences in the case considered (risk analysis). Performance uncertainties (as predicted by simulation) have to be specified, as well as (simulation predicted) sensitivities of these performances to: Conditions of use; (lack of) maintenance; aging, etc.

3.3. The Test Itself

A great deal of information is required to prepare, carry out and analyse the results from a functional performance test:

- **Objectives and test sequence;** what is to be tested, how and expected results.
- **List of verification points, experimental conditions and acceptance criteria;** defined on the basis of preliminary simulations. These simulations can be performed with existing models, having been previously used by Designers, Manufacturers and Installers, and/or with some 'adapted' models, such as those presented in the following section.
- Equipment required.
- Time required.
- Preliminary operation required.

A functional performance test can be performed at any time during the building life cycle. The starting point is an evaluation of all information and data available. Performance criteria must be established in accordance with that information; i.e. the performance goals to which the plant should perform must be realistic.

The following should be considered during this evaluation:

- Measuring and control points already installed which could be used for the test;
- actuators performance;
- experimental design and measuring techniques;
- technical documents issued from the designers (including design goals and relevant parameters, having to be passed on to the construction phase);
- documents supplied by the contractors (including sizing calculation);
- laboratory testing results (if any);
- preliminary (visual) verification records; and
- previous commissioning test report (if any).

In order to monitor a given system under test, complementary instrumentation may be required. Considerations include the HVAC equipment type, reference (example) building zones and the outside weather conditions (drives load). The 'preparation' may also include some adaptation of the BEMS data logging and storage system so that all the relevant variable data can be collected.

3.4. The Test Method

Different components, subsystems and whole systems require a range of test methods that are designed to generate specific performance criteria to be observed. There are a number of considerations:

- Operational conditions and time required to conduct the test

- **Measuring techniques and instrumentation required -** using BEMS sensors, as well as movable equipment and other components already calibrated.
- **Pre-requisites -** what needs to be achieved in the whole building and HVAC system, before verifying the performances of the system or component considered.
- **Data pre-processing -** (cross-checking, filtering, curve fitting, etc) simple mass and energy balances can be used to check the measuring consistency. First principle (static and dynamic) models are used for measurement cross-checking fluid flow, pressure, mass, momentum and energy balances and transfer laws, in steady state and transient regimes. The checking consists in verifying if space and time variations observed (from one sensor to another one and on a same one, from time to time) make sense.
- **Data processing and result analysis**

The content of each Functional Performance Test report should be structured in such a way to make it easier for further functional performance tests to be carried out. This report should present a results synthesis to be included in the as-built records. This technique becomes more useful when HVAC components that have been previously tested in laboratory have calibrated simulation models that are already available.

An important consideration when evaluating the measurement requirements for a specific test is whether existing control measurements are sufficient, or whether supplementary measurements are required. One further possibility is to use calibrated models as ‘measuring devices,’ where a known input is used to infer a critical value, such as control signal and water flow rate though a valve. Control valves, refrigeration expansion valves, compressors, pumps, registers and fans can all be used in this way.

3.5. Functional Performance Test Specifications

Twelve test specifications were developed in the framework of Annex 40 covering:

Residential buildings,	VAV terminal units,
building tightness and air renewal,	sensors installed HVAC systems,
air conditioning systems,	temperature sensors,
fans,	pressure sensors,
humidifiers,	flow sensors, and
cooling towers,	air quality sensors.

Although the specifications developed in Annex 40 require further development, they demonstrated that the use of simulation models in Functional Performance Testing is very promising.

Both residential and commercial building types have been considered in the project, although only specifications for the latter are reported here. In larger, more complicated buildings, a system hierarchy exists and testing can be tiered to focus on; the whole building, the HVAC system as a whole, HVAC subsystems (where air and water distribution networks are two of the most common) and finally specific components (such as fans or heating coils). A number of test specifications are outlined in the following sections and an example specification for the air conditioning systems is given in more detail. Full specifications for all twelve of the highlighted components and systems can be downloaded from the project website (www.commissioning-hvac.org).

3.6. BEMS, Sensors, Actuators and Control Systems

Priority must be given to the Functional Performance Testing specifications for the BEMS and its actuators, sensors, connections, control units and software. Functional Performance Testing consists of:

- Checking the sensors and *re-calibrating* then (if required);
- checking the correct working of the actuators (a visual inspection is mandatory);
- identifying the signal conversion and tuning them (if required);
- identifying the control laws imbedded in the system (with all parameters concerned).

The functionality of the BEMS software and signalling from the sensors / components to the BEMS is of critical importance, without reliable component actions and measurement data, testing and analysis cannot proceed.

3.7. Whole Building

Balances on zone contaminant mass, energy and water mass can be considered to verify that the whole system is performing in an expected manner. This can be done in conjunction with simulation, for which a simple example is given Figure 2.

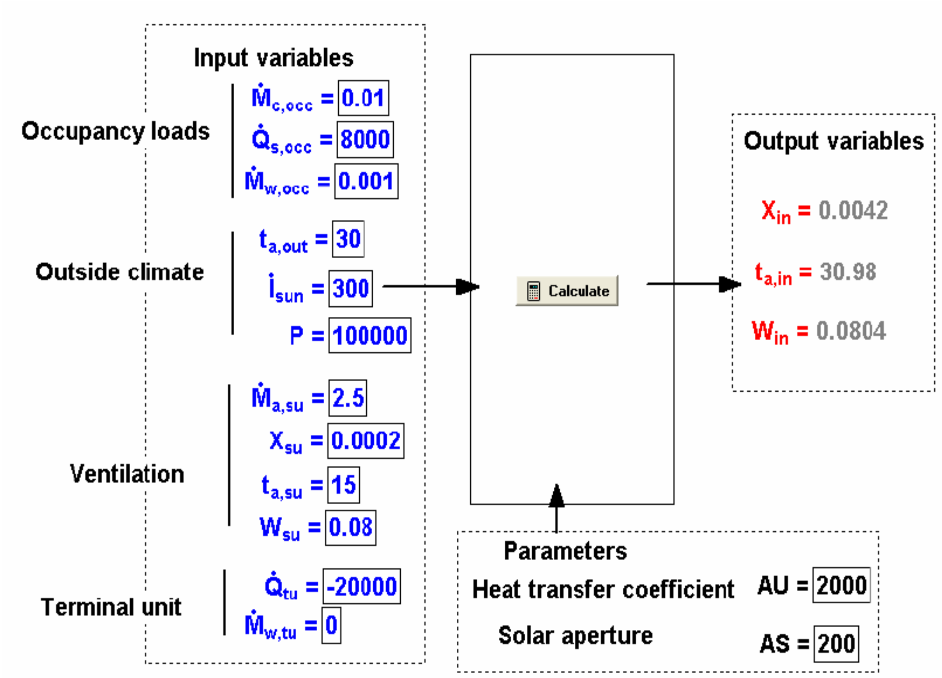

Figure 2: Simplified building zone model.

3.8. Air Handling Units (AHUs)

These subsystems can be evaluated on global performance or in more detail by distinguishing components.

3.8.1. Fans

The fan is one of the most significant energy users in a building. Commissioning and re-commissioning fans and drives is a key factor for ensuring that a building's efficiency goals are met over the life of the building.

There are both indirect and direct components to fan energy use. The indirect component relates to the system the fan serves. The direct fan energy component relates to how efficiently the fan can convert the energy going into its prime mover (usually electricity into a motor) into air flow and pressure in the fan system.

The fan energy use is a function of several fundamental components: flow rate, static pressure, fan efficiency and motor efficiency. Commissioning efforts are targeted at these factors, to ensure system efficiency, performance, and reliability.

3.8.2. Dampers

The economizer can pay a key role in commissioning by:

- Functional performance testing and coordinating with the balancing at start-up, to ensure proper minimum outdoor air flow rates and building pressure relationships;
- Training the operating staff, to help them understanding the initial settings and to ensure their persistence;
- Document the initial settings, as well as the procedure used to obtain them, thereby further ensuring their persistence.

3.8.3. Heating and Cooling Coils

These are usually well defined, but the location inside AHU's hampers tests: Temperature averages are not easy to define on the air side and the water flow rate is not always measurable.

3.8.4. Humidifiers

With liquid water humidifiers it's important to verify the contact effectiveness and the global efficiency (in terms of water consumption). The risk of condensation on internal duct surfaces needs assessment when using steam humidifiers.

3.8.5. Heat Recovery

Heat recovery is essential for good energy performance in extreme climates and there are many types of devices. Each type has a particular issue, For example: The effectiveness of a rotary heat exchanger is controlled by tuning the rotation speed and this control might be faulty; A flat plate heat exchanger is usually equipped with a by-pass system, which may be the cause of a unsatisfactory effectiveness; In a coil-and-brine-loop heat recovery system, it's the brine flow rate which must be controlled and this control also might be faulty.

3.8.6. Control of the AHU

Specific methods are also developed for commissioning of control logics of AHU. Verification of supply temperature is illustrated in Figure 3.

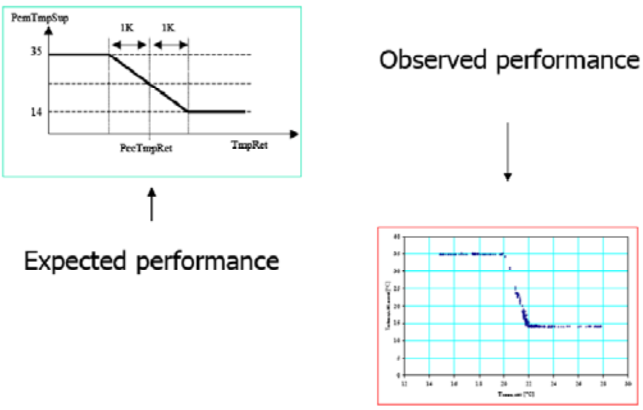

Figure 3: Verification of supply air temperature.

3.9. Test Specification S04: Air Conditioning System (Abridged)

The objective of the aeraulic system in a building is to control for each occupied space the air quality, environmental temperature and air humidity.

3.9.1. Operating Principles

A typical VAV system includes (Figure 4): Air Intakes; Air Handling Units including (which comprise; economizer, filters, coils, humidifiers, supply and return fans); an air distribution network; terminal units (VAV boxes); and control system with sensors, actuators and controllers. The energy saving potentials lie in; air network configuration, network tightness, building insulation, pressure drops, fans characteristics, control strategies, coil characteristics and heat recovery characteristics.

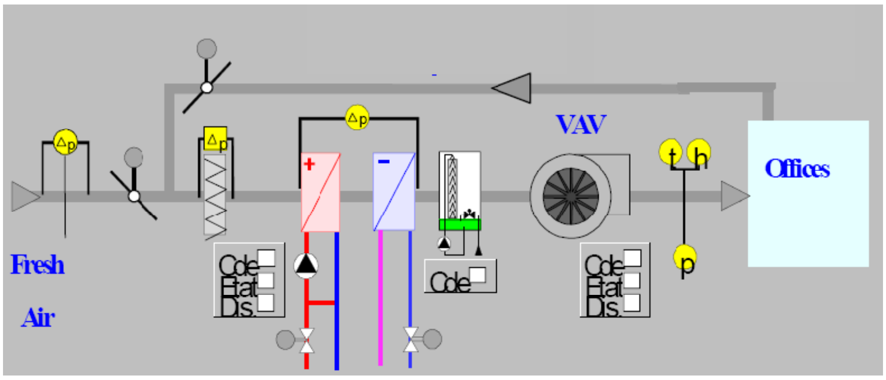

Figure 4: General view of a typical air distribution system.

3.9.2. Data Provided by the Manufacturers

Data provided by manufacturers is usually as component data-sheets. All designer, manufacturer and installer data should be included in the as-built records, including: The owner's project requirements; the design documents (construction specification, guide for system control and operation, calculations); testing, tuning and balancing results for air distribution network and control; previous commissioning results (if any); other technical documents (such as, the list of the components actually installed, installation plans, the technical documentation of each component).

3.9.3. Problems to be Considered

Installation problems include commissioning methods to detect and to correct mistakes early, i.e. when all components concerned are still easily accessible. This is particularly true for problems such as:

- Connections (electrical, pneumatic and mechanical);
- balancing;
- tightness;
- set point tunings;
- sensors;
- conversion laws;
- control parameters;
- component location (VAV boxes, sensors, …);
- calibration of measuring devices;
- noise;
- interferences;
- control programming;
- data storage.

Other problems that are likely to occur (especially during normal operation) are:

- corrosion;
- sensor drift;
- dirtiness of filters, coils, humidifiers and registers;
- broken belts.

During FPT focus is given to the verification of a few characteristics: air-tightness, pressure drops, fans characteristics and control strategies.

3.9.4. Description of the Testing Procedure

Objective of the Test

To verify if the installation is realized according to the specifications given in the ‘design documents’.

Prerequisites

Design documents; BEMS measurements; the system is fully connected and operational; the spaces are at ‘neutral’ temperature, i.e. at the middle of the control range of the VAV terminal units (usually around 22°C or 23°C); the primary equipment is working correctly; the installation status is the most appropriate for the test considered (for example, a tightness test should be preferably performed when the network is totally accessible, i.e. during the elaboration phase, before insulating the ducts).

Required Material

BEMS for storing the following points for installation control; a portable pressure sensor; a combined temperature/humidity sensor; a portable air speed sensor; a portable CO_2 sensor; a wattmeter; a tachymeter and a sound meter.

Preparation Phase

Before starting the testing phase the available measurement points, actuator characteristics and control strategies already implemented in the BEMS should be identified. Given the complexity of most systems, additional information in the form of modelling results or special measurement techniques can be useful.

The performance of individual components can be verified with the help of specific procedures. After being commissioned, components can be used as additional measuring devices, for example: the pressure drop across the coils (heating and cooling) can be used to determine the air flow rate supplied by the AHU; or the pressure rise across the fan, associated to its rotation speed, can also be used to determine the corresponding air flow rate.

If not already available, the following measuring points should be added in the AHU:

- supply and exhaust static pressures;
- fan rotation speed and supply-exhaust static pressure difference;
- supply and exhaust air temperatures.

Additional instrumentation can be used to test: spaces (probes for measuring environmental temperatures or a tracer gas to check air renewal); and ducts (for measuring the static pressures in all the main ‘branches’ of the network).

Execution Phase

The method consists of testing the performance of a certain number of components and subsystems of a ventilation system. The originality of the method is to combine different functional performance tests, elaborated individually per component and sub-systems, in such a way to make the most efficient use of all experimental conditions encountered: Dealing with each component separately would generate a important waste of time because almost the same experimental conditions would have to be reproduced several times.

The Test Method

This is illustrated in Figure 5.

1st step : test in manual operation

Objectives
▪ **Verification of the actuators in ON/OFF and modulation commands**
Actions
The plant should operate in "manual" mode (i.e. no longer under control of the BEMS), in order to generate the required conditions. Therefore, the following actions have to be performed through the BEMS: Open "manually" all dampers and valves Set the maximal fans rotation speeds Set "ON" the pumps and fans commands
▪ **Verification of the commands and modulations of the control devices** Compare the real state of the components to the controls and modulations imposed by the BEMS: valves, dampers, pumps and fans. From the BEMS, put each fan at its minimal rotation speed and, in situ, verify its real state.

2nd step : test in manual stop

Objectives
▪ **Verification of the commands and modulation of the control devices** ▪ **Verification of the sensors** ▪ **Verification of the BEMS archiving capabilities**
Actions
In order to put the installation in "manual" stop, the following actions have to be performed through the BEMS: "Manual" closing of all dampers and valves (modulation to 0%) "Manual" turning off of the pumps and fans (command "OFF")
▪ **Verification of the commands and modulations of the control devices:** Compare the real state of these components with the commands and modulations given by the BEMS ▪ **Verification of the sensors** **Duct temperature and humidity sensors :** Check temperature and humidity sensors by the "manual checking" method [6] **Room temperature sensor :** Check room temperature sensors by the "physical redundancy" or "diagnosis test" method [6] ▪ **verification of the offsets of pressure sensors:** Check pressure sensors by the "diagnosis test" method [6] ▪ **Control of the data storage (BEMS)** Check the data storage function of the BEMS by the "sensors measurement observation" method [6]

3rd step : test in "normal" operation

Objectives
▪ **Verification of fan performances**
Actions
Put the fan in normal operation From BEMS : Put the valves, dampers, pumps and fans in automatic mode.
Verification of fan performances by the method described in [7]

4th step : test in maximum air flow rate (summer condition)

Objectives
▪ **Verification of the controls set point** ▪ **Verification of the air flow rates at the level of the AHU (fresh air, re-circulated air and addition of both) and at the level of a reference office** ▪ **Verification of pressure drops and air leakages in the air distribution network** ▪ **Verification of the authority of the control devices (valves and registers)** ▪ **Verification of the tightness of the network**
Actions
Put the ventilation in maximum flow ▪ Verify that the office is at "neutral" temperature (ideally the point in the middle of the control range of the VAV boxes) ▪ Put the thermostats of the VAV boxes at their lowest set points (in order to "call" for a maximum of cooling power) ▪ Wait for a stabilization of the regime
Measure static pressures at different points of the network; compare with installer aeraulic calculations and with other modeling results, if available Measure fan flow rate by the method given in [7] Optionally, measure air renewal rates in selected offices by tracer gas technique.

5th step : test in minimum air flow rate (winter condition)

Objectives
▪ **Verification of the performance of the fresh air flow control in minimum regime** ▪ **Verification of the minimum fresh air supplied in the reference office**
Actions
Put the ventilation in minimum flow ▪ Put the thermostats of the VAV boxes at their highest set points (in order to "call" for a minimum of cooling power) ▪ Wait for a stabilization of the regime
▪ Same measurements and comparisons as in the previous (4th) step…

6th step : test in automatic stop

Objectives
▪ **Verification of the system state in automatic stop**
Actions
The plant should operate in "stop" mode, in order to generate the required conditions. Therefore, the following actions have to be performed through the BEMS: Put the ventilation in automatic stop from the management program of the BEMS
▪ **Verification of the system state in automatic stop:** Are all valves, dampers, pumps and fans closed?

Figure 5: FPT procedure for an air conditioning system.

4. Using the Building Control System for Commissioning

Microprocessor-based control systems are used to automatically operate many of the major energy systems in buildings. As technology continues to evolve, the trend is for more systems to come under the action of automatic control and for disparate systems to be integrated across communication networks. Automatic control systems eliminate the need for dedicated manual operators and can reduce costs. Modern control systems also allow the operation of multiple energy systems to be coordinated according to advanced building-level strategies. The proliferation of automation in buildings has led to a situation in which realizable building performance is fundamentally dependent on the control system. An important part of commissioning should therefore be to ensure that the control system is operating properly. The components that constitute the building control system are considered to be hardware (sensors, actuators, wiring, switches, and microprocessor-based control devices) and software (control algorithms, user interface, and other miscellaneous functionality that is typically packaged in modern systems). Before testing the operation of the BEMS, it is assumed that the performance of the components of the system have been validated using the procedures described in the previous section.

4.1. Practitioner Surveys

A questionnaire was prepared to assess current practice with regard to control system commissioning and also to ascertain the demand for tools that could help in the process. Practitioners in four countries (Japan, France, Canada and USA) were surveyed and the drivers, barriers and issues are highlighted in Table 3.

Table 3: Drivers, barriers and issues for the implementation of tools to assist the commissioning process.

Drivers	Barriers	Issues
Comprehensive data driven controller level FPT is being carried out today (USA)	Too much data required for configuration of tools	Standardisation of measurements, point names, procedures and tests
Potential to reduce on-site labour costs	Tools are too complicated	To be beneficial, tools must demonstrably reduce costs and reduce the need for technical expertise on site.
Potential to reduce skill set required to carry out on site commissioning	Insufficient documentation and training	Specification and checking of system operation is not clearly defined
There is a demand for better utilisation of the control system (France, Canada)	Difficulty in attaining factory inspection documentation	Creation of benchmarking procedures and tools.
	Lack of standardisation (reinforces above points)	

4.2. Commissioning Methods

There are two classifications of test, passive and active and both utilise the BEMS. Passive tests use the control system to monitor and record sensor and actuator signals from energy systems operating under normal conditions. These tests are non-invasive and the most important aspects of The approach is to properly select points to monitor and to apply appropriate data analysis methods. Active testing involves making artificial changes to the systems under control in order to interrogate behaviour. Active tests can reveal more information about a system in a shorter time period than passive tests, but can be more expensive to implement.

Table 4 gives guidance on the selection for the correct approach.

Table 4: Selection of passive or active tests.

	Passive test	**Active test**
Commissioning types	On-going	Initial, re and retro
Level of automation of the tool	Manual to automatic	Manual to automatic
Tool location	Stand-alone, embedded	Stand-alone
BEMS communication with other platform	Read	Write – Read
Data monitoring	Long-term monitoring	Short-term monitoring
Knowledge of the users	Medium	High
Impact on the building operation	None	High
Commissioning budget	Low	High

A number of prototype tools were considered in the project and Figure 6 details the methods, intended user, type of HVAC system (the prototype was developed for), method basis, intended building type and type of commissioning. These approaches were developed to allow fully or semi-automated Functional Performance Testing. The approaches that were developed were built on a model-based, rule-based, Performance index-based and a logic tracer based approaches.

4.2.1. Model-Based

This involves comparing predictions of a model with the measured performance of a component or system. Significant differences indicate the presence of one or more faults. For a heating coil, the inputs to the model are the measured inlet air and water temperatures and the control signal. A model of the coil, valve and actuator predicts the outlet air temperature, which is then compared to the measured value.

4.2.2. Rule-Based

Formalises system logic and expert knowledge into a set of rules (‘IF/THEN’ are one type). The method developed in the project for commissioning comprises three main steps:

Define the operating modes of the AHU by using control signal information (i.e. heating, free cooling, mechanical cooling with minimum outside air, mechanical cooling with 100% outside air, stop of the ventilation and frost protection).

Apply rules according to the specific mode (for the example the rules are based on 3 main types of fault: Inconsistency between two measured values for a specific mode (example T° supply air >

1

T°mixed air in heating mode); inconsistency between measurements in case of redundancy (example T° supply air ≠ T°mixed air in Free Cooling mode); and inconsistency between setpoint and its measured value (example T° supply air > T° supply air setpoint).

Define the diagnostic adapted to the violated rule, examples given Table 6.

Commis-sioning tool	Main End-Users: Building Operator	Energy Service Company	BEMS Installer	Building Owner	Mechanical Installer	BEMS Designer	Maintenance Company	Commissioning Agent	BEMS Supplier	Building Type	HVAC System	Type of Cx	Method	Communi-cation with BEMS
DABO	■	■					■			Large commercial buildings	AHU VAV	On-going Cx	Expert system perfor-mance indice	ODBC and Bacnet driver
CLT	■		■			■				Any type	Any type	Any type	Emulation	XML
Cite-AHU	■	■					■			Medium and Large commercial buildings	AHU	Re-Cx	Expert rules	OPC
WebE	■			■					■	Any type	Any type	On-going Cx	Perfor-mance indice	
Ecole Cx	■	■								Medium buildings	Hydronic heating	On-going Cx	Expert rules	ASCII and EXCEL® files
Macro-CX	■	■					■			Any type	Any type	Re-Cx	Perfor-mance indice	ODBC and Bacnet driver
Phil tool	■				■			■		Any type	AHU		Model based	
OHC-AHU	■	■					■			Large commercial buildings	AHU	Re-Cx	Model based	Data file and Bacnet driver

Figure 6: Test approaches developed in the project.

Table 6: Example diagnostics.

Heating Mode	Toa	Tsa	Tma	Tra
Toa		- Sensor fault : Tsa or Toa - Cooing Coil valve leakage	- Sensor fault : Tma or Toa	- Sensor fault : Tra or Toa
Tsa			- Sensor fault : Tsa or Tma - Cooling Coil valve leakage	?
Tma				- Sensor fault : Tra or Tma
Tra				

4.2.3. Performance Index-Based Method

Performance indices are calculated values or control values that quantify the performance of a control loop, component, or system. The performance index-based method applied to real time commissioning involves comparing indices of similar controllers or components under specific conditions (outside air temperature, humidity, etc.) or under a specific period (instantaneous, one hour, one week). Performance index values can be normally distributed. Limits can be set to define a range of values corresponding to acceptable behaviour and values that lie outside the range can indicate that a problem exists. Performance index values can also be used to optimize set points and improve system performance. Limits can be manually set or be estimated continuously. Performance indices can be analyzed by expert rules aided by control values and parameters to diagnose faults.

4.2.4. Logic Tracer

This tool was developed for checking the operation of control logic. It focuses on sequences of operation and allows control algorithms to be visualized via a graphic tool. The tool reads operational data in format and displays the control sequence as a diagram using coloured lines to actively indicate the current control path. The main benefits are that it:

- Provides BEMS designers and building operators with easy-to-understand information about HVAC control logic;
- allows users to visualize the sequence of HVAC control over time;
- diagnoses failures by tracking down the causes traceable to the system control and provides the user with information to correct operation or control failures.

4.3. Implementation of Automated Commissioning Tools

A commissioning tool can be implemented in the control system or in a separate hardware device such as a laptop computer that would be temporarily attached to the control system. The main elements of a commissioning tool include architecture, level of interface to the control system, method used, data management, data communication and user interface.

4.3.1. Architecture Types

Building systems consist of HVAC components that are organised in subsystems. Every HVAC unit includes a number of sensors. Each sensor has a unique address and provides data to a control panel or central control network. The control panel can include other information describing the building system. Information from the control panel can be stored in a general database that could be used by different building optimization software such as a *Fault Detection and Diagnosis*, automatic commissioning or trending tool. A commissioning tool could be embedded in the control system or connected directly to it in order to use existing measurement and communication equipment in a building and reduce cost and time for commissioning tasks. When connected, the tool could reside on the operation workstation or could be in a remote site. Table 7 lists different architecture types.

4.3.2. Communication Issues

A practical barrier to the adoption of commissioning tools is the difficulty of setting up communications between the tool and the control devices. From a tool developer's standpoint, control systems that use open protocols can greatly simplify the implementation. A communications shell was developed as part of the project that used the BACnet protocol.

Table 7: Architecture Types.

Tool Architecture	Location	Communication
Stand alone	Remote Management Level, Remote operator workstation	Via Internet or phone network
Stand alone	On site Management Level On site operator workstation	Via Local Area Network
Stand alone or Embeded	Automation level Local Controllers & outstations	Automation communication level or Additional Instrument connected to the backbone network (LAN)
Stand alone or Embeded	Field level Terminal & room Controllers	Field communication level Additional or Instrument connected to the field network

4.3.3. Database

A database is a central component of a commissioning tool that can have a direct impact on tool performance. Databases can include a knowledge base used by the tool, commissioning models, performance test libraries, internal tool relationships, building and HVAC system configuration data, commissioning parameters (design data, sequences of operation, internal tool, etc.), operating control values, and finally the commissioning results. For an on-going commissioning tool, the database should have the capacity to store data for many months and years. In Annex 40, most of the tools that were developed used relational database such as a SQL server.

4.3.4. User Interface

This allows the user to enter system configuration data and invoke various fault detection modes. It also facilitates data communication and management between the building control system, database and commissioning module, as well as generating reports and getting online help. To be effective, an interface should be: (1) reliable, (2) easy to use, (3) easy to engineer, (4) maintain, (5) configure and (6) understand. It should allow good interactivity with the user and be visually well designed.

4.3.5. Data Handling

An SQL database can be used to access control system data and the interface allows data to be imported from different control systems. During the import, data are checked for consistency (missing data is filled with ‘not a number’ information - NaN) and plausibility (non-plausible data causes warnings). Data sets with different time ranges are joined together and duplicate data are deleted. Once a database is constructed, data can be filtered and exported in a format suitable for a data visualisation tool. The database also holds information about sensor location (building, story, room, facility), threshold values for plausibility checks, minimum and maximum values for visualization scales, etc.

4.3.6. Data Visualisation

As part of the interface enhanced visualization techniques can be employed to deliver and analyze information in the control system data. PIA is a visualisation tool box (developed at the Royal Institute of Technology in Stockholm, Sweden) used in the project. Time series plots can be produced with a Data Browser. In addition to conventional line plots, data can also be displayed as carpet plots, where data are transformed into a colour scale. This is depicted in Figure 7a. Data from each day are then displayed in separate columns. Carpet plots allow large amounts of data covering periods of several weeks or even months to be displayed simultaneously. Also, snapshots of data from certain times each day can be displayed in order to focus on critical periods of operation such as start-up and shutdown. At present, the Data Browser can only handle data with a sampling period of 5 minutes.

The data can also be displayed in scatter plot form using pmBrush (Figure 7b). A single scatter plot allows the dependency of two data points to be analyzed whereas a matrix of scatter plots allows analysis of the dependency of n x m data points (where n x m is the size of the matrix). A brushing function allows the user to interactively select data points and save the selections for use in subsequent calculations. Selected points are highlighted in all the scatter plots of the matrix. Further development will connect the database with the visualization tools directly. Also there is need to extend the interface to different types of control system, and to improve the plausibility checks that are carried out automatically.

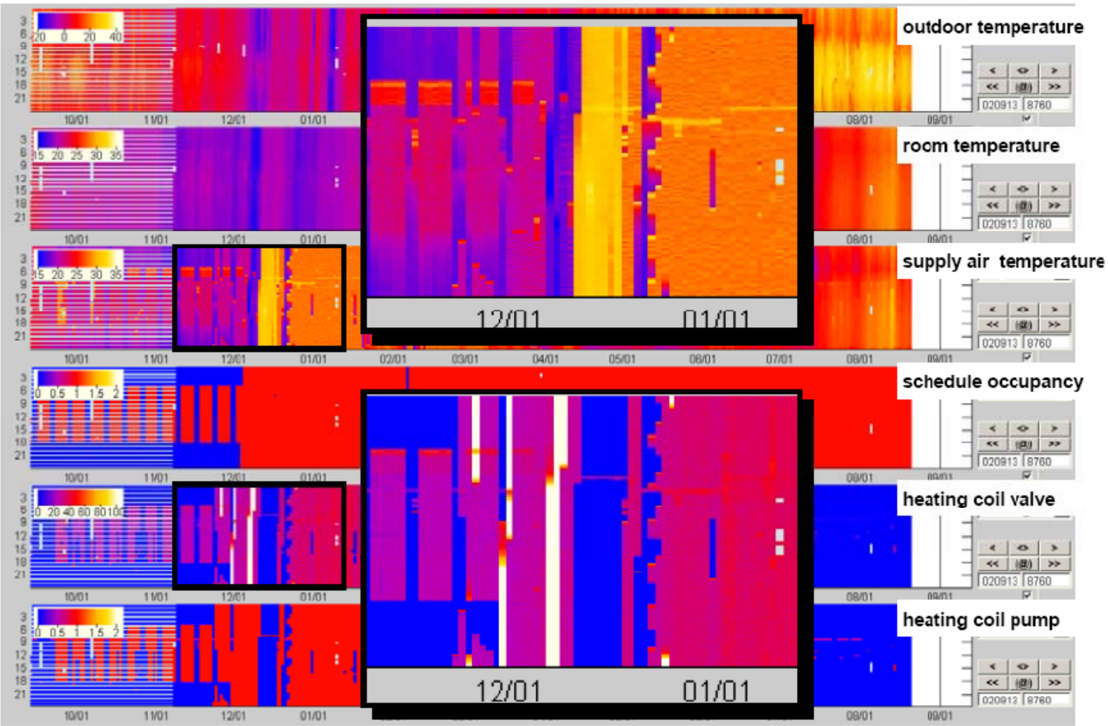

Figure 7a: Carpet plot of 6 data points for a time range of 11 months.

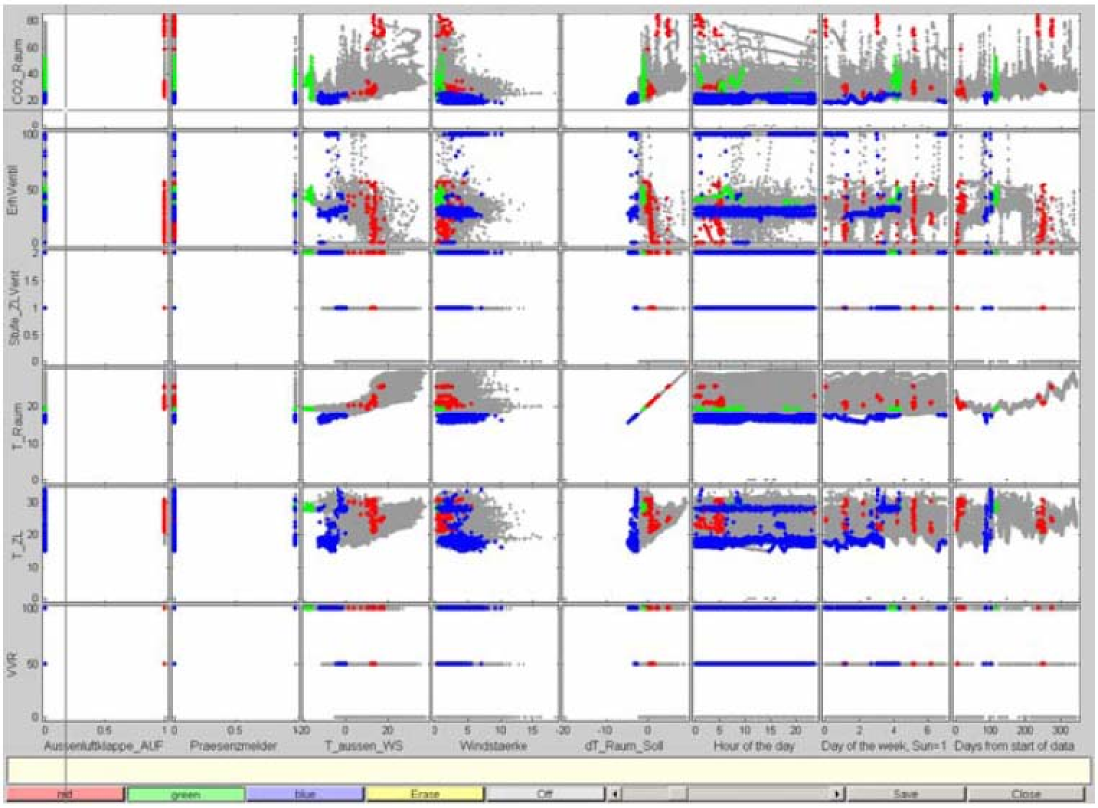

Figure 7b: Scatter plot matrix

4.4. Conclusions

Control systems in buildings have the potential to greatly improve the commissioning process. In particular, control systems can be used to carry out automated testing on the energy systems in a building in a systematic way.

Technologies for carrying out automated commissioning are still in their infancy and very few tools are available for practitioners to use. However, tools can be built using existing infrastructure at relatively low cost. In many cases, tools are software programs can be implemented on most microprocessor-based platforms.

One obstacle to getting tools deployed on a wide scale is the difficultly in setting up communication with control products from different vendors. However, open protocols such as BACnet and LON are making this easier. Also, there is a cost in identifying the correct sensors and command signals on a control system this cost needs to be balanced against the benefits of the automated methods.

5. Using Component Models in Commissioning

The use of computer models to analyze the performance of whole buildings, subsystems and components is becoming more common. The most frequent use is for design-related purposes, such as sizing, energy performance and code compliance. Models also form the basis of Fault Detection and Diagnosis tools for use in monitoring routine operation. Commissioning is then a natural application of models for two reasons:

- FDD methods can be applied to commissioning, including active functional performance testing; and
- Models used in design are a quantitative representation of intended performance and hence provide a baseline against which to compare measured performance during commissioning.

Model-based commissioning procedures use mathematical models of whole buildings, components and systems to link design, commissioning and operation. Models can also be used to develop functional performance testing procedures, which can then be performed manually or automated.

5.1. FPT and Performance Monitoring

The following steps comprise a ‘use case’ for a general purpose, component-level, model-based commissioning tool that can be used both for initial commissioning and for performance monitoring during routine operation:

1. For automated functional performance 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, etc.

This process is illustrated in the following example of a heating coil in a constant air volume system that is controlled by varying the inlet water temperature (as opposed to the water flow rate).

5.1.1. Configuring the Model

Since the air and water flow rates remain approximately constant during operation, the performance of the coil can be characterized by a fixed overall heat transfer value (UA), which can be determined from the design specification or the manufacturer’s data (e.g: inlet air, outlet air and inlet water temperatures and air and water volume flow rates). In the case of a more detailed model with multiple parameters, the parameters must be determined using data from multiple operating points. The operating points must be carefully chosen to ensure that each parameter is well-determined numerically. If the model is non-linear in the parameters, as most first principles models are, a search-based optimization method is required.

5.1.2. Designing the Test

Operating points are selected to test for common faults, which in this case are: Loss of capacity, valve leakage, non-linearity (response characteristics), hysteresis, actuator/valve mismatch/maladjustment (travel of actuator and valve do not match). Consequently a number of demanded valve positions are required to reveal these faults, given in Table 8.

Table 8: Demanded valve positions for and FPT on a heating coil.

Fault	Demanded valve Position (% open)
Loss of capacity, e.g. fouling	100%
Leakage	0%
Non-linear, e.g. incorrect valve authority	50%
Hysteresis	50%, opening and closing
Valve/actuator misadjustment	5%, 90%

5.2. Developing FPT

Models can be used to identify operating points to be included in functional performance testing.

In the heating coil example, the component is simple enough that the critical operating points can be identified using 'expert knowledge' and a model can be used to confirm or optimize these operating points. For more complex components, a model may be needed in order to identify the combination of operating points needed to detect all the faults of interest. Extending this, the model can be used to determine the sensor accuracy required to verify correct performance according to specified acceptance criteria or, equivalently, to identify a specified degree of a particular fault. For example, Figure 7 shows the effect of valve leakage on the relationship between air temperature rise across the coil and valve stem position calculated using the heating coil model. The temperature rise when the valve is nominally closed varies between 0 and 10 K, depending on the degree of leakage. If the combined error in the measurements of the entering and leaving air temperatures is 2 K, leakage of 1% can be detected.

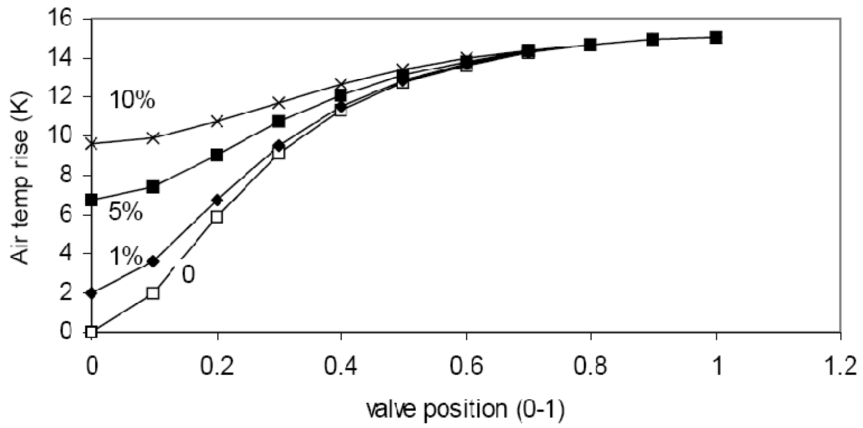

Figure 7: Heating coil air temperature rise as a function of valve position

for different values of valve leakage.

5.3. Performing Indirect Measurements

Simulation models can be used in the experimental design, in the analysis (and extrapolation of FPT results) and in the measurements themselves, illustrated here.

The measurements of air flow rates are difficult to make in existing distribution networks: long enough straight lines are seldom available or accessible and velocity profiles are usually not uniform enough. A large series of measuring points is required and the final accuracy is often disappointing. A much better solution consists in using the fan as an air flow measuring device. It just requires the use of a classical 'phi-psi' model to be tuned on the basis of manufacturer data. The air flow rate then can be determined as function of rotation speed and measured supply - exhaust static pressure difference.

The 'phi-psi' model uses the fan similarity laws to normalize the flow rate and the pressure rise. Polynomials representing the normalized pressure rise (psi) and the efficiency as functions of the normalized flow rate (phi) are fitted to manufacturer's performance data. Attention is paid to the distinction between total and static pressures: manufacturers present fan performance in terms of total pressure rise, whereas the measurements are usually made in terms of static pressures. Attention is also paid to the effects of both atmospheric pressure and air humidity. The air-flow rate is defined in 'specific' value (i.e. in kg of dry air per second). Isentropic power and isentropic heating of the air stream can also be calculated to provide additional consistency checks.

The model can be used to derive a simple parabolic psi – phi characteristic, which appears to be accurate enough for fans with backward-curved blades. The air-flow rate can be determined with an accuracy of about 5%.

5.4. Performing Functional Performance Testing and Tool Automation

A tool for manual commissioning of coil energy recovery loop systems has been implemented in a Tablet PC, using the Energy Equation Solver (EES). It could be extended to an entire AHU. The tool consists of two parts, the first part is used for estimation of the heat transfer parameters of the heat recovery model, and the second part is use for calculation of optimal fluid flow. For the parameter estimation, there is a theoretical minimum need for one data point for each parameter that is to be determined, but the more data points the better. It is important to have data points for a large range of air and fluid flows. For each data point there is need for information about air temperatures, air flows, fluid flow and fluid temperatures.

When using the parameter estimation tool, the parameters that are calculated can be saved in a file that can be retrieved by the flow estimation tool. In the current version of the parameter estimation tool, it is possible to assume that both coils have the same configuration and then the same calibration parameters. It is also possible to set some of the parameters to fixed values. This can be useful when there is limited data available. A few parameters describing the coils need to be given. They are pipe diameters, number of flow paths and type and concentration of freeze protection added to the water in the fluid circuit. The data used for the calibration are put into EES lookup tables; these can be saved for archival purposes. This tool can also be used to determine the supply and exhaust air flows and the temperatures of the air leaving the coils. The current version of the tool does not take condensation into account.

The key elements of an automated tool are: a set of suitable models; a set of test sequences; and supporting software to implement the test sequences and analyze the results using the models. It is also possible for a functional testing tool to be semi-automated, so that is can be used when the data trending functions of the BEMS system are not available.

Figure 8a shows the architecture of the tool. Shaded boxes are software routines. The model is first configured using manufacturer's performance data and design information. The test generator then executes the test by forcing the system to the predefined series of operating points. The test generator waits for the system to come into steady state before proceeding to the next operating point.

Figure 8b illustrates the operation of the test signal generator. On start-up, the tool requires the user to choose between the closed loop test and the open loop test. If the open loop test is selected, the feedback control loop is then disabled. If the closed loop test is selected, the maximum and minimum values of the set-point are needed as inputs. After that, the program requires the user to input the addresses or names of the control and sensor points. The step test generator will then override the control signal value automatically, based on predefined sequence, as described above. The new value is then uploaded into the controller. The trended data is analyzed in real time to determine whether the system is in steady state. When the system reaches steady state, the tool will move to the next step until the end of the test sequence. The software structure is generic with only the data transfer between control system and the software being vendor-specific.

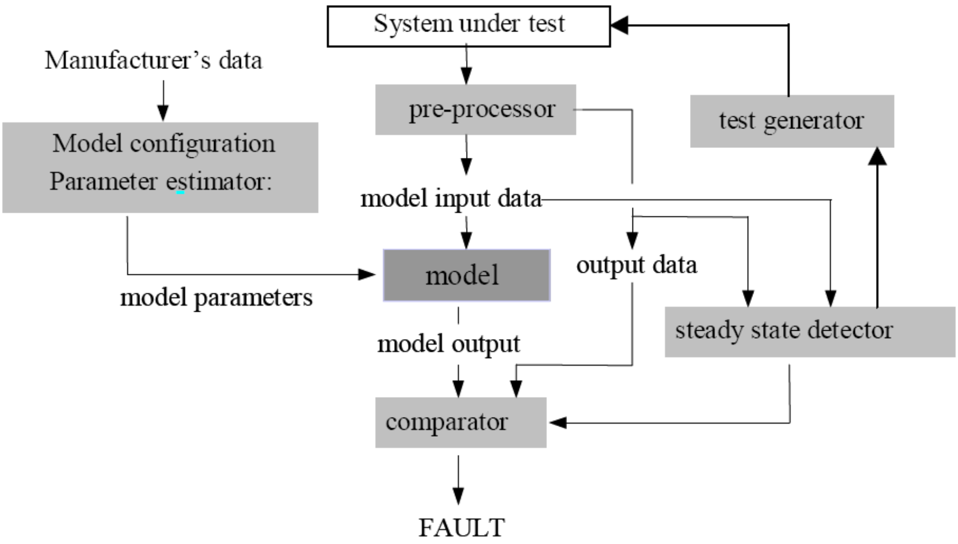

Figure 8a: Architecture of a model-based functional testing tool.

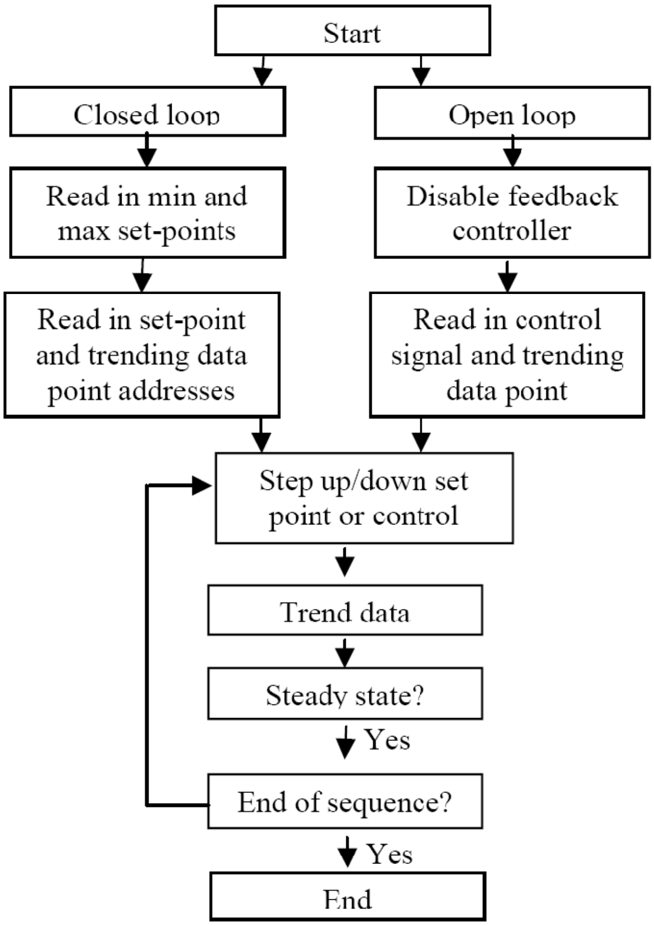

Figure 8b: Automated test signal generator.

5.5. The Model Library

A library of HVAC component models for use in model-based commissioning has been developed. The model library is web-based to allow for continuous maintenance. Lawrence Berkeley National Laboratory (LBNL) will continue to host and maintain the website http://cbs.lbl.gov/diagnostics/model_library. These models are freely available; the only restriction is that no-one other than the author may claim ownership or attempt to restrict their use in any way. In addition, no guarantee of the correctness or accuracy of the results obtained by using the models is given by the authors or LBNL. In general, the models are implemented in one of two formats:

- EES (Engineering Equation Solver), which is an environment that is well suited to prototyping, documenting, demonstrating and exchanging models of single components or simple subsystems;
- and SPARK (Simulation Problem Analysis Research Kernel), an equation-based simulation environment for dynamic and steady state non-linear models of components and systems that is freely available from LBNL.

The following component or subsystem models have been developed:

Air-to-air plate heat exchanger	Heat pump
Building zone	Heat recovery wheel
Coil heat recovery loop	Heating coil and control valve
Cooling coil and control valve	Humidifier
Cooling tower	Mixing box
Fan (variable speed)	Terminal unit
Fan and Drive Train	Terminal unit control
Fan/duct system (VAV)	VAV terminal units
Heating coil and control valve	Vapour compression chiller
Heat pipe heat recovery	Mixing box

5.5.1. Verification of Model Performance Using Real Data

A number of the models in the library have been verified off-line by configuring them with manufacturer's data and comparing their predictions to field measurements. A statistical model of multiple VAV boxes has been verified using the operational data collected from VAV systems in a real office building in Tokyo. Performance was verified on 150 VAV terminal units in 10 AHU systems, which are not equipped with airflow rate sensors. The FDD method was able to reduce the number of suspected faulty units from 150 (100%) to 18 (12%), with all the 6 units that truly have faults falling in the group of 18 suspected faulty units. This result shows that this model can reduce the required time and manpower or cost for commissioning by about 90% compared with those needed by the present manual check, which is generally done by checking all the units one by one. Further model verification has been done on the rotary heat exchanger model and the heat pump model.

6. Using Building Level Simulation Models in Commissioning

Whole-building models are routinely used in the design of building HVAC systems but are not widely used for commissioning. Various models or simulations are sometimes used during the pre-design phase. These models generally simplify the input process with numerous default inputs to speed their use to enable rapid feedback on the significance of major envelope or system configuration options early in the design process. More detailed models are customarily used to size the heating and cooling equipment during the design phase, and a detailed simulation model such as DOE-2, TRNSYS, EnergyPlus, IDA, RIUSKA, etc. may be used to explore the implications of a limited number of design options on annual energy use. While the continuous use of simulation throughout the life cycle of a building has been contemplated for the last two decades, it has not yet been employed. Progress in linking simulation programs to CAD programs, however, seems likely to change this in the future. In addition, European directives are now calling for energy use calculations for new buildings, which is likely to increase the use of energy simulation.

Simulation has only been used as part of the commissioning process for isolated retro-commissioning projects. Simulation is sometimes used during the design process in a way that may be viewed as part of 'commissioning' the design. The results of Annex 40 demonstrate that there are significant other opportunities to utilize simulations to improve the commissioning process. This is particularly true when simulation models have already been used as part of the design process, as part of a savings determination process, since the input parameters for the design simulation are a direct expression of the design intent. The simulation can then be used to predict building performance and deviations would indicate the need for commissioning measures to bring the building to design intent. The number of building parameters required for an adequate simulation will vary depending on the building type, location, and use.

The simulation will generally be used to evaluate passive or active testing. An example of passive testing:

- Check room temperatures and humidity levels. Trend logs of the temperature and humidity in every zone can be tracked over one or more days. As long as these values stay within the set points, temperature and humidity control are acceptable for the occupancy and ambient conditions during the test. If not, diagnostics (that may or may not involve simulation) are required. If this test is passed;
- 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 for the occupancy and ambient conditions during the test.
- Extrapolate performance from limited trend data to design conditions. It is necessary to determine whether equipment capacity and other parameters are adequate to provide comfort at design conditions.

It is desirable to verify multiple operating parameters (such as airflows and supply temperatures to individual zones) since this increases the reliability of the analysis. The depth of detail of the analysis is limited by the capabilities of the simulation and the available measurements. Active testing is restricted in much the same way, the principle difference is that the system is forced to operate at prescribed operating conditions that allow possible faults to be most readily detected. These are often more extensive and intrusive to execute and would probably be invoked if the system has failed a passive test, in order to gain further insight. A number of tests are needed to fully explore 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.

The general issues for using building level simulation models for commissioning include:

- Capability requirements of simulation models for specific commissioning applications, building and system types;
- dependency of the model based analysis on test characteristics;
- incorporation of energy balances with simulation in the commissioning process;
- the degree to which experimental results are used to tune inputs to models;

- number of simulation inputs to be measured;
- time required for simulation and the realistic time constraints;
- efficient methods for determining capability of the equipment to meet peak loads;
- determining equipment efficiency with regard to meeting building requirements under normal operating conditions;
- the impacts of occupant behaviour on building performance estimation using simulation;
- the impact does the shape of the building envelope on performance.

There are a number of applications for building level models for commissioning.

- **During the design process:** To assist in ‘commissioning’ the design. Typically, models will be configured for quick analysis using TRNSYS Light, Enerwin, etc. They may or may not be used for energy simulation. These models are not used during the commissioning after construction. The use of more detailed simulation models may be used at the design stage.
- **Post-construction commissioning of new buildings:** A design simulation may be used to predict the heating and cooling performance of the actual building. The predictions are compared with measurements and differences are used indicate problems in the building. Details such as occupancy schedules must be verifies if the simulation is to represent the real building. Relatively complex simulations will be used for this purpose.
- **Design simulation for on-going commissioning:** The design simulation may be run at specified intervals (weekly, monthly, annually) and the model predictions compared with the measured energy use. Deviations could trigger an alarm if building performance degrades. These simulations would probably run off-line, due to computational demand.
- **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.
- **Calibrated simulation for on-going commissioning:** The calibrated simulation developed in the retro-Commissioning process may then be run in a similar manner as the ‘Design Simulation for On-Going Commissioning’ case.
- **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. It is most likely that this will be done off-line. In principle, this could be done without using whole building simulation but its use is desirable to evaluate control options before implementation.

7. Commissioning Projects

A collection of 27 demonstration sites has been used to assess the Commissioning tools developed within the project. Each participating country has been involved in at least one commissioning project. The objectives were to test and to improve the procedure developed and to demonstrate the advantage of commissioning. This report is the result of these trials and Figures 9 to 13 detail the building types and locations and describe the make-up of the demonstration stock in terms of size, type, phase of construction, type of commissioning targeted and the type of tools tested.

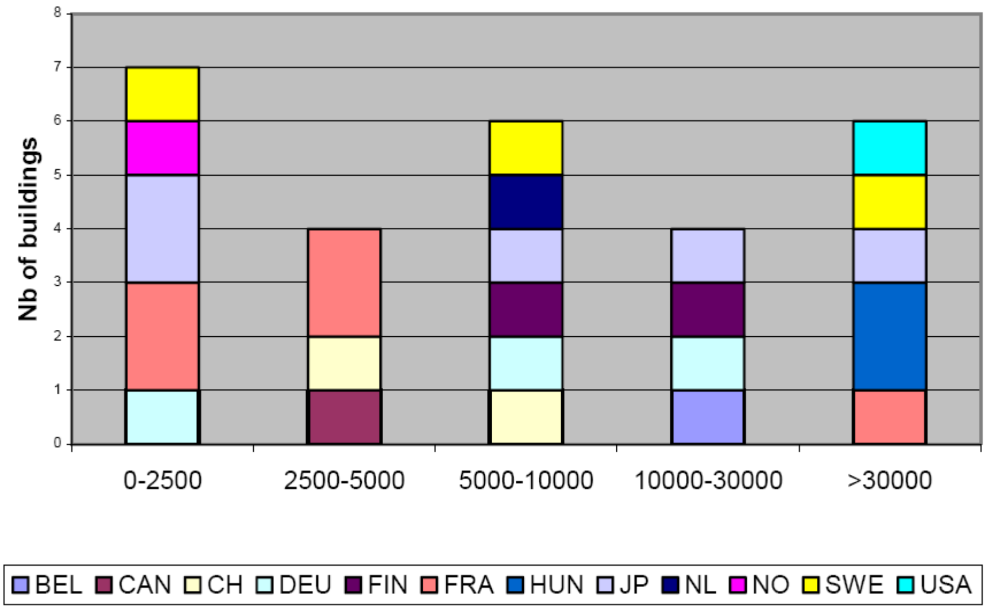

Figure 9: size of the demonstration sites

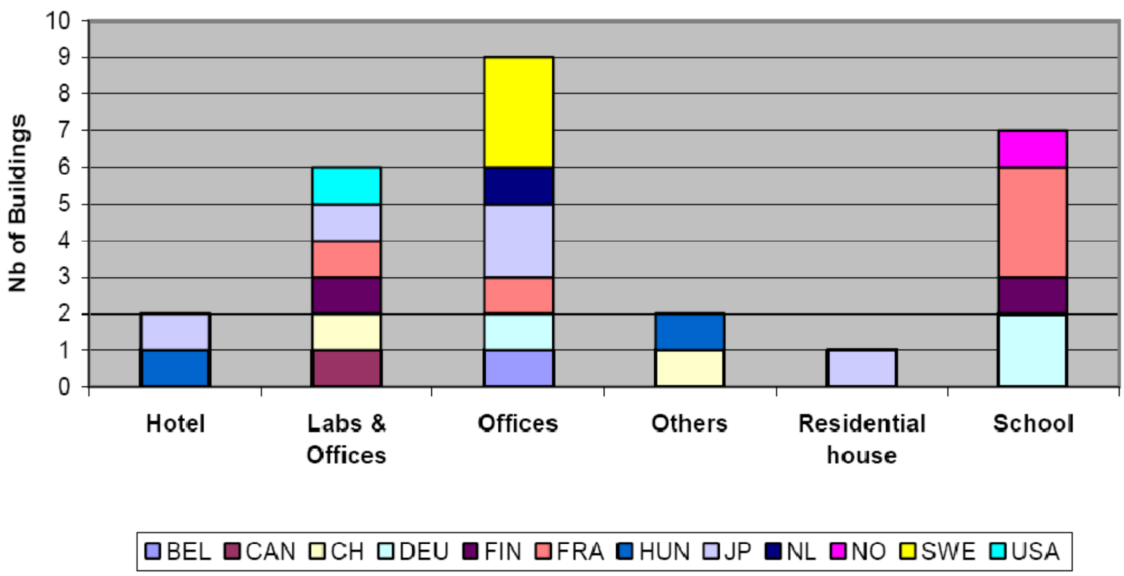

Figure 10: Type of buildings used as demonstration site

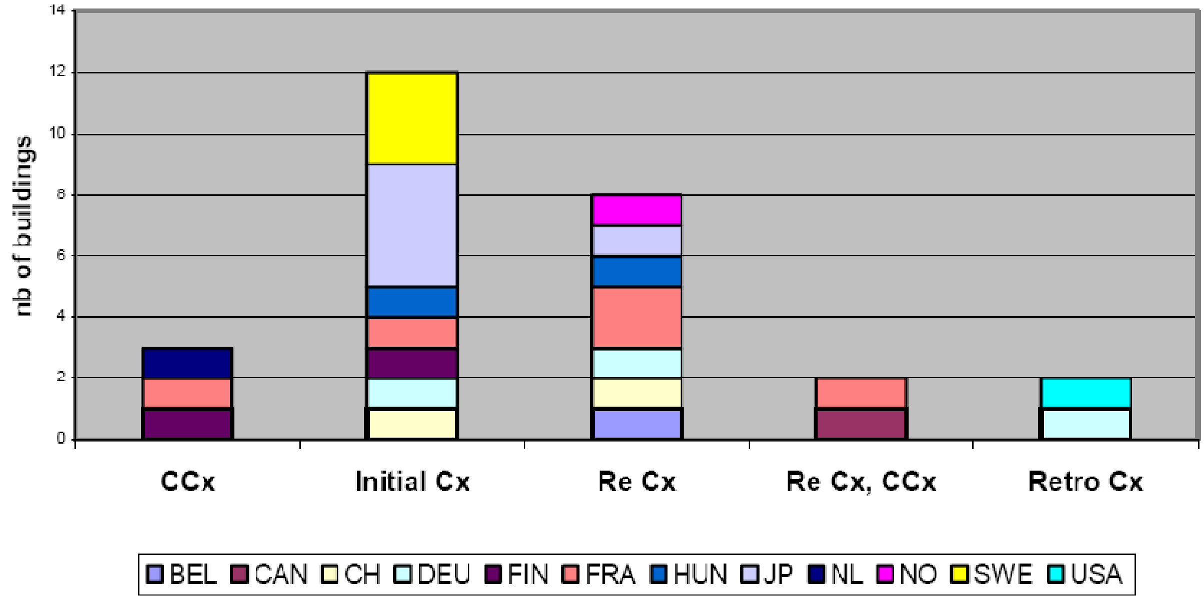

Figure 11: Type of commissioning targeted on the demonstration sites

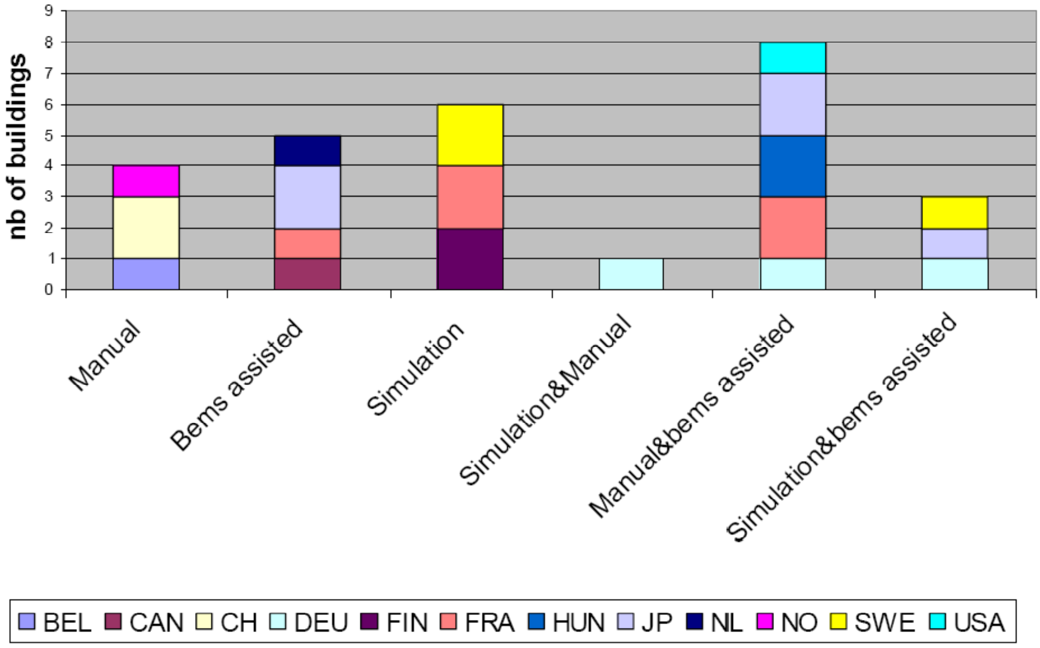

Figure 12: Type of tools tested on the demonstration sites

	Building's name	Type				Size (m²)	Phase			Cx type			Tools tested		
		School	Office	Lab & Office	Other		Design	Construction	Operation	Ini Cx	Re Cx	C Cx	Manual	BEMS assisted	Simulation
	CA-MET headquarters of the Ministry of Equipment and Transport		x			15000			x		x		x		
	CANMET Energy Techno1ogy Centre			x		3600			x		x	x		x	
	GMS	x				10000	x			x			x		x
	BSZ	x				2500			x		x		x	x	
	Munchener Ruckversicherung		x			9100			x		x			x	x
	Nursery school of Crevecoeur legrand	x				2700			x	x			x	x	
	Aria, Research building of CSTB			x		2000			x		x		x	x	
	PB6 headquarters of EDF		x			63200			x		x				x
	Schools of the town of Paris	x				500-5000			x			x		x	
	University Rhone-Alpes	x				600			x		x	x			x
	Dynamo building of Jyväskylä Polytechnic	x				10000			x			x			x
	Digital building			x		8300		x		x					x
	Cultural Palace				x	60000		x		x			x	x	
	NH Eurobuilding Hotel (Spain)				x	50100			x		x		x	x	
	K Building				x	86000			x	x				x	
	Shinkawa building		x			5400			x		x		x	x	
	Tepco Building		x			16765			x	x			x	x	
	Yamatake research centre			x		1692			x	x				x	
	O House, residential building				x	150			x	x				x	x
	Postbank office building			x		7000			x			x		x	
	primary school of Trondheim	x				1600			x		x		x		
	KV Valten		x			1200			x	x					x
	KV Katsan		x			6300	x			x					x
	Kista Entré		x			46000			x	x				x	x
	Swiss federal institute for forest, snow and landscape			x		3675			x		x		x		
	Wankdorf Bern New stadium and commercial centre				x	5500	x			x			x		
	Government office building of the City of Oakland		x			6300	x			x					x

Figure 13: List of demonstration sites.

8. Conclusions

8.1. Background Factors

- Correctly operating buildings minimise energy use.
- Most buildings never operate correctly.
- Lack of commissioning is part of the problem.
- Complicated buildings are difficult to commission.
- Commissioning is time consuming and expensive.
- There is currently very little done to verify a buildings performance with the design intent – is the owner getting what has been paid for?

8.2. Outcomes of Annex 40

- Organisational procedures can assist the commissioning process.
- An independent commissioning authority can help guide the commissioning process and help meeting the owner's requirements.
- Simulation models at whole building or component level shows great potential to assist the commissioning process.
- The increase in demand for simulation at the design stage will help create a platform for moving simulation into the verification of installed systems with the design intent.
- On-going systems monitoring, fault detection and commissioning has the potential to improve the energy and comfort performance of building systems for the life of the building.

8.3. Barriers to Implementation

- Commissioning is difficult, time consuming and expensive. The tools that have been implemented in Annex 40 are prototypes and have not yet fully addressed these issues.
- The tools developed use advanced simulation techniques and correlating this with a thorough understanding of the systems under scrutiny is not a trivial task.
- It is not clear that the stakeholders that could benefit from automated commissioning tools are aware of the technology and the potential benefits in terms of time and cost savings.

8.4. Editor's Concluding Remarks

- There is clearly a need for improving commissioning.
- The tools and techniques develop under Annex 40 address this problem and although barriers exist, it is envisaged that these will be addressed as the techniques mature.
- The work carried out under Annex 40 addresses the boarder question about the emphasis the governments and societies place on ensuring building consume the minimum amount of energy. The building systems must operate optimally for this to be realised and there needs to be ways of formally validating this. The tools described here are the proposed solution.

Appendix A: Glossary

There are some sector specific terms and abbreviations that are used in this report as well as those that have been defined during the course of the project: These are described here.

Acceptable performance: Permissible environmental and energy performance values for equipment and systems (i.e. calculated from measured data including seasonal/time fluctuations and space distributions occurring under all ranges of actual loads).

Active test: A test to assess performance by analyzing data obtained from systems that are subjected to artificial changes in operational conditions.

As-built records: Documents that accurately represent actual installed conditions, equipment, and systems, such as drawings, computer graphics, equipment data sheets, operation manuals, and maintenance manuals. They also include the training program and training videotapes.

Basis of design: All information necessary to accomplish the design requirements, including weather data, interior environmental criteria, other pertinent design assumptions, cost goals, references to applicable codes, standards and regulations, and guidelines and tools for prediction of environmental and energy performance.

BEMS-assisted commissioning: Making use of the control system to perform commissioning procedures. Typically, the control system is used as a means of interfacing to energy systems in buildings through sensor and control signals.

BEMS-assisted commissioning Tool: An automated software tool that monitors building control data and stores it in a structured database to be used on-line or upon request. Data from standardized test procedures invoked manually or automatically could also be stored. The tool performs intelligent analysis, i.e. FDD.

Certificate of readiness: A document stating that all equipment, systems, and controls have been correctly installed; operated as specified; tested, adjusted and balanced; and are verified as ready for functional performance testing and other acceptance procedures. The commissioning authority issues the certificate of readiness to the contractor after verifying the results.

Checklist: SMCxP customized for practical use for countries and specific buildings. A CA or a project manager will use it when proceeding from one project phase to the next.

Commissioning (Cx): Clarifying building system performance requirements set by the owner; auditing different judgments and actions by the commissioning related parties in order to realize the performance; writing necessary and sufficient documentation; and verifying that the system enables proper operation and maintenance through functional performance testing. Commissioning should be applied through the whole life of the building under the supervision of a qualified CA. It ensures that building systems are designed, installed and functionally tested and are capable of being operated and maintained to meet OPR from viewpoints of environment, energy and facility usage.

Commissioning Authority (CA): A person, company or organization designated by the owner, responsible for managing the overall commissioning process. The CA is generally not the design professional or the contractor in the I-Cx process. Currently in some countries, the CA is authorized by the nation or state.

Commissioning plan: A document written by the commissioning authority that defines the contents of the commissioning process according to the project risk and complexity in order to completely finish each commissioning phase and/or step. The commissioning plan can be defined through customization of standard models of commissioning plans.

Commissioning process (CxP): A quality-oriented process to accomplish the commissioning aim.

Commissioning process progress report: A progress report submitted during the commissioning process by the commissioning authority to the owner when a phase or step in the commissioning process, a contract deliverable, or the budget year is finished.

Commissioning process report: A final report on the results of the commissioning submitted by the commissioning authority to the owner. In the case that commissioning is needed in the post-acceptance step of the initial commissioning process, a provisional commissioning process report is submitted in the acceptance step and the final report is submitted at the end of the post-acceptance step.

Commissioning related parties: The commissioning related parties cooperate with the commissioning managing team to share information, promote instruction and communication, and finally to implement the commissioning process smoothly. These parties include the owner, the designer, the contractor, etc. who are related to the project as described in the commissioning phases and steps.

Commissioning specification: A document developed by the design professional as a part of design documents that details the objectives, scope, targeted items and performance description for the commissioning tasks following the design phase. It is based on the commissioning plan, and should be clearly shown to the contractors in the decision process such as in bidding.

Commissioning managing team: The commissioning managing team consists of the commissioning authority and the assistants. The design professional and the contractor for the project are not included in the commissioning managing team during the initial commissioning process to ensure independence of the commissioning process.

Commissioning team: A generic term for the commissioning managing team and commissioning related parties, who cooperatively implement the commissioning process.

Construction documents: Comprehensive documents for the construction bidding that summarize the design documents, the range and terms of construction, and additional documents needed for bidding.

Design documents: Documents that detail all design work performed by the design professional including working design, construction specifications, the design intent document and the guide for system control and operation. Technical guidance for prediction of equipment performance, method of the system control, references for performance verification, required and estimated values of environmental and energy performance, the manual for system operation, commissioning specifications, etc. should be clearly described in the design documents.

Design intent document: A document written by the design professional as a part of the design documents, which clearly states design intent, and provides an outline of the design and the basis of design. There are cases in which it includes the guide for system control and operation.

Design professional: A legal representative in the design team for the project. In cases where a person and/or group within the design team have primary responsibility for the design, they can be called ‘designer’.

Design requirements (DR): A document on the basic performance conditions for the design summarized by the commissioning authority and based on the owner’s program. Details include; building type, the project risk, the conditions of use, and the criteria and acceptable performance of the building energy systems and indoor air quality. The CA develops the DR to harmonize with the budget and the performance of the project based on the OP.

Fault detection and diagnostic tool (FDD tool): An automated software tool that assists the building operator in maintaining optimal operation of mechanical systems. The tool collects control information or other data and analyses them to detect symptoms of abnormal behaviour in various HVAC components, such as uncalibrated or failed sensors, actuator or linkage failure, controller instability, non-optimal sequence of operations, etc. The tool also diagnoses their possible causes and provides explanations. It goes beyond the capabilities of conventional BEMS single-point alarms and integrates information from multiple sensors to establish a more comprehensive understanding of the status of operation.

Functional performance testing (FPT): A set of tests that define the functionality and verify the behaviour of a system. These tests are usually defined by the commissioning authority in order to verify that building systems are completed to satisfy the owner’s project requirements and demonstrate functional performance. In the case of the systems having seasonal performance, such as HVAC systems, FPT should be continued for at least one year and subsequently decide the initial performance of the system. The FPT lays emphasis on the overall operation of the system and should be differentiated from the TAB on the performance of the equipment itself.

Guide for system control and operation: A guide written by the designer from the design viewpoint and intended to inform operating and maintenance personnel of the system design intent, system structure, system control, and provide guidelines for system operation.

Initial commissioning (I-Cx): A systematic process applied to production of a new building and/or an installation of new systems that begins with the program step and ends with the post-acceptance step. In cases where new equipment is installed in an existing building (e.g., installing a cooling system in an existing building which previously had only a heating system), it should be referred to as I-Cx. Basically, the range of the CxP implemented depends on the owner's desires and can be defined in a contract between the owner and a CA. It is strongly recommended that consistency be maintained in the I-Cx process, but before commissioning becomes business-as-usual in a society, there will be cases where Cx in the pre-design and design phases have not been implemented as mentioned in the definition and explanation of 'Preparation Procedure for Commissioning Starting at Construction Phase'. In such cases, the I-Cx can be called 'Partial Initial Commissioning'.

Issues log: A formal document that records questions, answers, problems and resolutions occurring during the commissioning process.

On-going commissioning (on-going Cx): On-Going Cx is a CxP conducted continually for the purpose of maintaining, improving and optimizing the performance of building systems after I-Cx or Retro-Cx. The large difference between On-Going Cx and periodic Re-Cx is that the Re-Cx refers to the original building systems performance, while On-Going Cx lays emphasis on the performance optimization. The On-Going Cx is a successive CxP during the Operation & Maintenance Stage to resolve operational problems, improve comfort, optimize energy use, and recommend retrofits if necessary.

Owner's program (OP): A document written by the owner that describes the owner's vision and philosophy including budget, distribution of costs, expected profitability and environmental and energy objectives of the project.

Owner's project requirements (OPR): A document based on the owner's program and the design requirements. The owner develops it with help from the commissioning authority.

Passive test: A test to assess performance by analyzing data obtained from systems operating under normal conditions.

Preliminary design documents: The preliminary design documents are developed by the design professional to confirm the basic design content before starting a working design. These documents include tables and layouts of equipment, schematics of duct and piping systems, a control system, basis of design, a draft design intent document and a commissioning specification based on the schematic planning documents. At the completion of preliminary design, all contents of the preliminary design documents should comply with related laws and regulations. The CA judges the appropriateness of the contents and organization written in the preliminary design documents; this judgment includes evaluation of whether they comply with the OPR, the design intent is appropriate, and the quality control of the design process is adequate.

Preparation procedure for commissioning starting at construction phase: Specific actions that should be performed before the construction phase when commissioning of re-design phase and design phase have not been implemented. They are implemented for clarifying the system performance requested in the commissioning. The CA audits related documents (e.g. OPR and design documents); clarifies the possibility of Commissioning; and informs the owner if the design is incomplete.

Re-commissioning (Re-Cx): A CxP implemented after the I-Cx or the Retro-Cx process when the owner hopes to verify, improve and document the performance of building systems. Reasons to re-commission a building are diverse. It could result from a modification in the user requirements, the discovery of poor system performance, the desire to fix faults found during the I-Cx, etc. Periodic Re-Cx ensures that the original performance persists. Re-Cx is the event that reapplies the original Commissioning in order to maintain the building systems' performance.

Request for proposal (RFP): A document written by the owner to solicit a commissioning authority (RFP_CA) or to select a design professional (RFP_Des) for the project.

Retro-commissioning (Retro-Cx): The first time commissioning is implemented in an existing building in which a documented CxP was not previously implemented. In many cases, design documents of the existing building have been lost or they don't match the current situation. Therefore, the Retro-Cx process may or may not include verification of the design shown in the I-Cx.

Risk evaluation (RE): A specification provided by the owner or the commissioning authority in which the accepted risk level (with respect to not meeting the OPR) for the building's HVAC systems is fixed. RE is an overall evaluation of qualitative and quantitative damage if the system does not meet the requirements. It considers the main human risks (e.g. responsibility, knowledge, consciousness, etc.) as well as the main system risks (e.g. risk management, time to discover and react in case of failure, time to get under control, trends, etc.). It considers the probability of its occurrence and the resulting damage (e.g. human health, environmental load, energy savings, cost, image, etc.).

Schematic planning documents: The schematic planning documents are documents

presented to the owner by the design professional when the design professional begins a preliminary design. They include a design philosophy, environmental and energy criteria, functional requirements, environmental control requirements, and outlines of building systems that meet the OPR. If the design proposal made by the design professional is adequate, it can serve as the schematic planning documents. However, if the OPR and the commissioning plan are further developed, the schematic planning documents should be revised.

Standard models of commissioning plans (SMCxP): Standard models which list typical tasks to be carried out in the commissioning process. These were developed under Annex 40 to help understand the commissioning plan for non-residential buildings and to be applied as one of the commissioning tools. The five SMCxP models are based on the commissioning levels. The commissioning levels are defined based on the combination of the building size, HVAC complexity and the risk level. In real projects, the SMCxP would be modified according to the project's characteristics and the social customs in each country and/or state.

System manuals: Summary documents describing system operation and maintenance. They are developed by the commissioning authority from the guide for system control and operation provided by the design professional and the system operation and maintenance manual provided by the contractor. They include additional information collected during the commissioning process.

System operation and maintenance mManual: A manual of system operation and maintenance for operating and maintenance personnel summarized by the contractor. It includes the handling manual for the equipment and systems, the seasonal operation changes needed, the guide for checking and cleaning, the correspondence in an emergency, etc.

Testing, adjusting and balancing (TAB): A testing and adjustment of constructed and installed equipment and systems conducted by a contractor to ensure that the equipment and systems operate to meet the specifications written in the design documents. It includes adjusting water flow in pipes, air flow in ducts, and tuning control parameters.

Appendix B: Participants

Austria

Gerhard Faninger, Unversity of Klagenfurt
Helmut Schoeberl, Schoeberl + Poell OEG, Vienna
Sture Larsen, Architect, Hoerbranz

Australia

Richard Hyde, Univ. of Queensland, Brisbane

Belgium

Andre de Herde, Kristel de Myttenaere, Univ. Catholique de Louvain

Brazil (observer)

Marcia Hammerle, Fed. Univ. of Minas Gerais Belo-Horizonte

Canada

Pat Cusack, Arise Technology, Kitchener ONT

Czech Republic

Miroslav Safarik, Czech Envir. Institute, Praha

Finland

Jyri Nieminen, VTT Bld. & Transport, Espoo

Germany

Andreas Buehring, Christel Russ, Karsten Voss, Fraunhofer ISE, Freiburg
Hans Erhorn, Johann Reiss, Fraunhofer IBP, Stuttgart
Frank D Heidt, Udo Giesler, Universitaet-GH Siegen
Berthold Kaufmann, Passivhaus Institut, Darmstadt
Joachim Morhenne, Ing. Buero Morhenne GbR, Wuppertal
Carsten Petersdorff, Ecofys GmbH, Koeln

Iran (observer)

Vahid Ghobadian, Azad Islamic, Tehran

Italy

Valerio Calderaro, University La Sapienza of Rome
Luca Pietro Gattoni, Politecnical di Milano
Francesca Sartogo, PRAU Architects, Roma

Japan

Ken-ichi Hasegawa, Akita Prefectural Uni., Akita
Motoya Hayashi, Miyagigakuin Womens College, Sendai
Nobuyuki Sunaga, Tokyo Metropolitan Univ., Tokyo

Netherlands

Edward Prendergast, Peter Erdtsieck, MoBius consult bv., Driebergen-Rijsenburg

New Zealand

Albrecht Stoecklein, Building Research Assoc., Porirua

Norway

Tor Helge Dokka, SINTEF, Trondheim
Anne Gunnarshaug Lien, Enova SF, Trondheim
Are Rodsjo, Norwegian State Housing Bank, Trondheim
Harald N. Rostvik, Sunlab/ABB, Stavanger

Sweden

Hans Eek, Architect, Goeteborg
Tobias Bostroem, Uppsala University
Bjoern Karlsson, Vattenfall Utveckling AB, Alvkerleby
Maria Wall, Johan Smeds, Helene Gajbert, Lund University

Switzerland

Robert Hastings, AEU Ltd., Wallisellen
Tom Andris, Renggli AG, Sursee
Daniel Pahud, SUPSI-DCT-LEEE, Canobbio
Alex Primas, Annick d'Epinay, Basler & Hofmann AG, Zuerich
Anne Haas, EMAP, Duebenford

UK

Goekay Deveci, Robert Gordon University, Aberdeen

USA

Guy Holt, Coldwell Banker Assoc., Kansas City, MO.

International Energy Agency (IEA)
Energy Conservation in Buildings & Community Systems Programme (ECBCS)

The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Co-operation and Development (OECD) in 1974, with the purpose of strengthening co-operation in the vital area of energy policy. As one element of this programme, member countries take part in various energy research, development and demonstration activities. The Energy Conservation in Buildings and Community Systems Programme has co-ordinated various research projects associated with energy prediction, monitoring and energy efficiency measures in both new and existing buildings. The results have provided much valuable information about the state of the art of building analysis and have led to further IEA co-ordinated research.

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International Energy Agency
Energy Conservation in Buildings and Community Systems Programme