Review of possibilities and necessities for building lifetime commissioning

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Abstract

The article presents review of possibilities and necessities for a practical application of lifetime commissioning in building facilities. The implementation of life-long commissioning of buildings implies energy efficiency, ensures a rational use of energy and thereby decreases CO_2 emissions. Therefore, first the term “commissioning” is explained in the article. Commissioning necessities, which are induced by different operational faults, the new laws driven by idea for decreasing CO_2 emission, and benefits, are explained, too. Besides USA’s and European laws for the energy performance of buildings, the Norwegian state of the art in this area is also presented. The difference in terms and methods for fault detection and diagnosis are elaborated in the article. Finally, examples of different commissioning tools are briefly introduced and compared. In order to make building sustainable and encourage energy savings, potential commissioning users are suggested.

Keywords: Building, Commissioning, Fault detection and diagnosis (FDD), Maintenance

Contents

1. Introduction

Commissioning is a systematic process of ensuring that all building facility systems perform interactively in accordance with the design documentation and intent. Therefore, commissioning methods and tools have to ensure that buildings reach their technical potential and operate energy-efficiently. These methods and tools are oriented to assess and optimize building performances, and improve maintenance services. Commissioning begins with planning and includes design, construction, start-up, acceptance and training, and should be applied throughout the life of the building. The overall objective of the life-long commissioning of building HVAC systems is implementation of a standardized way for operating and maintaining buildings. This improves energy efficiency, ensures a rational use of energy and thereby decreases CO_2 emissions [1]. In addition, the life-long application of this process enhances the indoor environment in buildings.

In 1999, the International Energy Agency's (IEA) Implementing Agreement on Energy Conservation in Buildings and Community Systems (ECBCS) initiated the activity "Annex 40: Commissioning of Building HVAC systems for Improved Energy Performance". The Annex 40 project was finished in 2004 by publication of the final report. In 2005 the Executive Commeete for the same Implementing Agreement decided to launch a new activity "Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings". The goal of IEA - ECBCS Annex 47 is to enable the cost-effective commissioning of existing and future buildings in order to improve their operating performance, so that the low energy buildings are possible. The commissioning techniques developed through this Annex will help transition the industry from the intuitive approach that is currently employed in the operation of buildings to more systematic operation that focuses on achieving significant energy savings [2].

The aim of this review article is to explain both the commissioning importance and necessity for a further work in this area, so that buildings can become a sustainable and energy-efficient system. At the beginning of the article the term commissioning is explained as a help tool for improving building performances. The building performance is measured by a performance metric, which is a standard definition of a measurable quantity that indicates some aspect of performance [3]. The third part of this review article deals with reasons for the commissioning implementation. A practical meaning of the commissioning work is presented in the fourth part through giving methods and their applications. Since building has different users during lifetime, the fifth part suggests their possibilities to save building energy.

2. Commissioning as a help tool for improving building performance

Buildings are becoming more complex system with lots of including elements (heating/cooling components, hot tap water system, ventilation components, complex control system, etc.). In addition, users may have different demands from a building. To make this complex system sustainable, there are lots of participants during a life of the building, such as: designers, managers, caretakers, users, owners etc. A building life-cycle can be described in a few phases: design, construction, operation and disintegration. Even though the building complexity is growing, communication/understanding between the participants and the building elements during the building life is poor.

Energy management in buildings is the control of energy use and cost, while maintaining indoor environmental conditions to meet comfort and functional needs [4]. Building energy management system (BEMS) provides lots of data about building performances. These data are useable for caretakers and managers. Caretakers can use performance data for maintenance and improving the building performance. Energy management requires technical knowledge to understand how well, or how poorly, a building and its systems are functioning, to identify opportunities for improvement, and to implement effective upgrades. Well-trained and diligent building operators are very important to the financial success of energy management [4]. In order to utilize BEMS data more successfully for maintenance, it is necessary to provide useful information about the building performance to the caretakers, actually understanding what really happen in a building.

Commissioning is a systematic process of ensuring that all building facility systems perform interactively in accordance with the design documentation and intent. It implies accepting the different methods, guidance and procedures. Process eliminating the need for costly capital improvements, and can give short payback time [5, 6]. The hierarchy of building needs including commissioning as a new part in the building system can be placed as in Figure 1.

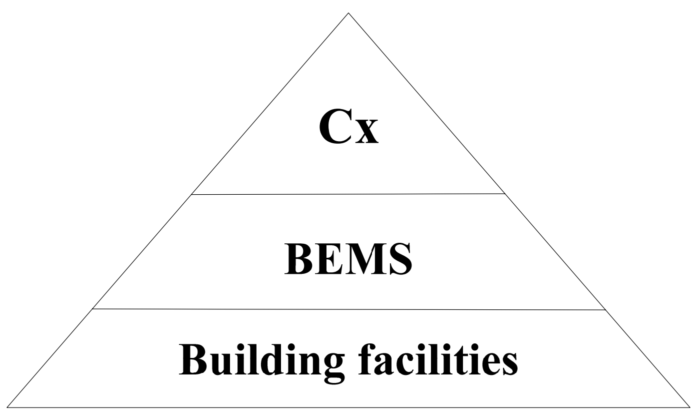

Figure 1. The hierarchy of building needs

Since commissioning can be applied throughout the life of the building and is team-oriented [4], it is placed on the top of the building needs in Figure 1.Therefore building facilities and BEMS must exist that commissioning can be applied. Building facilities in Figure 1 can also be a building design. Since commissioning should be understand as a help mean or tool for improving building performance, it is recommended for construction of new buildings as well as existing buildings. The goal is to confirm that a facility fulfills the performance requirements of the building owner, occupants, and operators [4].

3. Why commissioning is necessary?

3.1. Faults in building operation

There is an increasing realization that many buildings do not perform as intended by their designers. Reasons include faulty construction, malfunctioning equipment, incorrectly configured control systems and inappropriate operating procedures [7]. On the other hand, due to abnormal physical changes or ageing of HVAC components, inadequate maintenance, HVAC components easily suffer from complete failure (hard fault) or partial failure (soft fault) [8]. Even though building performances are normally supervised by BEMS, when a fault enters in the system the BEMS programs currently available do not adequately assist in finding the underlying cause of the fault. Therefore diagnosis of the defect is thus left to the operator [9]. However, both increase in energy consumption and degradation in the indoor environment follow each fault regardless of source.

Research on fault detection and isolation in automated processes has been active over several decades. The HVAC process has also been a subject of interest during the last 10 years. Annex 25 [9], organized by International Energy Agency (IEA) and its Energy

Conservation in Buildings and Community Systems (ECBCS) was a leading forum in this field in the beginning of 1990s. A number of methodologies and procedures for optimizing real-time performance, automated fault detection and fault isolation were developed in the Annex 25. Many of these diagnostic methods were later demonstrated in real buildings in Annex 34 [10] (also organized by IEA ECBCS), which concentrated on computer-aided fault detection and diagnosis [11].

A short list of some of the faults in three typical HVAC systems is given in Table 1. The faults are chosen from Annex 25, which obtained these results using the survey among designers, constructors and operators. The list classifies faults based on systems, related faults and type of fault (design, maintenance, due to user, etc.).

Table 1. List of some typical fault in three typical systems listed in Annex 25 [9]

System	**Fault**	**Comment**
Hydronic heating system	Heating imbalance between different parts of the building	Design fault
	Over or under-sizing of radiator in certain rooms or specific parts of the system	Design fault
	Heating curve badly tuned	Operating fault
	Incorrect calculation of the optimum start or stop by the operational mode controller	Operating fault
	Leakage of the: valves of the control of secondary circuits	Operating fault
Chillers and heat pumps	Compressor not pumping	Maintenance fault
	Plant undersized	Design fault
	Too much pressure drop in evaporator	Design fault
VAV air handling unit	Condensation due to improper thermal insulation	Fabrication fault
	Excessive internal heat generation	User fault
	Insufficient noise control	Design and fabrication fault
	Air filter being clogged	Maintenance fault

Since the building complexity is growing, new faults can always appear. Therefore in the near future, energy savings will be obtained mainly through optimal control and early fault detection of building HVAC systems. Lowering of energy consumption and building operation cost with proper occupant comfort level will be reached together with well-organized maintenance, fast detection and correction of faults and best use of equipments' performances [9].

3.2. Legislative force

Since most of the building users are not aware of an important issue of energy use and influence on the environment, legislative regulation can encourage the users to utilize commissioning tools for improving building performances. Currently, two legislations are in practice for this purpose:

- Energy Performance of Buildings Directive (EPBD) [12] in Europe,
- Leadership in Energy and Environmental Design (LEED) in USA.

EPBD is based on the Danish experience, among others. Since 1997, the Danish energy-saving policy has been using an energy labeling scheme for buildings as mandatory. While at the beginning of 2006 the EPBD has been implemented for all EU countries. Concerning owner-occupied households, the idea in the Danish labeling scheme is that all houses shall be labeled before they are sold, so that the new owners can see the energy performances of the house they intend to buy [13]. In general, the objective of the EPBD is to ‘promote the improvement of the energy performance of buildings within the community taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost effectiveness’ [14].

In Norway after 1 February 2007 the requirements for the EPBD certification of only new buildings have been coming into force for building permits requested. While certification of buildings, inspection of boilers and air conditioning systems could come into force from 2008 for some building categories [15].

The LEED Green Building Rating System was developed by the United States Green Building Council (USGBC) to further the development of the high-performance, sustainable buildings in the United States. LEED provides a framework for assessing a building's performance and for achieving sustainability goals. Commissioning is a requirement to achieve LEED certification for both new and existing commercial buildings. In addition to commissioning being a fundamental requirement, additional credits towards certification can be earned through additional commissioning activities [16].

In order to decrease energy use in buildings and CO_2 emission, commissioning tools encouraged by the legislation are necessary. In addition, these legislative certifications have to be implemented for the entire building lifetime in order to completely improve building performances.

3.3. Commissioning benefit

Commissioning benefits can be defined as:

- Energy benefit,
- Non-energy benefit.

Energy benefit can be achieved by a proper "tuning up" building. A proper "tuning up" means that building performs according to its intent. Previous case studies have found that "tuning up" an existing building's HVAC systems results in an average savings of 5-15% of total energy consumption in full commissioning of existing buildings [17]. Building energy consumption is one of the most important building energy performance indicators. Since an energy performance certificate can influence building value when building is sold or rented out [14], energy benefit encouraged by the legislation can be turned into pure profit. Therefore, application of different commissioning tools through building lifetime can both improve building energy performance and save energy.

Some of the most important non-energy commissioning benefits are:

- operation and maintenance budget savings,
- improved thermal comfort, and
- liability reduction.

Operation and maintenance service, equipped with appropriate commissioning tools, results in less labor, a few failures and improved thermal comfort. Therefore, a certain savings can be achieved. Improved thermal comfort in a building gives increased productivity and tenant retention value. Finally an improved maintenance service results in the building liability reduction. Even though these commissioning non-energy benefits are sometimes difficult to express directly in money value, they seem to be very important in now days.

4. How does a commissioning tool work?

4.1. Assessment, fault detection and diagnosis

Regardless of applied logic in the background of a commissioning tool, the main point of the tools is the assessment of building performances. Building assessment tools can be organized into three categories: benchmarking, energy tracking, and diagnostics. Benchmarking is a macroscopic level of performance assessment, where metrics are used to measure performance relative to others. Buildings are typically benchmarked using coarse data, often from utility bills, and some procedure for normalization for variables such as weather and floor area. Tracking energy performance over time is a logical enhancement of one-time benchmarking. Energy tracking can result in an overall understanding of load shapes. Although the data needed for diagnostics are more extensive than for energy tracking, this jump in complexity is essential to obtain the information needed to aid in correcting problems. Benchmarking and energy tracking are useful in identifying inefficiency at the whole building level and focusing efforts toward large energy end-uses, while diagnostics allows detection of specific problems and helps target the causes of these problems [17].

There are two levels or stages of ‘diagnostics’:

- fault detection, and
- fault diagnosis.

Fault detection is the determination that the operation of the building is incorrect or unacceptable from the expected behavior. Fault diagnosis is the identification or localization of the cause of faulty operation. Therefore, diagnosis involves determining which of the possible causes of faulty behavior are consistent with the observed behavior [18]. The nature of the fault unambiguously may be possible to identify, but often it is only possible to eliminate some of the possible causes. The process of diagnosis requires that the most important possible causes of faulty operation have been identified in advance and that these different causes give rise to behaviors that can be distinguished with the available instrumentation. The costs of detecting a particular fault include the cost of any additional instrumentation, computer hardware and software, and any human intervention. Both the costs and the benefits will depend on the particular building and application and must be determined on a case-by-case basis [19]. Fault diagnosis methods can include rule-based diagnosis, recognition of statistical pattern, artificial neural networks and fuzzy logic [20].

4.2. Methods for fault detection and diagnosis

Commissioning tools for building performance assessment can be defined as:

- functional performance testing (FPT),
- fault detection and diagnosis (FDD).

FPT is the process of determining the ability of HVAC system to deliver heating, ventilating, and air conditioning in accordance with the final design intent [4]. FPT is more important during the construction and delivering phase of building, while FDD tools are necessary during operation and maintenance.

FDD tools can be manual and automated. Manual tools imply different guidelines for the building operators. Automated commissioning involves analyzing system performance in order to detect and diagnose problems (faults) that would affect the operation of the system during normal use [21].

Most of FDD tools are based on combinations of predicted building performance and a knowledge-based system. They compare the performance of all or part of the building over a period of time to what is expected, so incorrect operation or unsatisfactory performance can be detected. The expected performances can be assumed, desired and model-based. The model takes an operating point as input and makes a prediction of the set-point expected to drive the system to that operating point. By configuring the model to represent correct operation, a deviation in the actual operating point of the system from the desired point represents an indication of faulty behavior [21]. Compare of the expected and deviated performance is fault detection, while diagnosis means fault identification. Therefore, different FDD tools have diversity in a fault classifier. A fault classifier is a way how faults are diagnosed.

Principles and application of six FDD tools are compared briefly in the following text. A model-based feed-forward control schema for fault detection is described in [22]. An example of monitoring-based commissioning by use of information monitoring and diagnostics system (IMDS) was reported in [23, 24]. FDD tools can use the statistical classifier, as reported in the following methods: principal component analysis (PSA) method for sensors [8], the combination of model-based FDD (MBFDD) method with support vector machine (SVM) method [25], and the transient analysis of residual patterns [20]. Air handling unit performance assessment rules (APAR) is a fault detection tool based on expert rules [26]. A brief comparison of the above tools is given in Table 2.

Table 2. FDD tools comparison

Tool name	**Background**	**Example of use**	**Benefit**
Model-based feed-forward	Model-based	PI(D) feedback loop in the dual-duct AHU	Improvement in the control process
IMDS	Monitoring-based	Whole building and HVAC systems	Data visualization and useful information for the building operators
PSA for sensors	Statistical	Sensors faults in AHU	The existence of component faults does not affect the capability of the strategy
MBFDD with SVM	Statistical	AHU with cooling coil supplied by chiller	High accuracy and small amount of training samples
Transient analysis of residual patterns	Statistical	VAV-HVAC	Classification of slow and fast faults
APAR	Rule-based derived from balance equations	AHU	Suitable for embedding in commercial HVAC equipment controllers

The statistical methods indicate a fault based on an index value of faulty conditions. An index can have different background depends on the method. For example, the FDD application of PSA method uses the squared sum of the residual, named the Q-statistic or squared prediction error (SPE), as an index of faulty conditions. Consequently, the Q-contribution plot can be used to diagnose the fault. The variable making a large contribution to the Q-statistic or SPE is indicated to be the potential fault source [8]. In MBFDD method combined with SVM method, an SVM method is used to design a fault classifier, which is based on the statistical learning theory that transforms the signal to a higher-dimensional feature space for optimal classification [25].

Since system availability is more important than reliability in most HVAC systems, a FDD system, which is developed using knowledge about typical or important faults, is necessary [27]. Even though a FDD tool can have different theoretical background, their most important aim is to give good information about the building performance.

4.3. Commissioning tools application

A commissioning tool for the design phase improves building performance in the operating phase, while tool for the operating phase improves maintenance, so that the building performances are as intended to be. Application of a commissioning tool is related to a tool realization and a tool user. These tools can be automated or manual. Automated tools are embedded in the HVAC control system. An important means for practical application of any tool in existing building is BEMS. Therefore, availability of performance metrics [3] is necessary for any assessment in any FDD method.

There have been developed two user interfaces for a commissioning tool under Annex 40, diagnostic agent for building operation (DABO) in Canada and Cite-AHU tools in France [28]. DABO is a software tool running in the central building operator station. It analyses data from the BEMS in order to identify faults in the operation of energy consuming equipment and systems. DABO uses expert knowledge to identify these faults through the use of a hybrid knowledge-based system composed of an Expert System and a

Case-Based Reasoning module [29]. DABO and Cite-AHU tools have been devoted for the building operator, maintenance company and the energy service company [28].

A practical barrier to the adoption of commissioning tools is the difficulty of setting up communications between the tool and the control devices. Technologies for carrying out automated commissioning are still in their infancy and very few tools are available for practitioners to use [28].

5. Commissioning users

To put into practice commissioning, it is necessary to develop tools according to an intended user. Since building lifetime has few phases with different participants, the commissioning users could be most of these building participants. Therefore, these users can be: designers, constructors, operators, building managers and occupants, etc. For example, designers and constructor can be the users of the FPT methods to confirm ability of a system. Since building operators and managers need assistance in extracting useful information from the large volume of data produced by new monitoring technologies [24], they can be user of commissioning tools, too. Finally, market and legislative means can contribute in attracting the building occupants and owners as potential users.

6. Conclusion

Commissioning methods and tools for improving the building performances seems to be promising for making the sustainable buildings. These tools can be both manual and automated, and devoted for different users. This review article has explained the necessity, application and users of commissioning. The FDD tools discussed in this review article are rule-based, monitoring-based and statistical. The commissioning techniques help transition the industry from the intuitive approach in the operation of buildings to more systematic operation that focuses on achieving significant energy savings.

Growing building complexity can induce increased energy consumption in the further without tools for improving building performances. Actually, in the near future, energy savings can be obtained mainly through optimal control and early fault detection of building HVAC systems. Therefore, different commissioning tools are necessary to make the sustainable and energy-efficient buildings.

Even though there have been lots of international works in the commissioning area, still new tools are necessary for all the building participants during building lifetime. In addition, the legislative means should encourage commissioning application and development in order to decrease energy use in buildings and CO_2 emission. The idea of promoting the improvement of the energy performance of buildings with taking into account outdoor environment, as well as indoor climate requirements and cost effectiveness has to be supported by the legislative means. In addition, authorities should try to implement different energy-efficiency laws that cover the entire building lifetime.

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