Department of Automation and Systems Technology

Transforming building automation data into building performance metrics – design, implementation and evaluation of use of a performance monitoring and management system

Heikki Ihasalo

Aalto University

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Heikki Ihasalo

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Abstract

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Abstract

This dissertation focuses on the construction and evaluation of a continuous building performance measurement tool. These kinds of tools provide a method for improving the quality and performance of buildings. There is a need for performance measurement, since it is quite common that buildings do not perform as intended. As the development trend is towards low and zero-energy buildings equipped with new and complex technologies, the significance of quality and performance assurance becomes even greater.

The constructive research approach was the main research method in this thesis. This method was used to build the continuous performance measurement solution. The primary method was supplemented with qualitative research methods in the evaluation part of the study. The solution was evaluated from the users' perspective by interviewing solution users with the help of a semi-structured guide. The interview data was later analysed using content analysis to identify emerging themes.

The solution presented in this study utilizes building automation data from real buildings and transforms the data into a set of performance metrics. The solution is capable of visualizing a building's performance from energy, indoor conditions and HVAC system perspectives. In addition, the solution presents the performance information in a format that it can be used in both building performance monitoring and management. Although the users were satisfied with the solution in general, they used it only for testing and experimental purposes. The main challenges to using the solution were related to accessibility, trust and management practices.

The methods used to transform building automation data into building performance metrics as well as the methods of presenting the information in a format that can be used in both building performance monitoring and management are such that they offer new knowledge to the research field. In addition, the results of the user evaluation suggest that the users may not be satisfied with a web portal dedicated to displaying performance information. Rather they would prefer to receive information in the easiest possible manner, such as via applications that they would otherwise use in their daily work

Keywords building automation, performance monitoring, performance management, performance metric, evaluation of use

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Tiivistelmä

Tekijä
Heikki Ihasalo

Väitöskirjan nimi
Rakennusautomaation tiedon muuntaminen kiinteistön suorituskykymittareiksi – suorituskyvyn valvonta- ja johtamisjärjestelmän suunnittelu, toteutus ja käytön arviointi

Julkaisija Sähkötekniikan korkeakoulu

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Tiivistelmä

Tämä väitöskirja keskittyy jatkuva-aikaisen kiinteistön suorituskyvyn mittaustyökalun rakentamiseen ja arviointiin. Työkalu tarjoaa menetelmän kiinteistöjen laadun ja suorituskyvyn parantamiseksi. Suorituskyvyn mittaamiselle on tarvetta sillä on varsin yleistä että rakennusten toimivuudessa on puutteita. Laadun ja suorituskyvyn varmistuksen merkitys on kasvamassa tulevaisuudessa, koska kehitys on menossa kohti matala- ja nollaenergiarakennuksia jotka hyödyntävät uutta ja monimutkaista teknologiaa.

Työn päätutkimusmenetelmä on konstruktiivinen tutkimusote, jota hyödynnetään rakennettaessa jatkuva-aikaista suorituskyvyn mittausratkaisua. Päämenetelmää täydennetään laadullisilla tutkimusmenetelmillä työn arviointiosuudessa. Tutkimuksessa rakennettua työkalua arvioidaan käyttäjien näkökulmasta haastattelemalla ratkaisun käyttäjiä puolistrukturoituja kysymyksiä hyödyntäen. Haastattelut arvioidaan sisällön analyysin avulla.

Tässä työssä esitetty ratkaisu hyödyntää todellisten kiinteistöjen automaation dataa ja muuntaa sen suorituskykymittareiksi. Ratkaisu visualisoi kiinteistön suorituskykyä energian, sisäilman olosuhteiden ja LVI-järjestelmän näkökulmista. Lisäksi ratkaisu esittää suorituskykytiedon siinä muodossa, että sitä voi hyödyntää koko kiinteistön käyttö- ja ylläpito-organisaatio sekä kiinteistön suorituskyvyn valvonnassa että johtamisessa. Ratkaisun käyttäjien haastatteluissa havaittiin, että käyttäjät olivat yleisellä tasolla tyytyväisiä ratkaisuun mutta he käyttivät sitä vain testi tarkoituksiin. Suurimmat haasteet ratkaisun käytössä liittyivät saavutettavuuteen, luottamukseen ja johtamiskäytäntöihin.

Menetelmät rakennusautomaation tiedon muuntamiseksi kiinteistön suorituskykymittareiksi sekä informaation esittäminen muodossa jota voidaan käyttää sekä kiinteistöjen suorituskyvyn valvonnassa että johtamisessa tarjoavat uutta tietoa alalle. Lisäksi haastattelututkimuksen tulokset viittaavat siihen, että tiedon saavutettavuuden tärkeyttä ei ole otettu huomioon aiemmissa alan tutkimuksissa. Käyttäjät eivät ole välttämättä tyytyväisiä suorituskykyinformaation esittämiseen keskittyneeseen internet-portaaliin, vaan haluavat saada tiedon mahdollisimman helposti mieluiten sovelluksiin joita he käyttävät muutenkin päivittäisessä työssään.

Avainsanat rakennusautomaatio, suorituskyvyn valvonta, suorityskyvyn johtaminen, suorituskykymittari, käytön arviointi

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I would have not been able to write this thesis without the people participating in the interviews. I would like to thank all the interviewees who made the gathering of empirical data possible.

My deepest appreciation goes out to my family for their encouragement throughout the dissertation process. I am grateful to my mother for her support during my studies and, last but not least, I warmly thank my wife Nina for her understanding and support throughout the process of writing this thesis as well as our daughters Isabel and Emilia for all the joy and happiness they have brought into my life.

Helsinki, February 26th 2012

Heikki Ihasalo

Table of contents

List of abbreviations

AHU	Air Handling Unit
BAS	Building Automation System
BEMS	Building Energy Management System
BMS	Building Management System
BREEAM	Building Research Establishment Environmental Assessment Method
CIBSE	Chartered Institution of Building Service Engineers
CMMS	Computerized Maintenance Management System
DDC	Direct Digital Control
EMCS	Energy Management Control System
ERP	Enterprise Resource Planning
FDD	Fault Detection and Diagnostics
FMS	Facility Management System
HVAC	Heating, Ventilation and Air-Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IRR	Internal Rate of Return
LEED	Leadership in Energy and Environmental Design
NPV	Net Present Value
OASIS	Organization for the Advancement of Structured Information Standards
oBIX	Open Building Information eXchange
OEE	Overall Equipment Effectiveness
OPC	Object linking and embedding for Process Control

PEMMS	Performance Monitoring and Management System
PEU	Perceived Ease of Use
PMV	Predicted Mean Vote
PPD	Predicted Percent Dissatisfied
PU	Perceived Usefulness
ROI	Return On Investment
SOAP	Simple Object Access Protocol
TAM	Technology Acceptance Model
TPM	Total Productive Maintenance
USGBC	U.S. Green Building Council
UTAUT	Unified Theory of Acceptance and Use of Technology
XML	eXtensible Markup Language

List of symbols

εt	threshold parameter accounting for errors in temperature measurements
εhc	threshold parameter for the heating coil valve control signal
εf	threshold parameter accounting for errors related to airflows
ΔTsf	temperature rise across the supply fan
$\Delta Tmin$	threshold on the minimum temperature difference between the return and outdoor air
uhc	normalized heating coil valve control signal
Tsa,s	supply air temperature set point
Tsa	supply air temperature
Tra	return air temperature
Toa	outdoor air temperature
Tma	mixed air temperature
t_{22}	supply air outlet
t_{21}	supply air inlet
t_{11}	exhaust air inlet

1. Introduction

This chapter provides an introduction to the research work presented in this thesis. The chapter describes the research background as well as explains the research motivation and research questions. In addition, it presents the research method used in the study and outlines the structure of the thesis. The chapter ends with a discussion on the author's contributions and contributions of the study.

1.1. Background and motivation

Several countries have set ambitious goals for greenhouse gas reductions for the coming decades. For example, the European Union is committed to reducing its overall emissions by at least 20% by 2020 and by 80-95% by 2050 compared with 1990 levels (EC 2011). Buildings account for a third of global carbon emissions (IEA 2011) and are therefore in a central role in reaching the carbon dioxide reduction goals. Various strategies are needed to reduce carbon emissions, such as energy efficiency, renewable energy and carbon capture and storage. Energy efficiency measures are particularly promising, but must be done with care, because they can potentially affect the indoor environment and the health, productivity and comfort of the building's occupants. However, even without energy efficiency measures, indoor air quality and other quality problems are not uncommon in today's buildings (e.g., GAO 1995, Huizenga et al. 2006, Mills & Mathew 2009). As the development trend is towards low and zero-energy buildings equipped with new and complex technologies, the significance of quality and performance assurance becomes even greater.

One approach to improving the quality and performance of buildings is continuous performance monitoring (Haves & Hitchcock 2008). The approach aims at reducing energy use and improving indoor environmental quality by continuously tracking and analysing issues mainly related to heating, ventilation and air-conditioning (HVAC). Several studies, such as (Piette et al. 2001, Brown et al. 2006, Mills & Mathew 2009), have shown that building performance can be improved with this approach. An essential part of the approach is the tool used for performance monitoring. Since current building automation systems, systems used to manage and control

HVAC equipment, have a limited ability to collect, archive and visualize data (Brambley et al. 2005a, Haves & Hitchcock 2008), there has been a need for more advanced performance monitoring tools. During the years these tools have been developed from the perspectives of fault detection and diagnostics (FDD) as well as, commissioning and performance measurement. Despite significant research work in this area, there are still many issues to be addressed. For instance, although FDD and continuous commissioning tools have been developed for years in research institutes, they have failed to be adopted in the marketplace. Although numerous commercial performance measurement products exist they have mainly focused only on energy measures. Non-energy measures should also be measured to avoid sub-optimization, such as improving energy performance at the expense of indoor conditions.

Although current building automation systems do not offer performance measurement capabilities, they still collect, process and transmit data that is related to several aspects of a building's performance, such as indoor conditions and equipment performance. This data could be used to measure building performance from multiple perspectives and to provide an overall picture of the building's performance.

1.2. Research problem and questions

The problems that this research addresses are building energy efficiency requirements, building performance problems and especially the tools intended for continuous building performance measurement. The thesis approaches these challenges from the viewpoint of building automation and performance measurement.

There are two research questions in this study:

- What kind of solution for continuous building performance measurement transforms building automation data into a set of performance metrics that describe a building's performance from multiple perspectives?
- What are the experiences and especially the challenges associated with the use of this solution?

The study concentrates not only on constructing a new solution but also on evaluating the solution from the users' perspective. This is seen to be important because many of the earlier solutions, especially those based on fault detection and diagnostics methods, have not gained success in the marketplace.

1.3. Research method

This study was conducted using the constructive research approach. Constructive research is a form of applied research that aims at solving real world problems through constructions, such as models, diagrams, commercial products and information system designs (Lukka 2003). At the center of the approach is the belief that by creating a new reality (a construction) and analysing it in detail, one can make both a practical and theoretical contribution. The approach or similar approaches have been widely used in technical sciences, mathematics, operations analysis and clinical medicine (Kasanen et. al 1993). The research approach of solving problems through constructions is sometimes also referred to as design science (March & Smith 1995, Järvinen 2004).

Kasanen et. al (1993) and Lukka (2000, 2003) have developed the constructive research approach in the field of business administration. Although they have developed the approach in business science, its potential application field is broad. Their research approach has been used in various fields of study such as logistics and supply chain management (Laine 2005), real estate and facility management (Lindholm 2008) as well as computer sciences (Buss 2011).

Kasanen et al. (1993) present that the constructive research consists of five elements: practical relevance of the problem, connection to the theory, a construction as a solution to the problem, practical functioning of the solution and theoretical contribution of the solution as presented in figure 1.1. An essential part of this approach is to tie the research problem and its solution to an accumulated theoretical understanding. In addition, the research has to demonstrate the novelty of the solution and evaluate the results critically.

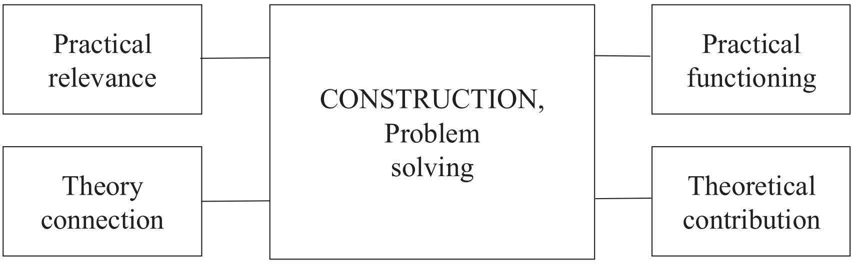


Figure 1.1 Elements of constructive research (Kasanen et al. 1993)

The aim of creating concrete solutions and the ability to provide a practical as well as theoretical contribution were the reasons why the constructive research approach was chosen for this research. The approach served all aims in the research process. The research provided a practical solution for the building services company where the research was conducted as well as offered an opportunity for the author of the study to make a theoretical contribution to the field.

The constructive research approach can be illustrated by dividing it into process phases (Kasanen et al. 1993):

1. Find a practically relevant problem which also has research potential
2. Obtain a general and comprehensive understanding of the topic
3. Innovate, i.e., construct a solution idea
4. Demonstrate that the solution works
5. Show the theoretical connections and the research contribution of the solution concept
6. Examine the scope of applicability of the solution

In this study, the first step of the process, the identification of a practically relevant problem, was based on the groundwork conducted during the author's licentiate's thesis (2008) and also during Houttu's master's thesis (2008). In the building services company, where both of the studies were conducted, the decision was made to concentrate on this specific problem as it was identified to be relevant in field of building operation and maintenance. The state-of-the-art review presented in this study forms the second step of the process. The main sources used in the review included academic journals, conference proceedings, research reports and standards. In addition to these, online materials as well as books written on the area were used. The third step, constructing the solution, was an iterative process which included gaining ideas from many people. Several persons from the building services company and their customers provided valuable feedback for the development work. The solution demonstrated in this research is the performance monitoring and management system (PEMMS) which is presented in chapter 10. The system is a commercialized product that utilizes data from real buildings. In addition to describing the system, chapter 11 of this study focuses on evaluating the system from the users' perspective. The last two steps of the process are discussed at the end of chapters 10 and 11 as well as in the conclusions.

Although the constructive research approach is the primary research method in this study, also qualitative research methods are used to evaluate the constructed solution. The qualitative research methods used to evaluate the solution are presented in more detail at the beginning of chapter 11.

1.4. The focus and the structure of the thesis

The main focus of the thesis is the utilization of building automation data in building performance measurement. This decision significantly limits the perspectives of this research. From the building life cycle phases, this study concentrates on the operation and maintenance phase as it is the phase when the building automation system is in use. The main user group of this study is building operation and maintenance organisations. The building services company where this research was conducted represents this kind of organisation. Residential buildings do not necessary have building automation systems and are therefore not always maintained by professional operation and maintenance organisations. Hence, this building type is left out of the scope of the study. In addition, of the numerous building performance aspects, only those that can be measured with a building automation system are investigated in more detail in this study.

The thesis is structured as follows. After the introduction in the first chapter, chapter two presents the problem domain in more detail and outlines the literature review. Chapters three to nine provide a state-of-the-art review on the research subject. The review begins with an introduction to the building operation and maintenance field which is the environment where the research is conducted. Chapter four outlines the technology used in this study, namely the building automation system. This is followed by a presentation of the approaches from which the research problem has been examined in the previous studies. The described approaches are fault detection, diagnostics and prognostics, commissioning and performance measurement. In addition to describing the basic ideas of the three approaches, examples of current tools based on these perspectives are presented in chapter eight. The state-of-the-art review ends with a discussion on information and automation system adoption and use. Based on the state-of-the-art review and especially on the lessons learned from the earlier building performance visualization and fault detection and diagnostics tools, a new solution is constructed. The novel solution is described and analysed in chapter 10. The presented solution is evaluated from the users' perspective in chapter 11. Chapter 12 concludes the study by summarizing the research findings, evaluating the results and exploring directions for future research.

1.5. Contributions of the study

The constructive research approach aims at producing innovative constructions and by this make a contribution to the theory of the discipline in which it is applied (Lukka 2003). The novel solution in this study is the construction of a continuous building performance measurement system which utilizes automation data from real buildings and transforms the data into a set of performance metrics. The system is capable of:

- Visualizing building performance from energy, indoor conditions and HVAC system perspectives
- Displaying the performance metrics in a manner that is easy and intuitive to understand also for non-technical users
- Providing high-level performance reports which enable the overall building performance to be assessed at a glance
- Offering drill-down capabilities to view detailed information behind each metric
- Providing information that can be utilized by the whole building operation and maintenance organisation in both building performance management and performance monitoring

The users of the system identified all the above mentioned capabilities. Despite this, the system was only used for testing and experimental purposes and not taken into operative use. The main challenges to using the system were related to accessibility, trust and management practices.

Some of the main characteristics of the constructed solution as well as the user evaluation findings provide new knowledge to the field of building performance visualization and fault detection and diagnostic tools.

The characteristics of the solution that accumulate prior knowledge are:

- The principles of transforming building automation data into building performance metrics with multiple performance perspectives
- Presentation of the performance information in a format that can be used by the whole building operation and maintenance organisation in both building performance monitoring and management

The results of the user evaluation suggest that the importance of information accessibility has been overlooked in previous studies. The users may not be satisfied with a web portal dedicated to displaying performance information. They would rather receive information as easily as possible through applications that they would otherwise already use during their daily work, such as email or the Computerized Maintenance Management System (CMMS). The other two findings from the user evaluation strengthen the prior understanding that lack of trust in the system and a lack of management practices can be obstacles to adopting advanced information systems.

1.6. Author's contributions

This thesis is part of a larger research effort which was conducted in a Finnish building services company. The research project aimed at utilizing building automation systems in the development of new services for building operation and maintenance. The author initiated the research effort in 2007 and led the project until this thesis. During the research project, a licentiate's thesis and three master's thesis have been published before this study. The licentiate's thesis *Building Automation System Enabled Services for Real Estate Maintenance* has been written by the author of this thesis. It focused on investigating the possibilities of using building automation systems to develop new services (Ihasalo 2008). Chapters three and four of this study are partly based on the licentiate's thesis. The author has instructed all three master's thesis published during the project. Houttu's (2008) master's thesis, *Facility technical metrics - industrial maintenance methods and solutions applied to facility maintenance*, and the author's licentiate's thesis were the starting points to the development of the solution described in this thesis. During the master's thesis project the goal was set to develop building maintenance metrics similar to the ones used in the industrial sector, such as the overall equipment effectiveness. The first version of the continuous performance measurement solution was developed during Houttu's thesis. This version included metrics for indoor air quality and air handling unit performance. Kukkonen (2008) continued the development work in his thesis *Facility maintenance metrics – tool for analyzing energy performance*. In his work, Kukkonen extended the solution to include energy performance metrics which measure the factors that affect energy use in buildings. Wacklin (2010), on the other hand, investigated the performance monitoring of frequency converters in the thesis *Utilization of Frequency Converter Measurement Data in Facility Technical Drives*. He also examined the possibilities equipment manufacturers had to utilize frequency converter data when developing products. After the completion of the master's theses, the solution and especially the user interface of the solution has been developed further. The author has directed this development work in which several persons from the building services company and their customers have participated. The development of the solution is summarized in figure 1.2.

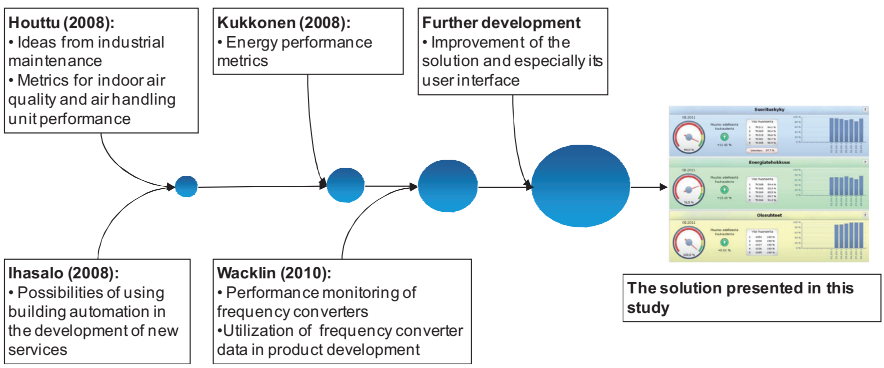


Figure 1.2 The development steps of the solution

The author's contribution to the research work has been in initiating and leading the project as well as providing ideas and lesson's learned from the perspectives presented in the state-of-the-art review of this study, namely building automation, fault detection, diagnostics and prognostics, commissioning, performance measurement, building performance visualization and FDD tools and information and automation system adoption and use. The first version of the solution was presented in Houttu's master's thesis (2008) and it was later extended by Kukkonen (2008) and Wacklin (2010). However, the general principles of transforming building automation data into building performance metrics as well as the further developed solution as a whole including three performance perspectives and the capability to serve both monitoring and management purposes are described for the first time in this thesis.

The author himself has not programmed the solution or constructed the interface of the solution. This work has been conducted by experts dedicated to this field. The author is by himself responsible for writing the state-of-the-art review, describing and analysing the constructed solution, interviewing the solution users, analysing the interview results and drawing conclusions from his observations.

2. Framing the research field and the problem domain

This chapter presents the problem domain of this study in more detail and outlines the state-of-the-art review. The beginning of the chapter describes the research environment, namely the building operation and maintenance field. The rest of the chapter introduces the problem domain and at the same time summarizes the literature review by describing the meanings of the terms used in the problem statement.

2.1. The research environment

This research was conducted in the field building operation and maintenance. This phase of the building life-cycle starts when the construction project ends. Building operation and maintenance aims at maintaining the property's value and providing a comfortable indoor environment for building users. Operation and maintenance work is often undervalued and is often one of the first items considered when budgets are cut. It is also often considered to be inefficient and not as developed as industrial maintenance. However, there have been a number of developments in building operation and maintenance during the last couple of years. One of the most significant changes is the increasing importance of environmental issues. As mentioned in the introduction, buildings are a large source of carbon emissions and therefore have a central role in preventing the global climate change. Several countries have tightened building codes and introduced incentives to reduce carbon emissions in buildings. This has also changed how buildings are constructed and maintained. Another clear change has occurred in the relationships between the actors of building operation and maintenance. In the past it was common that building owners, users and service providers belonged to the same organisation, where as nowadays there is a tendency of separation where the actors are a part of different legal entities. The drivers for this change have been outsourcing and real estate's "sale-and lease-back" model. This change has highlighted the importance of contracts, service descriptions, service level agreements and performance measurements. The research environment is discussed more thoroughly in chapter three.

2.2. Solution for continuous building performance measurement

The first research question included words such as building automation, continuous building performance measurement, performance metrics and performance from multiple perspectives. The following paragraphs describe the meaning of these terms.

The roots of building automation are in the control of heating, ventilation and air-conditioning systems. The system has traditionally been used to maintain comfortable indoor conditions whilst minimizing the energy used. However, current building automation systems are capable of performing much more than this. Through technological development, present automation systems are able to control and manage various building systems, for instance, lighting, safety, security and transportation systems. Today's building automation systems are also capable of communicating with other information systems, such as Computerized Maintenance Management Systems (CMMS) and the Enterprise Resource Planning (ERP) systems. The ability to collect, process and transmit data from several building systems was the reason behind choosing the building automation system for the solution in this study. By utilizing the automation data, no additional sensors or equipment are needed in the implementation of the solution. Building automation systems are introduced in depth throughout chapter four.

Despite recent developments, building automation systems still have limited capabilities to collect, archive and visualize a building's performance. To address this deficiency, more advanced continuous building performance measurement tools have been developed in the fields of fault detection and diagnostics and building commissioning. Also the term building performance monitoring and fault detection and diagnostics tools is used in this study in referring to this kind of tools. Fault detection and diagnostics provide a means of identifying process defects, locating the causes of the faulty operation and giving instructions for corrective actions. On the other hand, building commissioning is a quality assurance process which aims at ensuring that the owner's as well as user's needs are taken into account during the whole lifecycle of the building and the building performs in reality according to the design intent. Fault detection and diagnostics and prognostics are introduced in chapter five, whilst building commissioning is discussed in more detail during chapter six. In addition, chapter eight provides examples of tools previously used in this field.

The terms performance metrics and performance from multiple perspectives are discussed in chapter seven. The idea of performance measurement is to provide quantitative information which can be used in effective decision making and improving operation. Building performance, like any other form of a performance, can be assessed from multiple perspectives. There are several performance aspects involved with a building's performance since different actors approach it from different perspectives. Investors, for example, tend to focus on economic performance, whereas building occupants are more interested in indoor air quality issues. To give the reader an understanding of the amount of possible building performance measures Lavy et al. (2010) identified 35 major building performance indicators as a part of their research.

2.3. Experiences and challenges associated with the use of the solution

The key terms used in the second research question were experiences and challenges. Experiences and challenges associated with the use of the solution were gathered as a part of this research because it is not unusual to find that information systems fail to reach their goals. The evaluation is especially important since the prior solutions based on fault detection and diagnostics methods have not gained success in the building sector. The factors that affect information system success and user acceptance as well as satisfaction are presented in the chapter nine. The same chapter provides also a theoretical framework for the user interviews which are presented in chapter 11.

STATE-OF-THE-ART REVIEW

3. Building operation and maintenance

Building operation and maintenance starts when the construction project ends. This phase of the building life-cycle is often undervalued and is often one of the first items considered when budgets are cut. Maintenance of buildings has been described as the "Cinderella" of the building industry, an activity with little glamour, unlikely to attract very much attention and frequently regarded as unproductive (Seeley 1987). Though Seeley's description may be true even today, there have been a number of developments in building operation and maintenance during the last twenty years. For example, environmental issues, technological development and outsourcing of services have changed the way building operation and maintenance is conducted today. Building upkeep is not only seen as a cost but also as an essential part of maintaining property value and providing comfortable indoor environment conditions for building users.

This chapter introduces the research environment of the study. The beginning of the chapter discusses the definitions related to the subject. This is followed by a description of the significance of building operation and maintenance as well as a discussion of the different actors involved in this field. The chapter ends with an overview of the different maintenance strategies.

3.1. The concept of building operation and maintenance

The main purpose of buildings is to provide a comfortable living environment for their occupants (Roulet 2001). Building operations and maintenance is carried out to ensure that this is achieved over the many years that the building is used.

3.1.1. Definition

In literature, the terms building maintenance and building operation and maintenance are used describing the phase that follows a construction project. Often the terms are used only to represent a wide range of activities and functions needed to upkeep a building, but do not specifically state what the actions include. In fact, there is a substantial difference in literature as to what the terms building operation and building maintenance mean. There is very little information on building operation compared to the volumes written on building maintenance (PECI 1999a).

Maintenance has been described by many authors and there are standards defining the terms used in maintenance. The European standard EN 13306 defines maintenance as ”combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” (CEN 2001). This definition is intended to define all types of maintenance irrespective of the type of item considered except software. Seeley (1987) introduces a more functional description of building maintenance. He describes the principal functions of building maintenance as:

- To ensure the safety of the occupants, visitors and general public
- To maintain services, such as heating, lighting, escalators and fire alarm systems
- To maintain decorative surfaces
- Carry out adequate cleaning
- To prevent or diminish significant deterioration of the fabric

In addition to defining the word maintenance, the standard EN 13306 lists and specifies maintenance activities. The activities are:

- **Inspection**: check for conformity by measuring, observing, testing or gauging the relevant characteristics of an item.
- **Monitoring**: activity, performed either manually or automatically, intended to observe the actual state of an item.
- **Compliance test**: Test used to show whether or not a characteristic or a property of an item complies with the stated specification.
- **Function check-out**: Action taken after maintenance actions to verify that the item is able to perform the required function.
- **Routine maintenance**: Regular or repeated elementary maintenance activities which usually do not require special qualifications, authorization(s) or tools.
- **Overhaul**: A comprehensive set of examinations and actions carried out, in order to maintain the required level of availability and safety of an item.

- **Rebuilding**: Action following the dismantling of an item and the repair or replacement of those sub-items that are approaching the end of their useful life and/or should be regularly replaced.
- **Repair**: Physical action taken to restore the required function of a faulty item.
- **Temporary repair**: Physical actions taken to allow a faulty item to perform its required function for a limited interval and until a repair is carried out.
- **Fault diagnosis**: Actions taken for fault recognition, fault localization and cause identification.
- **Fault localization**: Actions taken to identify the faulty item at the appropriate indenture level.
- **Improvement**: Combination of all technical, administrative and managerial actions, intended to ameliorate the dependability of an item, without changing its required function.
- **Modification**: Combination of all technical, administrative and managerial actions intended to change the function of an item. (CEN 2001)

Building maintenance is thoroughly described in literature whereas building operation is less discussed. Two reports by the Portland Energy Conservation Inc. (PECI) provide some insight into the building operation topic. In the report *Fifteen O&M Best Practices for Energy Efficient Buildings*, it is described that energy-efficient building operations includes activities such as optimizing schedules, control strategies and sequences of operation (PECI 1999a). In another PECI report, equipment setpoint adjustments, parameter settings and performance tracking are also included in the operation of a building (PECI 1999b). In these reports they are referring with building operation to the daily use of equipments, such as turning on and switching off devices or adjusting temperature setpoints. Depending on building management practices, service contracts and the considered equipment, those responsible for building operations may be, for example, tenants, custodians, security personnel or building managers (PECI 1999a).

One of the few definitions of building operation and maintenance is presented by the U.S. Department of Energy's guide *Operations & Maintenance Best Practices, A Guide to Achieving Operational Efficiency* (Sullivan et al. 2010):

> *"Operations and Maintenance are the decisions and actions regarding the control and upkeep of property and equipment. These are inclusive, but not limited to, the following: 1) actions focused on scheduling, procedures, and work/systems control and optimization; and 2) performance of routine, preventive, predictive, scheduled and unscheduled actions aimed at preventing equipment failure or decline with the goal of increasing efficiency, reliability, and safety."*

Thus, it can be concluded that the term 'maintenance' refers to procedures that aim at maintaining equipment, improving their reliability or increasing their lifetime whereas the term 'operation' relates to the efficient use of equipment and activities such as schedule changes and setpoint adjustments.

3.1.2. Significance

The economic importance of buildings and their operation and maintenance is considerable. Building assets account for a significant portion of the gross capital stock of many nations. For example, in the United Kingdom the value of dwellings and other buildings was £4 600 billion in 2009, which is approximately 70 % of the country's gross capital stock (ONS 2010). Operating and maintaining such a valuable asset is a big business. The expenditure on building maintenance in Great Britain is estimated to be £70 billion per year, which is 5 % of the gross domestic product (BCIS 2010).

People in industrialised countries spend a considerable amount of time indoors, living, working, shopping and travelling in enclosed vehicles. The indoor environment, in which people spend time, affects their well-being and productivity (Clements-Croome 2000, Seppänen 2004). A comfortable indoor environment includes, among other things, thermal, visual and acoustic comfort as well as good indoor air quality (Claude-Alain 2001). Building operation and maintenance contributes to all these factors and is therefore an essential part of securing comfortable indoor condition for building occupants.

In addition to being important to the economy and contributing to the well-being of humans, building operation and maintenance have a significant role in the production of global greenhouse gases. Buildings account for 40 percent of total energy use and a third of the CO_2 emissions in the European Union (EC 2010).

3.1.3. Actors

Several actors are involved in the operation and maintenance of buildings. In the studies by Tuomela & Puhto (2001), Kadefors & Bröchner (2004) and Rembrand (2004) the actors have been categorised into building owners, users and service providers. The relationships between these actors have changed during the last decades. In the past it was common that the actors belonged to the same organisation where as nowadays there is a tendency of separation where the actors are a part of different legal entities (figure 3.1).

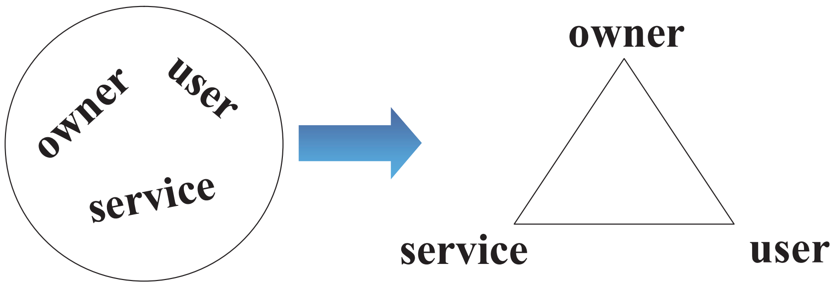


Figure 3.1 The relationship between the actors in the building operation and maintenance field (adapted from Rembrand (2004))

The drivers for this change have been outsourcing and the "sale-and lease-back"- model where owners sell their real estate assets to outside investors. In the global marketplace, which is changing rapidly and where competition is fiercer than ever, organisations have outsourced their non-core activities and leased their capital to concentrate on their core business. One of the most often outsourced services in the real estate sector has been building maintenance (Tuomela & Puhto 2001).

The separation of the actors to different organisations has changed management practices. Building operation and maintenance management is no longer about managing people, for example planning and assigning work and supervising maintenance personnel, it is rather about managing contracts. This has highlighted the importance of contracts, service descriptions, service level agreements and performance measurements. These documents and methods are used to insure the quality of the service provider's work.

However, the separation of building owners, users and service providers to different organisations is not the only development trend. After first outsourcing their operation and maintenance some organisations have decided to return to in-house teams. Therefore, the relationship between building owner, users and service providers changes depending on the organisations goals and strategies. (Tuomela & Puhto 2001).

3.2. Maintenance types and strategies

There are several strategic options available to maintain a building. Ollila and Malmipuro (1999) divide maintenance activities into four main categories: reactive, preventive, predictive, and proactive. However, Chan et al. (2001) identify five maintenance strategies: time-based, performance-based, breakdown-based, renovation-based and integration-based. The European standard EN 13306 separates maintenance strategy into corrective, preventive, condition based and predetermined maintenance (figure 3.2) (CEN 2001). Furthermore, Wood (2005) describes innovate maintenance practices, such as just-in-time maintenance, intelligent building maintenance, call center maintenance and sustainable building maintenance. Thus, there exists several ways to classify maintenance strategies. In this study maintenance strategies are discussed in more detail according to the classification of the European standard EN 13306.

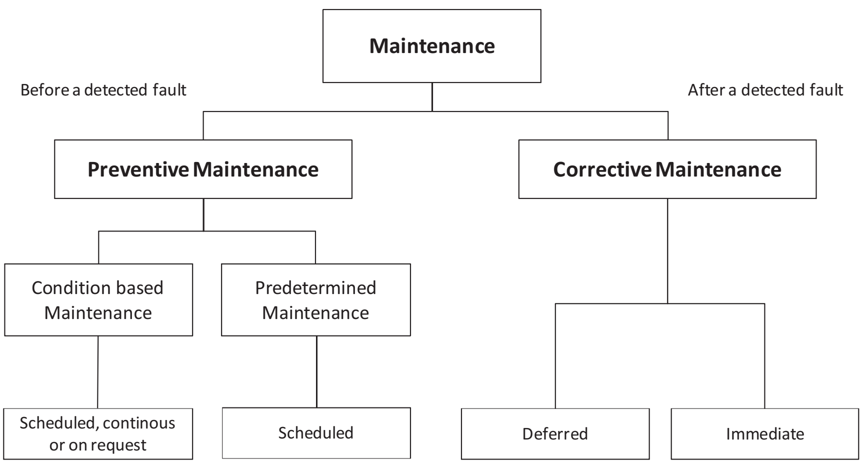


Figure 3.2 Maintenance strategies (CEN 2001)

3.2.1. Corrective maintenance

Corrective maintenance is maintenance that is carried out after fault recognition and intended to put an item into a state in which it can perform a required function. In deferred maintenance, the corrective actions are not carried out immediately after fault detection but are delayed in accordance with given maintenance rules. On the other hand, immediate maintenance is carried out without delay after a fault has been detected to avoid unacceptable consequences. (CEN 2001)

Corrective maintenance is the simplest maintenance strategy. This is where components are used until they break down (Horner et al. 1997). Therefore corrective maintenance is performed at unpredictable intervals. Corrective maintenance includes repair, restoration or replacement of the failed components. It is sometimes referred to as breakdown, post-failure, fire fighting, reactive or unscheduled maintenance (Kumar et al. 2000).

As part of corrective maintenance, unnecessary item replacements are avoided and the whole operating life of an item is utilised. The disadvantages of the corrective maintenance strategy are (Horner et al. 1997):

- Failure of an item can occur at a time which is inconvenient to both the user and the maintaining authority.
- Maintenance activities and spare part logistics are not planned.
- The failure of an item can cause a large amount of consequential damage to other items.

3.2.2. Predetermined maintenance

By the classification of the standard EN 13306 predetermined maintenance is placed under preventive maintenance strategy. In the standard preventive maintenance is defined as a "maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item." In addition, predetermined maintenance is specified as a "preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation." The predetermined maintenance strategy is also referred to as time-based maintenance, planned maintenance, planned preventive maintenance or cyclic maintenance (Horner et al. 1997).

If the failure can lead to economic losses or has an impact on safety or to the environment, it is desirable to reduce the probability of occurrence of failure and to avoid sudden failure (Kumar et al. 2000). In predetermined maintenance the probability of failure is reduced by performing the maintenance activities at regular intervals before the failure occurs. The frequency of the maintenance tasks are typically based on statutory requirements, manufacturers' recommendations or "standard" frequencies. Maintenance of items, that are critical in terms of the health and safety of users, are controlled by statutory legislation. Such items are, for example, elevators and electrical installations. Manufacturers also give recommendations for maintenance intervals. However, these recommendations are compiled with no knowledge of the particular application of the item. Therefore, they tend to include factors of safety and the maintenance frequency can be too high. Yet, adjusting maintenance intervals to achieve more cost-effective procedures can invalidate equipment warranties or guarantees. The third method is to use standard maintenance frequencies that are published by independent organisations, such as professional associations, and developed in collaboration with the actors in the industry. (CIBSE 2008)

According to Raymond and Joan (1991) the advantages of predetermined maintenance over corrective maintenance are (Horner et al. 1997):

- Maintenance actions are planned beforehand and performed when they are convenient to the building users.
- Maintenance costs are reduced by avoiding the cost of consequential damage.
- The downtime of the equipment is decreased.
- The health and safety of the user is improved.

However predetermined maintenance also has its drawbacks:

- Maintenance is conducted irrespective of the condition of the item and therefore too early and unnecessary replacements may be carried out. (Spedding (1987) in Lee & Scott (2009))
- The condition of the item may end up worse than it was before the maintenance, as a result of human error during the execution of the maintenance task. (El-Haram (1995) in Horner et al. (1997))
- Little published evidence exists regarding the cost effectiveness of predetermined maintenance. (Wood 2003)

3.2.3. Condition based maintenance

Condition based maintenance is maintenance based on performance and/or parameter monitoring and the subsequent actions. Performance and parameter monitoring may be scheduled, on request or continuous. (CEN 2001)

Condition based maintenance activities are not based on the operating times of the component, but rather on the actual operating condition of the component. Thus, condition based maintenance ensures that there is the maximum interval time between repair work, whilst minimizing the costs of unscheduled outages (Mobley 2004). Components are inspected by manual or automatic systems in order to assess their condition and to identify their degradation rates (Williams et al. 1994). Manual assessments can be routine inspections carried out by the maintenance personnel, for example, on a daily or weekly basis. The problem with manual assessments is that they only provide a snapshot of the building's condition at a specific point in time, i.e. when the assessment was conducted (Lateef 2009).

To gain the full advantage from condition based maintenance, the condition of the item should be monitored continuously and automatically. There are various methods and techniques available for continuous monitoring, such as vibration analysis, bearing shock measurement, frequency monitoring and oil wear analysis (CIBSE 2008). Due to the costs related to condition monitoring, it is usually applied to components that are critical to the reliability or safety of the operation. The technique most often used in industrial situations is vibration monitoring (Mobley 1998). The technique has the widest application since the majority of plant equipment is mechanical and the vibration created by these pieces of equipment correlate to their condition.

3.2.4. Selection of a building maintenance strategy

An optimal maintenance strategy for a building consists of a mixture of the three previously described maintenance strategies. There is no universal solution for maintenance planning, since buildings are different in physical conditions and their usage requirements differ (Mclean 2009). To find the optimum strategy, every component of the building should be analysed separately and the most appropriate maintenance strategy for each item should be selected. As a part of the selection process, health, safety and satisfaction of the user as well as the costs of maintenance tasks should be taken into consideration. (Horner et al. 1997)

The problem with maintenance planning is that maintenance is typically budget driven and not based on actual need (Horner et al. 1997). Often maintenance personnel on an operational level argue that maintenance budgets are below the needs. On the other hand, top management on the strategic level criticise the inefficiency of the maintenance organisation (Lee & Scott 2009). The arguments concerning maintenance resources are summarized in figure 3.3.

Figure 3.3 Summary of maintenance resource arguments (Lee & Scott 2009)

3.2.5.Adoption of different strategies in the building industry

There are several studies describing the use of corrective and predetermined maintenance strategies in buildings, for example Nita et al. (2002), De Marco et al. (2010) and Moseki et al. (2011). However, little information is available on the usage of condition based maintenance and especially on continuous on-line monitoring techniques in buildings. Although, condition monitoring methods and techniques are widely adopted in many industries (Davies 1998), such as power generation, petrochemicals, manufacturing, coal mining and the steel industry, there are only a few documents found that describe the use of condition monitoring in buildings. This is true even though equipment, such as pumps, compressors and gearboxes, can be found in both industrial and building use.

One of these documents is a guide called *Condition Based Maintenance - An Evaluation Guide for Building Services* published by the Building Services Research and Information Association (BSRIA) (Seaman 2001). It presents the six basic concepts surrounding condition based maintenance methods and indicates their potential applications, typical costs and benefits as well as problems. The described methods are:

1. Vibration analysis
2. Acoustic emissions monitoring
3. Thermography
4. Wear and oil analysis
5. Power quality monitoring
6. Monitoring via building management systems

Another report on condition based maintenance in relation to buildings is the *Reliability-centered Maintenance Guide for Facilites and Collateral Equipment* by the National Aeronautics and Space Administration (NASA 2008). The report offers guidance on implementing the reliability-centered maintenance (RCM) approach in facilities. It describes different condition monitoring techniques, such as vibration monitoring as well as lubricant and wear particle analysis, both of which can be applied to buildings.

However, neither of the previous guides provide information on how usual it is to apply condition monitoring in buildings. In the NASA guide it is only stated that RCM principles are used in NASA's buildings and that condition monitoring is included in this method to improve maintenance processes.

In addition to previous reports, there are a few case studies describing the use of condition monitoring in practice. McConville and LaRocque (1999) present how portable vibration analyzers can be applied to cooling tower gearboxes and fans whereas Ausbon and LaRocque (2001) use the same technique to air handling units.

4. Building Automation

The core domain of building automation is still in the automatic control of heating, ventilation and air-conditioning systems (Kastner et al. 2005). Building automation systems (BAS) are primarily used to maintain comfortable indoor conditions whilst minimizing the energy used. The importance of building automation systems has increased during recent years as current systems are now able to integrate various building systems, such as lighting, safety, security and transportation systems, with each other and to communicate with other information systems, for instance, the Computerized Maintenance Management Systems (CMMS) and the Enterprise Resource Planning (ERP) systems.

This chapter introduces the basic concepts behind building automation systems. The chapter begins with an illustration of the structure of an automation system. This is followed by a presentation on the history of building automation including recent development trends. Terms such as horizontal and vertical integration as well as different integration technologies are discussed in this chapter.

4.1. Introduction

Several names are used for building automation systems, for example, building management system (BMS), building energy management system (BEMS), energy management control system (EMCS) and facility management system (FMS). They all refer to a similar kind of technical solution that controls equipment in buildings. The International Energy Agency (IEA) uses the following definition to define a building energy management system: "An electrical control and monitoring system that has the ability to communicate data between control nodes (monitoring points) and an operator terminal. The system can have attributes from all facets of building control and management functions such as HVAC, lighting, fire, security, maintenance management and energy management. (Månsson & McIntyre 1997)”

A building automation system is used to optimize building operation by managing and controlling various devices in the building. Some of the functions of the BAS are (Månsson & McIntyre 1997):

- Automatic switching on and off

- Optimization of plant operation and services
- Monitoring of plant status and environmental conditions
- Provision of energy management information
- Management of electrical load
- Remote monitoring and control

4.1.1. The hierarchical structure of building automation

The architecture of a building automation system is typically presented in a three level hierarchical structure as in figure 4.1. Each hierarchical level has a particular set of functions as described below.

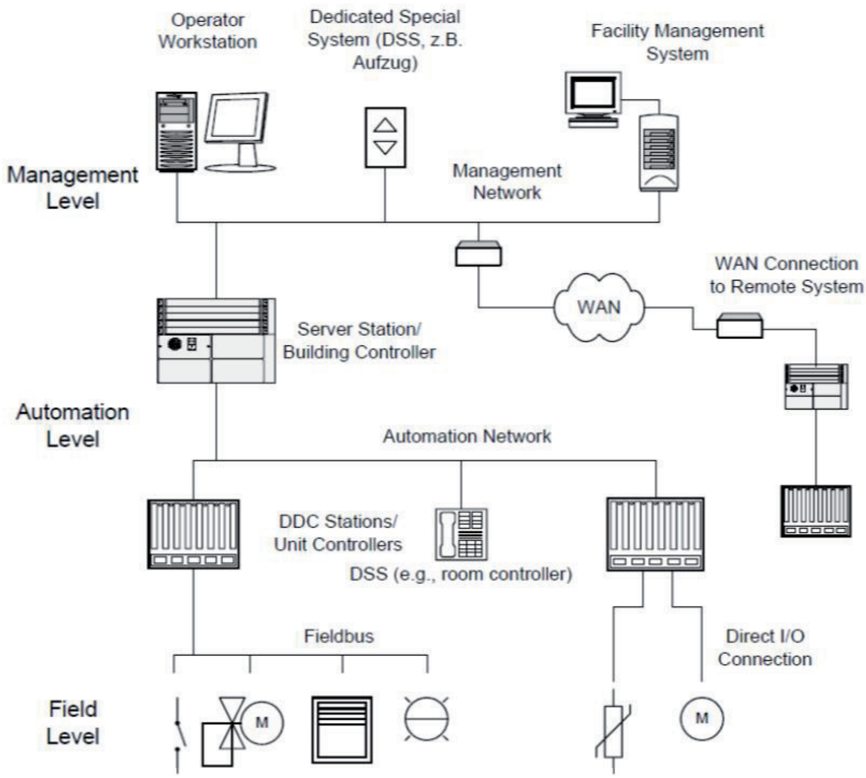


Figure 4.1 Three-layer model in BAS (Soucek & Loy 2007)

At the field level, various sensors, such as temperature and flow meters, collect status data of the physical process. The data is gathered to direct digital control (DDC) stations which process the data and control the actuators based on the processing. Actuators can be, for example, valves that regulate the flow rate in a heating circuit. Typically 4-20 mA signals (direct connections) or fieldbus protocols are used in communicating between the sensors, actuators and the DDC stations. At the automation level, DDC stations, on the other hand, communicate with each other and the management level via an automation network. The automation level operates the data provided by the field level, establishes logical connections and control loops and collects short-term historical data. The management level is responsible for the overall management of the system. This level provides the interface for the system users enabling, for example, time schedule and control loop parameter changes. In addition, data is archived for long-term historical analysis and reporting at this level of the hierarchy. (Soucek & Loy 2007)

4.2. The development of BAS

The evolution of building automation systems has followed the development of information technology and industrial automation (Levermore 2000). The early systems used pneumatic transmission and control to manage the mechanical systems in the buildings. The first computerized control systems were introduced in the 1960's consisting of a single central processing unit which collected, processed and transmitted data between the sensors and the actuators (Månsson & McIntyre 1997). In the 1970's, energy became a significant concern due to oil embargoes and this shifted the focus to energy conservation. Building automation system functionalities expanded to include energy saving features such as optimum start/stop, daylight control and demand control features (Wong & So 1997).

In the early 1980's the development of computer technology enabled the move to electronic-based control and thus direct digital controls started to replace pneumatic control systems (Roth et al. 2005). Along with the direct digital control and the introduction of low cost processors it was possible to distribute the intelligence of the system to multiple controllers. The central control station was no longer as vulnerable to malfunction now that intelligent controllers could function on a stand-alone basis. At first, the DDC systems were based on proprietary communications protocols and therefore components from different manufacturers could not be used in the same installation (Merz et al. 2009). However, the customers did not want to be locked into one particular automation vendor and this led to the development of open protocols. In this environment, several open communication protocols came to the market, such as BACnet and LonTalk (Roth et al. 2005). Over the years numerous competing communication standards have been developed as illustrated in figure 4.2. As the data transfer requirements vary on the different levels of automation, some protocols have focused on field level communication and others on system level communication.

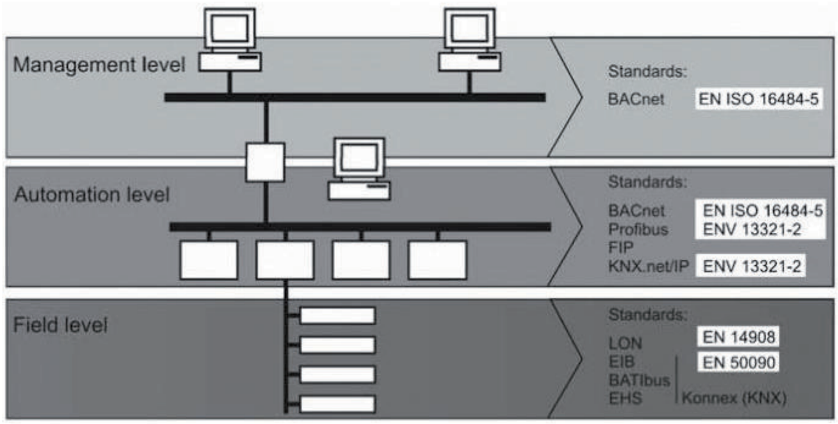


Figure 4.2 Standardized bus systems and networks in building automation (Merz et al. 2009)

In the 1990's, the internet changed the way we communicate. It provided an easy and cost effective method of monitoring building automation systems. Before the internet, telephone modems were used for remote access. However, the modem connection was relatively slow and often only one person at a time could access the automation system. With the internet also came web-based building automation systems. This meant that the automation system could be accessed through a regular internet browser. The web-based user interface had many advantages:

- No special software was needed to use the automation system (Tom 2004)
- The automation could be accessed from any device that had a web browser (Tom 2004)
- It enabled multiple simultaneous connections to the system (Finch 2001)

4.3. Current trends

This section discusses the current trends on building automation. The two introduced themes are system integration and wireless technology.

4.3.1. System integration

The development of open protocol standards and the internet created the basis for system integration. The goal of system integration is to enable different systems to work cooperatively with each other. With system integration, information is easier and faster to access. It also enables functions that would not be possible with separate systems. System integration can be divided into horizontal and vertical integration as illustrated in figure 4.3.

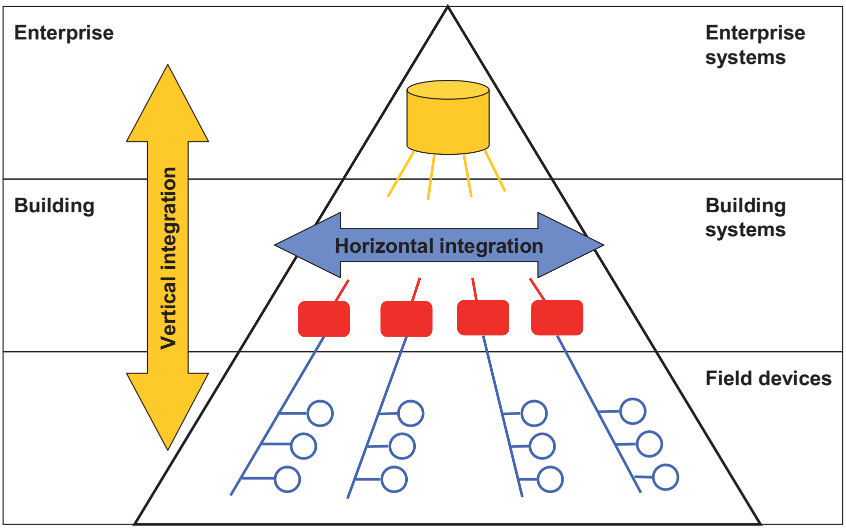


Figure 4.3 Horizontal and vertical integration (adapted from Capehart 2007)

In horizontal integration, data is exchanged on the same hierarchical level (Soucek & Loy 2007), for example, between HVAC, lighting and safety systems. The vertical integration, again, aims at data exchange between the field level and the enterprise applications, such as the ERP system. Table 4.1 presents examples of functionalities that the integrated building systems provide.

Table 4.1 Potential functionality of integrated building systems (Roth et al. 2005)

Building system	Sample functionality provided to other systems
Access control	- HVAC, lighting: Turn on/off lights and alter space conditioning setpoints when people enter/leave building; provide feedback on actual building occupancy levels
	- Security: Alert operator when people access building at a given location
	- Vertical transport: Active/deactive vertical transport when people enter/leave building
Fire / life safety	- Access control: Alter building access/egress based on emergency status
	- HVAC: Modify ventilation in case of fire
	- Lighting: Activate lights in case of fire
	- Security: Communicate information to occupants in emergency situations
	- Vertical transport: Disable or limit access in case of fire
HVAC	- Fire/ life safety: Detect and communicate abnormally high temperatures
Lighting	- Fire/ life safety: Communicate occupancy sensor status in case of fire emergency

There are several methods to integrate building systems with each other and with enterprise information systems. The methods range from hard-wired integration to open interfaces. The following paragraphs present three integration methods, namely integration platforms, Object linking and embedding for Process Control (OPC) and Web service.

4.3.1.1. *Integration platforms*

The variety of open communication standards used in the building sector has led to the development of integration platforms (Järvinen et al. 2011). They typically support several standard communication protocols as well as proprietary protocols of major equipment vendors as presented in figure 4.4. Integration platforms convert data messages from one protocol to another enabling data exchange between various systems from different vendors. Many integration platforms are also capable of performing the same control and management functions as the traditional building automation system. Therefore they can act as a controller and a protocol translator.

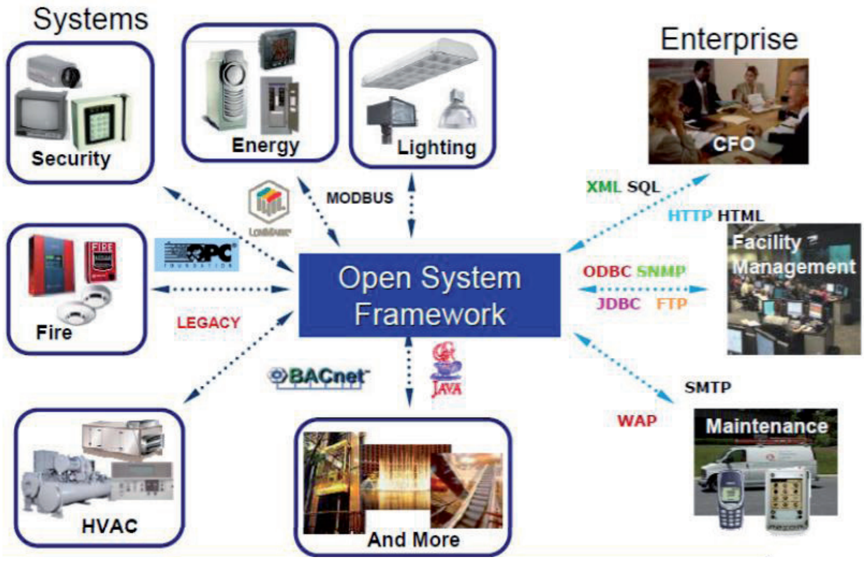


Figure 4.4 Examples of communication protocols that an integration platform supports

4.3.1.2. *OPC*

Object linking and embedding for Process Control (OPC) is an interoperability standard by the OPC Foundation. The OPC standard defines interfaces for real time data transfer to enable interoperability between various systems on the building automation management level (Wang et al. 2007). Previously, custom interfaces were used to exchange data with different systems, but the OPC eliminated this requirement by defining a common interface. A typical OPC implementation consists of OPC servers, drivers and clients as presented in figure 4.5. As part of the configuration the OPC servers or drivers provide data to OPC clients.

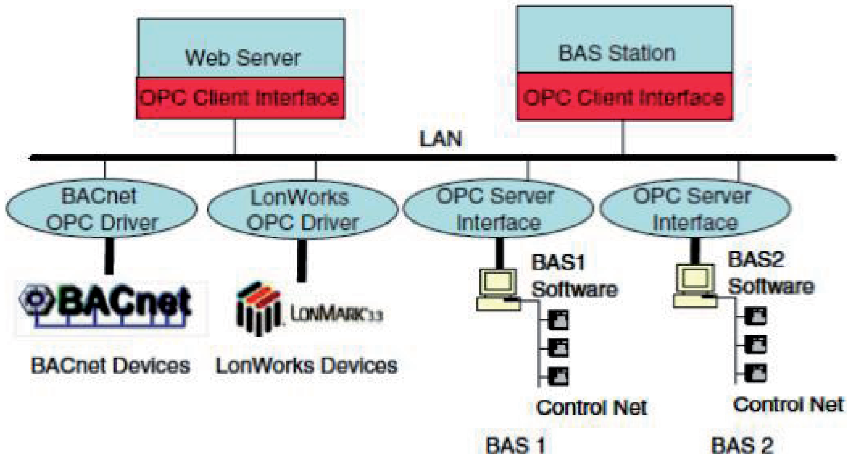


Figure 4.5 Integration using OPC (Wang et al. 2007)

4.3.1.3. *Web service*

Another method used in system integration is Web service. It has been used in business to business communication for years and is currently coming to the building automation sector. Web service is a method designed to support interoperable machine-to-machine interaction over a network (W3C 2004). It describes an interface that consists of a set of operations that can be accessed using well known internet technologies, such as Simple Object Access Protocol (SOAP) and eXtensible Markup Language (XML). With Web services different systems running on a variety of platforms can exchange data with each other.

Currently, there are two international organizations that promote the development of Web services in the building sector (Bai et al. 2009). One is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) which has developed the BACnet protocol. As a part of their development work, ASHRAE has defined a Web service interface for building automation data. Another organization is the Organization for the Advancement of Structured Information Standards (OASIS) which promotes Open Building Information eXchange (oBIX) technology. Similarly to ASHRAE the OASIS has defined a method which enables building systems and enterprise applications to communicate with each other (Bai et al. 2009).

4.3.2. Wireless technology

Wireless technology has become part of our everyday life. The technology for data transfer via radio frequency waves is used in many applications, such as radios, televisions and mobile phones. It is also an emerging technology in the building automation sector (Brambley et al. 2005b). In the building automation context, wireless communication is currently mainly used between sensors and controllers (Viglione 2010). The use of wireless technologies in automation offers several benefits. These are:

- Reduces the need for cabling (Österlind et al. 2007)
- Temporary building automation installations are easier to implement (Österlind et al. 2007)
- Allows placing sensors where cabling is not appropriate for aesthetic, conservatory or safety reasons (Reinisch et al. 2007)
- Enables better indoor conditions and energy savings through improved sensor location (Arens et al. 2005)
- Is easily reconfigured and extended (Reinisch et al. 2007)

However, there are also challenges associated with the use of wireless technology in buildings. First, wireless devices require a power supply to operate. They either have batteries or harvest energy from, for example, sunlight or temperature gradients. Communication range is another challenge. The range depends on a number of factors including the radio frequency, the space layout and the construction materials used in the building. Other electronic and wireless devices can also interfere with the wireless signals and may cause data exchange problems between the automation devices. In addition, there are challenges associated with the security of the information. Since wireless signals are broadcasted in the air, the data can be captured by anyone nearby the wireless device. However, data encryption techniques have been applied to prevent unauthorized data collection. (Brambley et al. 2005b)

5. Fault Detection, Diagnostics and Prognostics

Today, problems with building systems are usually detected as a result of occupant complaints or alarms provided by building automation systems (Katipamula et al. 1999). Finding the underlying cause for the problem or failure might not be an easy task, since building automation systems do not provide sufficient assistance with troubleshooting. The primary purpose of current building automation systems is to control building systems, not to provide assistance for building operators in detecting and diagnosing problems. Today's building automation systems have limited capabilities to manage and visualize large amounts of data and therefore it can be difficult and time-consuming to find causes for occupant complaints and equipment failures (Friedman & Piette 2001). As a result, building operators may perform inappropriate "quick fixes" leaving the root causes untouched which can lead to increased energy use and uncomfortable indoor conditions. In addition, some problems, such as simultaneous heating and cooling, can go unnoticed by occupants and building automation systems for extended periods of time until the deterioration in performance becomes so great that it triggers complaints or causes equipment failure (Schein & Bushby 2005). In the future, building processes and systems will become more complex as we reach for higher levels of energy efficiency. This makes it even more difficult for the operators to understand the operation and performance of their buildings. One solution to these issues is fault detection, diagnostics and prognostic tools, that help the operator in building management and optimization as well as detect performance problems and give instructions for corrective actions (Hyvärinen & Kärki 1996).

This chapter introduces the fault detection, diagnostics and prognostics concepts. It outlines the development of fault detection and diagnostics and describes the methods used in this field. In addition, the term prognostics is introduced briefly. The chapter ends with a discussion on the benefits and challenges of fault detection and diagnostics.

5.1. Introduction

The fault detection of a traditional process supervisory system is mostly based on limit or threshold checking of important process variables, such as temperature, pressure and speed. An alarm is raised if limit values are exceeded and it is assumed that operators will take the appropriate actions to protect the systems and therefore avoid greater damages. To set alarm limits, compromises have to be made between the detection size for abnormal deviation and false alarms caused by normal fluctuations of variables. Due to this, faults are detected rather late, for example after a large sudden failure. In addition, finding the underlying cause for the fault is difficult since alarms are based on the threshold violation of one or more variables. (Isermann 2005)

Fault detection and diagnostics (FDD) tools use more sophisticated methods to detect and diagnose performance degradation and faults. FDD tools collect data from several process components and process the data to identify defects, locate causes of the faulty operation and give instructions for corrective action (Hyvärinen & Kärki 1996). FDD tools help in analysing and organising large amounts of data and efficiently extracting useful information (Friedman & Piette 2001). With FDD tools it is possible to detect faults earlier and to find faults that could normally go unnoticed. Thus, maintenance personnel can be alerted before the actual failure occurs or before the fault affects indoor air quality or energy efficiency.

5.2. History

Research regarding fault detection and diagnostics began decades ago in the aerospace, nuclear and national defence fields (Katipamula & Brambley 2005a). In these fields FDD methods were used to improve the safety and reliability of complex and critical systems. While FDD has a long history in several other industries, the first systematic FDD research on building systems did not begin until the late 1980s (Zhivov et al. 2009). The first studies investigated automated FDD for vapor-compression-based refrigeration (Katipamula & Brambley 2005a).

Several research projects were conducted during the 1990s as the advantages of FDD gained the attention of many scholars. In 1991 the International Energy Agency (IEA) initiated Annex 25 to develop methodologies and procedures for optimizing real-time performance, automating fault detection and fault diagnosis in HVAC processes (Hyvärinen & Kärki 1996). Annex 25 introduced a building optimization and fault diagnosis framework, listed typical faults in HVAC systems and developed variety of fault detection and diagnosis methods. Annex 25 was followed by Annex 34, which aimed at developing HVAC fault detection and diagnosis tools for commercial purposes (Dexter & Pakanen 2001). During Annex 34 twenty-three prototype FDD tools were developed and thirty demonstrations in twenty buildings were conducted. The developed tools were able to detect several faults in HVAC systems.

During the 2000's the development of FDD methods and tools was continued in two building commissioning related annexes. Annex 40 (2001-2004) concentrated on developing tools for commissioning of buildings and building services (Visier 2004), where as the objective of Annex 47 (2005-2009) was to advance the state-of-the-art of building commissioning (Legris et al. 2010). In both annexes fault detection and diagnostics tools were seen as an opportunity to automate some parts of functional testing and continuous commissioning.

In addition to international annex research projects, FDD methods and tools have also been developed through national level research projects. For example, The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) funded several research projects, such as the development of FDD methods for air-handling units (Norford et al. 2002). At the same time, the U.S. Department for Energy sponsored development of a whole-building diagnostic tool, which detected anomalies in whole-building and major system energy consumption and included FDD for outdoor-air ventilation systems and economizers (Brambley et al. 1998, Katipamula et al. 1999, 2003). The California Energy Commission, in turn, funded seven research projects to develop and demonstrate fault detection methods and tools for HVAC systems (CEC). (Katipamula & Brambley 2005a)

5.3. Methods

The supervision of technical processes can be divided into four sequences as presented in figure 5.1 (Rossi et al. 1996). The first step, fault detection, includes identifying deviations from expected behaviour. Following detection, fault diagnosis determines which components are causing the fault. The first two steps compromise of fault detection and diagnostics. In practice, fault detection is much easier than diagnosing the cause of the fault (Katipamula & Brambley 2005a). The third step, fault evaluation, assesses the impact of the fault on system performance. Finally, the process ends with a decision regarding how to respond to the fault.

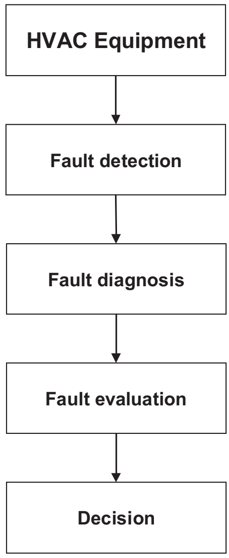


Figure 5.1 The steps of process supervision (adapted from Rossi 1996)

The steps involved in the supervision process can be performed automatically or manually. Most FDD tools use a combination of automated and manual steps. Often some degree of automation is used in collecting data, processing data and preparing presentations of data. The differences come on how much automation is used in fault identification and diagnosis. Manual tools visualise data in various ways and the interpretation of data as well as fault detection and diagnosis is left to a knowledgeable user. On the other hand, fully automated tools perform most of the reasoning without any human interventions. In this case, the user is only needed to perform the corrective actions proposed by the FDD tool. Automating parts of the fault detection and diagnosis process saves time in data monitoring and reduces the possibility of human errors. (Brambley & Pratt 2000)

5.3.1. Top-down and bottom-up approaches

Fault detection and diagnostics tools can have top-down or bottom-up approaches to reasoning (figure 5.2). In the top-down approach the starting point of reasoning is on the building level, for example observing the whole building energy consumption. When an undesired operation is detected on the building level, the cause of the problem is searched going down to system and component levels. The downside of the top-down approach is that in some situations the whole system may seem to perform fine, but faults may still exist in individual components (Visier 2004).

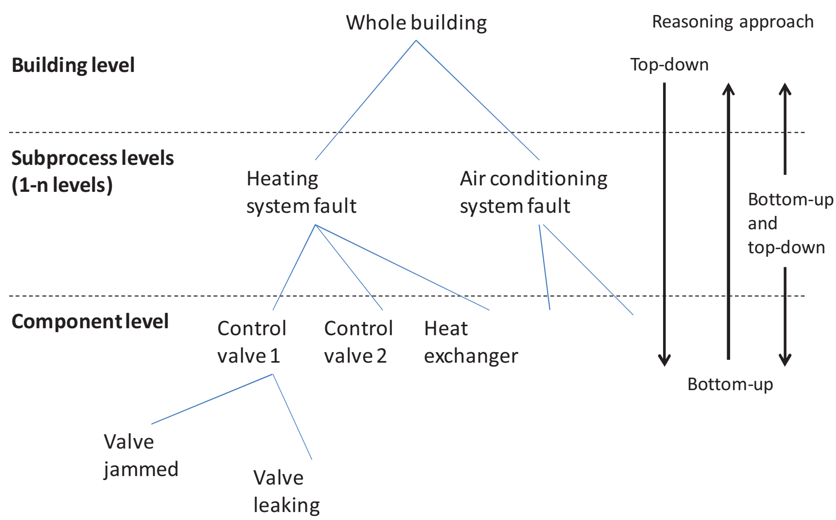


Figure 5.2 Main approaches in reasoning (Hyvärinen & Kärki 1996)

The bottom-up approach begins on the component level and the reasoning goes upstream to the system and building level. When a fault, for example too high temperature, is detected on the component level, the seriousness of the fault's effect to the whole building performance is then estimated. In the bottom-up approach individual faults might be easier to identify, but the challenge is in estimating the significance of the fault to the whole building. (Hyvärinen & Kärki 1996)

In the literature, there exist several different methods to detect and diagnose faults. In this research the FDD methods are classified into model-based, knowledge-based and process history -based methods. Each of these is described below in briefly.

5.3.2. Model-based methods

Model-based methods use mathematical models of the supervised process to detect and diagnose faults. The models can be based, for example, on the physical principles governing the behaviour of the process (Katipamula & Brambley 2005a). The predictions of the model are compared with the measurements of the process to detect anomalies. Significant differences between the predicted and the measured indicate the presence of faults. The weakness of the method is the significant amount of work required to develop the model, especially if the modelled process is nonlinear. (Visier 2004)

5.3.3. Knowledge-based methods

Knowledge-based methods use the insights and knowledge of individuals with expertise in a given field to derive a set of if-then-else rules which describe the function of the supervised process. The idea is, that the rules duplicate the same reasoning the expert would conduct when he analyses the performance of the process. A simple rule for an air handling unit could be such as: in the heating mode check if the air temperature after the heating coil is higher than before the coil.

Knowledge-based methods are relatively easy to develop, but it is difficult to find a complete set of rules describing the process. In addition, knowledge based methods are very specific to a system and are difficult to update or change. (Katipamula & Brambley 2005a)

5.3.4. Process history -based methods

In contrast to the model-based methods where a priori knowledge about the process is needed, in process history based -methods, only the availability of large amount of historical process data is needed (Venkatasubramanian et al. 2003). In the method, process history data is categorized into separate classes where each class represents a particular fault. After this, when on-line data is observed and a fault is detected, the fault can be related to one of these classes. If the fault is represented in the database, the fault can be diagnosed. Weaknesses of the method are that a large amount of history data is needed to represent both normal and faulty operation and the fact that models usually cannot be used to extrapolate beyond the range of the process history data (Katipamula & Brambley 2005a). (Chiang et al. 2001)

5.4. Prognostics

Whereas fault detection and diagnostics focused on the present state of the component, prognostics concentrates on looking forward into the future and estimating the remaining useful lifetime of the component (Holmberg et al. 2005). Prognostics use current and historical data as well as models to predict the future state of the component, as illustrated in figure 5.3. Estimating the remaining useful lifetime of the component is often the most challenging part of the prognostics and it is considered to be the Achilles heel of the prognosis process (Wang & Vachtsevanos 1999).

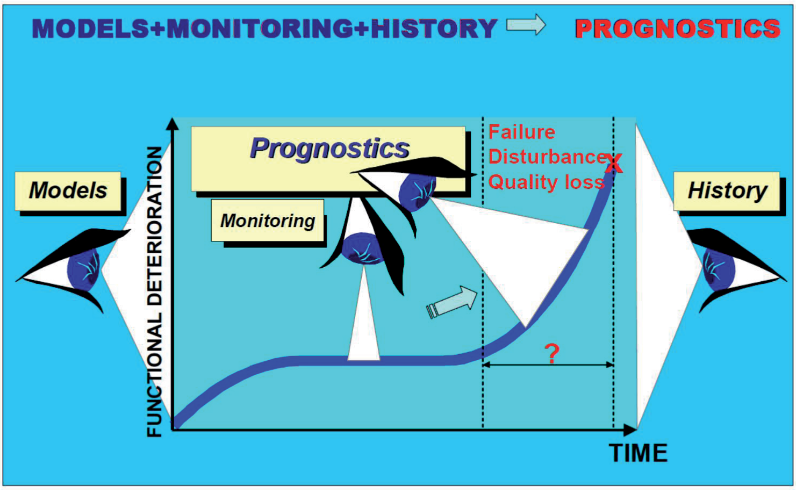


Figure 5.3 Schematic presentation of the deterioration of a machine or component with time (Holmberg et al. 2005)

Often condition monitoring is based on a single measurement technique, vibration analysis being the most often used method. However, in addition to condition monitoring systems, such as used for vibration analysis, maintenance personnel as well as process control and automation systems collect performance data, which could be utilized in prognostics. A general schematic diagram of diagnostics and prognostics based on multi-source data is presented in figure 5.4 (Holmberg et al. 2005).

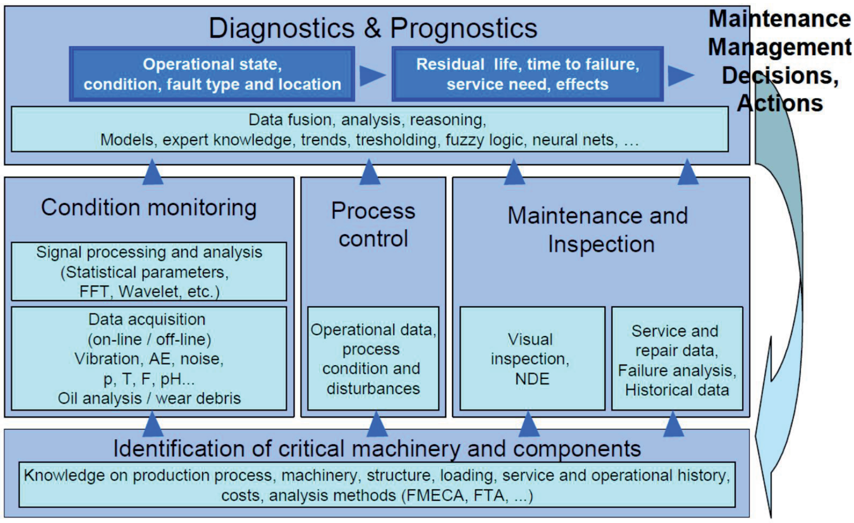


Figure 5.4 Schematic presentation of machine diagnostics and prognostics based on multi-sensor measurements and multi-source data (Holmberg et al. 2005)

Prognostics provide the means to move from scheduled maintenance to condition-based maintenance. Forecasts of the future conditions can be used to find the optimal time (not too early or late) to perform maintenance tasks instead of using industry averages and manufacturer recommendations which include factors of safety. Despite the benefits of prognostics, no research or development specifically targeted at developing and applying prognostics to building equipment is reported in the literature (Katipamula & Brambley 2005a).

5.5. Benefits

Most of the research regarding FDD has concentrated on development of the different techniques for fault detection and diagnostics (Katipamula et al. 1999). Some tools have been further developed and tested on real buildings. The tools tested have been able to detect various faults in HVAC systems (Braun & Li 2003, Katipamula et al. 2003, Schein 2006). By detecting faults earlier, FDD tools are often proposed of enabling several advantages. Hyvärinen & Kärki (1996) have listed the benefits of FDD as follows:

- Reduce energy use
- Increase quality of living
- Reduce maintenance costs
- Improve safety and health

Firstly FDD tools can reduce energy consumption in buildings by detecting inefficiently operating processes earlier. Secondly, quality of living is increased since faults can be detected before they affect indoor quality. Furthermore, maintenance costs can be reduced when faults are identified and located faster, maintenance work is planned beforehand, equipment lifetime is extended and process downtime is shortened. Finally, safety and health is improved by detecting faults before they cause personal injury or considerable damage.

Often the benefits of FDD are described in general terms, as above, and only rarely have they been quantified. This is because the benefits are difficult to measure in terms of economics (Hyvärinen & Kärki 1996). Energy savings and repair costs can be determined quite easily, but it is much more difficult to assess the benefits from a health and safety point of view. In some cases, the duration of the research project has not been sufficient enough to evaluate the benefits of the FDD tool (Haves & Hitchcock 2008).

One of the few studies, were economic assessment of the benefits has been performed, is by Katipamula et al. (2003). Their FDD tool was tested in seven buildings and the tool was able to find faults in every one of them. The identified faults were, for example, faulty sensors, mis-positioned sensors, stuck dampers, unscheduled operations and inadequate ventilation. The annual cost of single faults were estimated to range from $130 to $16 000. In another study by Braun and Li (2003), automated fault detection and diagnostics of rooftop air conditioners was tested in twenty-one systems and based on these experiments the potential savings associated with FDD were estimated. The economic assessment took, for example, preventive maintenance and utility cost savings into consideration. The calculations estimated that the annual net savings would range from $400 to $1000 per roof top unit, which means that the $300 FDD tool would pay for itself in less than one year.

However, in both of these studies the savings were based on estimations and not on realized savings. In the study of Katipamula et al. (2003) it was noted that faults identified by the FDD tool were seldom corrected by the building operator. The authors concluded that the estimated savings would not be realized if the building staff are not able use their control systems to correct the problems, or if they are too busy with other duties or there is a lack of resources to obtain help from control contractors.

5.6. Challenges

Despite the research efforts over the last two decades, fault detection and diagnostics in the field of building systems is still in its infancy (Katipamula & Brambley 2005a, Zhivov et al. 2009, Ulickey et al. 2010). Much of the research has been conducted at universities, hence only a few commercial FDD products exist today. There are several reasons for the lack of widespread availability of fault detection and diagnostics tools:

- A lack of quantified evidence regarding the benefits of fault detection and diagnostics
- Faults in HVAC systems rarely cause considerable economical losses or danger to safety or health.
- A lack of adequate sensors installed with HVAC systems
- The sensitivity and robustness of FDD methods need more investigation
- The time and cost of installing a FDD tool can be significant
- Intelligent algorithms are often neglected in practice
- The benefits of FDD are not realized since sufficient resources may not be available for the use of the FDD tools

As mentioned earlier in this chapter, there is very little quantified information available on the benefits of FDD. Possibly due to this, there is a lack of demand for FDD tools coming from building owners or the operations and maintenance community (Katipamula & Brambley 2005b). The users of the FDD tools want to be confident that the tools will save them money and therefore more demonstrations in real-buildings and well documented case-studies with savings calculations are needed (Dexter & Pakanen 2001).

Fault detection and diagnostics was first established in the aerospace and nuclear industries, where early identification of small malfunctions could save lives (Braun & Li 2003). In other industries, such as the process and automotive industry, unnecessary production line stoppages can cause significant economic losses. However, a high level of reliability and safety are not as important in building operations where processes are less critical. As a consequence of this, FDD has not generated the same level of interest among building researchers, owners and operators (Brambley et al. 2005a).

Typically only a small number of sensors are installed in HVAC systems to keep the system costs low (Seem 2001). In addition, the quality (accuracy, precision, and reliability) of the sensors installed can be inadequate (Katipamula & Brambley 2005b). This makes it difficult to develop fault detection and diagnostics methods for HVAC systems.

The detection sensitivity of the methods and occurrence rates for false alarms have not been thoroughly investigated in real buildings (Katipamula & Brambley 2005b). Setting fault thresholds is a challenging task since a balance between sensitivity in detecting faults and robustness in minimizing false alarms must be found (Norford et al. 2002). If the threshold is too low, normal variation in the data may trigger a false alarm. On the other hand, if the threshold is too high, only the most severe faults will be detected (Schein & Bushby 2005). In addition, many of the present FDD tools are able to detect single faults but fail to detect multiple simultaneous faults (Katipamula & Brambley 2005b).

The installation and tuning of a FDD tool may require expert knowledge and can be a time consuming task (Dexter & Pakanen 2001). For example, a set up time of one week was reported in Smith's (2003) study. Therefore the cost of setting up a FDD tool can be significant.

A variety of intelligent algorithms and software-based technologies, such as artificial intelligence, pattern recognition, neural networks and fuzzy logic, have been developed in recent decades in order to solve complex problems within technical systems (Hirvonen et al. 2010). Demonstrations and pilots in this field have shown good results but only few solutions have proceeded to commercial products. These techniques require considerable knowledge to be applied and maintained correctly, necessitating participation by skilled professionals which leads to high design and maintenance costs for the solution. In addition, these solutions are seldom transparent or well understood in field use, which leads to a lack of trust. (Hirvonen & Ventä 2009)

Often building operators and facility managers have several responsibilities beyond using the FDD tools. If operators and managers are too busy with other duties, such as taking care of occupant complaints, it can be difficult to find time for the use of the FDD tools. In addition to using the tool and analysing the diagnosis, resources are required to correct the faults that the tool identified. It is insufficient merely to identify problems and their impacts, building staff must correct them (Brambley et al. 2005a). The benefits of the FDD tool are not gained until the corrective actions have been taken to fix the faults. (Friedman & Piette 2001)

6. Commissioning

Within the building industry, it is widely recognized that it is quite common for buildings to not perform as intended. Several studies have reported quality problems within buildings. For example, every fourth school in the United States has reported of unsatisfactory indoor environment conditions (GAO 1995), a survey, conducted in 215 buildings, showed that in only 11 % of the buildings 80 % or more of the occupants expressed satisfaction with their thermal comfort (Huizenga et al. 2006), 1120 deficiencies in building systems were identified in 24 university buildings in California (Mills & Mathew 2009).

There are a number of reasons for these problems, such as short-sighted investment decisions (Legris et al. 2010), improper equipment selection and installation (Piette et al. 2000) and a lack of maintenance (Friedman et al. 2003a). In addition, a culture of low cost competitive bidding has streamlined quality control and documentation (Friedman et al. 2003b) and the fragmented structure of the building industry has led to inefficiencies and information gaps in the building lifecycle (Legris et al. 2010).

As we strive for low and zero-energy buildings, the significance of quality assurance becomes even greater. In energy efficient buildings, new and more complex technologies as well as advanced control strategies are used to reduce the energy demand. The increased technology and complexity may lead to errors and inefficiency if the systems are not designed, implemented, and operated properly. (Mills et al. 2004)

In response to growing quality concerns, a quality assurance process known as building commissioning has been developed during the past two decades. Building commissioning begins at the design phase and continues through the construction and operation and maintenance phases. The commissioning process ensures that the owner’s as well as user’s needs are taken into account during the whole lifecycle of the building and the building performs in reality according to the design intent. In addition to assuring the quality of new buildings, commissioning can be used to restore existing buildings to perform optimal. (Pietiläinen et al. 2007)

To gain an overview of building commissioning, different commissioning methods as well as the commissioning process are described briefly in this chapter. In addition, the benefits and barriers of commissioning are discussed in the chapter.

6.1. Definitions

ASHRAE Guideline 0-2005 *The Commissioning Process* defines building commissioning as “a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems and assemblies meet defined objectives and criteria.” Sometimes commissioning is viewed as a task performed between building completion and handover to check operational performance (Visier 2004). However, building commissioning should be seen as a broader process that begins at the pre-design phase and continues throughout the life of the building (ASHRAE 2005).

In building literature, different methods can be found to classify commissioning. In addition to distinct categorisation, there are also differences in terms used for describing these categories. In this study commissioning is divided into two main categories, new and existing building commissioning. The latter is then divided into three subcategories, retro-commissioning, re-commissioning and continuous commissioning. A short description of each of these is presented below.

6.1.1. New building commissioning

New building commissioning is a quality assurance process that begins during pre-design of a new building and continues through the construction, start-up and occupancy phases. New building commissioning assures by verification and documentation that the new building operates as the owner intended and that the building staff are provided with the sufficient information to operate and maintain the building. Terms such as initial commissioning, total building commissioning, whole building design commissioning and integrated design commissioning are also used in the context of new building commissioning. (CanmetENERGY 2010)

6.1.2. Existing building commissioning

Existing building commissioning consists of retro-commissioning, re-commissioning and continuous commissioning. According to Mills et al. (2004) existing building commissioning is more strongly driven by energy saving objectives, where as new building commissioning strives mainly for non-energy objectives such as overall building performance, thermal comfort, and indoor air quality.

Retro-commissioning is the commissioning of existing buildings that have not been commissioned before. The retro-commissioning process seeks to improve energy-efficiency and performance of the building and ensures that building equipment and systems are integrated to perform effectively and efficiently in order to meet the current occupant's needs. It also aims to resolve problems that occurred during the design, construction or operation and maintenance phases. (CanmetENERGY 2010)

Re-commissioning is implemented when a building that has already been either commissioned or retro-commissioned undergoes another commissioning process. The reason for a re-commissioning process may be operational problems, a change in building use or the will to improve and verify the performance of the building. Re-commissioning is similar to retro-commissioning, although it is less expensive since some of the data collection and documentation tasks were conducted during the previous commissioning (PECI 2006b). The primary focus of re-commissioning is to identify low cost operational improvements in order to obtain energy savings whilst maintaining comfortable conditions. (CanmetENERGY 2010)

As distinct from routine operations and maintenance, where the focus is on component-by-component care, retro- and re-commissioning take a holistic view and concentrate on the operation of the entire system or the building. The purpose of retro- and re-commissioning is to find the root causes of operational problems and hence avoid "quick fix" solutions. (PECI 2006b)

Where in the previous commissioning types activities were performed periodically, continuous commissioning is an ongoing process to resolve operational problems and to improve and optimize the performance of the building. Continuous commissioning exploits metering and trending software for continuous tracking and performance monitoring. Terms such as monitoring based commissioning and ongoing-commissioning are used when referring to these kinds of activities. The goal of continuous commissioning is to make energy savings and comfort indoor conditions sustainable and persistent. While most commissioning processes focus on bringing building operation to the original design intent, continuous commissioning focuses on optimizing system operation for the existing building conditions. When using continuous commissioning re-commissioning may still be needed, but it should be required at less-frequent intervals (PECI 2006b). (Liu et al. 2002)

Both existing building commissioning activities and energy audits aim to achieve energy savings. Therefore, they have common characteristics, but according to Poulos (2007) existing building commissioning concentrates on operation and maintenance improvements and no-cost/low-cost saving opportunities, where as energy audits focus on no-cost/low-cost energy saving opportunities and capital retrofit projects. Thus, existing building commissioning addresses improvements that are relatively fast and inexpensive to implement.

6.2. Commissioning process

New building commissioning begins at the pre-design phase of a construction project and continues through the whole lifecycle of the building. Several building commissioning guides have been written by different organisations worldwide describing the activities included in the commissioning process (Legris 2010). ASHRAE guideline 0-2005 divides the commissioning process into four main phases; pre-design, design, construction and occupancy and operation.

6.2.1. Pre-design

During the pre-design phase owner's needs and goals are developed and defined. An essential part of this phase is the Owner's Project Requirements document which includes, for example, project goals, performance criteria, budget, benchmarks and success criteria. This document will form the foundation for the design, construction, and operations of the building. To develop the owner's requirements a commissioning team with a responsible leader is formed. The commissioning team members may include design professionals, architects, construction project managers, commissioning service providers and owner's representatives, such as project managers, occupants, users, a facility manager, operation and maintenance personnel. Together they will define the Owner's Project Requirements and based on that develop an initial Commissioning Plan including a schedule of commissioning activities, responsibilities, documentation requirements, communication and reporting protocols and evaluation procedures. The Commissioning Plan is modified during the commissioning process to reflect changes in design, construction and occupancy and operations. Therefore it should be reviewed at certain milestones. (ASHRAE 2005)

6.2.2. Design

During design phase, the owner's needs and goals are translated into design and construction documents. Commissioning ensures that the design phase documents comply with the Owner's Project Requirements document. The commissioning Plan is updated and specified with the information developed during the design phase. The updated or added elements are, among other things, list of systems and assemblies to be verified and tested, commissioning schedule and documentation, reporting and communication requirements for construction and the operations phase.

The commissioning process requires quality assurance and control activities to be performed during construction. These contractor responsibilities, including equipment installation and start-up, documentation and functional testing, are included in the contract specifications. Commissioning responsibilities may be new to contractors and it is therefore important to highlight contractor requirements during the bidding process.

The design phase also includes preliminary planning of verification checklists, functional tests, systems manual, and training requirements. All of these are planned in more detail during construction. (ASHRAE 2005), (PECI 2006a)

6.2.3. Construction

During the construction phase, the commissioning process ensures that systems and equipments are installed, inspected, tested and placed into service according to the owner's requirements. Drawings and submittals and system manuals are reviewed and checked to confirm that they are in compliance with the Owner's Project Requirements document.

To observe the quality of the installation work, site visits are conducted. All perceived problems are recorded for further analyses.

Verification checklists are developed and utilized to ensure that equipment are properly installed and ready for functional testing. Whereas, verification checklists are used to ensure correct installation, functional tests are used to verify proper operation of equipment and systems. In addition to evaluating the performance of single equipment, functional tests assure that the building as a whole is operating as expected. A large amount of data on systems performance and function is gathered during the functional tests. This data can be collected by using the building automation system or portable data loggers.

After the completion of the construction work a commissioning report is prepared to summarize all commission tasks and results during the construction phase. The system manual is also completed and delivered to the owner. The system manual assists the owner with the proper operation and maintenance of the building. To conclude the construction phase commissioning, training of the building's caretakers is verified. The intent is to assure that the trainees are provided with the sufficient information to operate and maintain the building according to the owner's requirements. (ASHRAE 2005), (PECI 2006a)

6.2.4. Occupancy and operations

The last phase of the commissioning process is occupancy and operations. The objective of this phase is to maintain building performance at an optimal level. Commissioning actions include resolving outstanding commissioning issues, performing deferred and seasonal testing and conducting warranty-end review.

As some quality assurance issues may have remained unsolved after the building was turned over to its owners, finding a resolution to these issues is the responsibility of the commissioning team.

All functional tests can not be performed during the construction phase since some tests are dependent on weather conditions. For example, cooling systems might be difficult to test during winter. These deferred and seasonal tests are completed during occupancy and operations.

Before the warranty period expires, it is important to review whether all installed systems operate and perform as expected. All components that need to be repaired or replaced are to be reported to the contractors. (PECI 2006a), (GSA 2005)

6.3. Benefits and barriers of commissioning

The building commissioning process promises several benefits for building owners. Pietiläinen et al. (2007) have listed commissioning benefits and according them building commissioning:

- Ensures safety, healthy and comfortable spaces for living and business
- Improves design quality by more effective feedback
- Assures that all building services systems are compatible with each other
- Improves energy efficiency of buildings and building systems
- Decreases operation costs
- Improves introductory briefing and training of operation and maintenance personnel
- Improves documentation during the building lifecycle
- Improves meeting customer needs and expectations

A number of other studies and reports, for example (GSA 2005, PECI 2006a, PECI 2006b), have also presented a similar kind of building commissioning advantages list. Commissioning benefits and especially energy savings have usually been gained by correcting operational and control deficiencies in HVAC systems (Mills et al. 2004). The most common measures performed in existing building commissioning projects are presented in table 6.1.

Table 6.1 Most frequently implemented commissioning measures (Effinger & Friedman 2010)

Most frequently implemented
- Optimize airside economizer
- Reduce equipment runtime
- Reduce/reset duct static pressure setpoint
- Revise control sequence
- Add/optimize supply air temperature reset
- Add variable frequency drive to pump
- Reduce lighting schedule
- Replace/Repair/Calibrate sensor
- Add/optimize condenser water supply temperature reset
- Add/optimize chilled water supply temperature reset
- Add/optimize start/stop
- Add variable frequency drive to fan

In a meta-analysis of commercial building commissioning cost-effectiveness which consisted of 224 buildings, Mills et al. (2004) found that the median payback time for new building commissioning was 4,8 years and for existing building commissioning 0,7 years. The median energy saving in existing buildings was 15 percent. In the examined commissioning projects, all energy saving recommendations were not always implemented and non-energy benefits, such as reduced change orders, extended equipment lifespan and improved indoor air quality were rarely quantified. Thus, the median payback time for commissioning could be even shorter. The findings of the meta-analysis study were summarized by stating that "commissioning is one of the most cost-effective means of improving energy efficiency in commercial buildings".

6.3.1. Persistence of benefits

The persistence of energy savings and other benefits have a considerable effect on the success and cost effectiveness of building commissioning. There is a concern that the benefits of commissioning may not be sustained over a long period of time and that the benefits deteriorate. A review, consisting of five building commissioning persistence studies, concluded that the savings generally deteriorated over time (Frank et al. 2007). However, there was a wide variation in the persistence of benefits. Three to eight years after commissioning the savings persistence was from 50 percent to 100 percent in almost all buildings. The primary causes of degradation were undetected equipment and control problems. In a study by Bourassa et al. (2004) energy savings increased during the first two years after the commissioning, since it took time for the retro-commissioning measures to be implemented. In the third year, the savings began to level off and decline. In general, hardware measures such as moving a sensor or adding a valve, or changes to the control programming code tend to persist over time (Frank et al. 2007). On the other hand, control strategies that can easily be changed, such as schedules or setpoints, have problems with persistence.

According to Friedman et al. (2003b) there are three main reasons for problems with the persistence of new building commissioning. These are a limited operator support and operator turnover, poor information transfer from the commissioning process and lack of performance tracking. With the first problem, operator support, it was referred to the training on system operation and control, the time to control the operation of the building and the guidance and motivation for assessing energy use. Also operator turnover was seen as a major factor since it takes time to get acquainted with a new building. The poor information transfer from the commissioning process was faced when the original operator, who was involved in the commissioning, left the facility or when the commissioning documentation was inadequate. With poor documentation it is difficult for the operators to troubleshoot problems and understand the intended operation of the systems. Relating to the last problem, building performance tracking was not generally established during the commissioning process. Building automation data and point histories were occasionally viewed for troubleshooting but it was common that the operators were too busy responding to comfort complaints, performing routine maintenance and troubleshooting problems to track building performance. (Friedman et al. 2003b)

6.3.2. Strategies for ensuring persistence of benefits

To ensure the persistence of commissioning benefits California Commissioning Guides recommend the following actions (PECI 2006a & 2006b):

- Design review
- Building documentation
- Building staff training
- Preventive operations and maintenance
- Performance tracking
- Re-commissioning
- Continuous commissioning

In new building commissioning, issues concerning building operation and maintenance should be considered in the early stages of design. Issues such as equipment accessibility and maintainability should be taken into account when selecting and placing equipment. During the design phase, building staff should provide their view in terms of to improving the operability and maintainability of the building.

Good system documentation enhances that the knowledge obtained during commissioning can be utilized in building operation and maintenance. Documentation, such as equipment lists, O&M manuals, control system documents and systems diagrams, help building operators to maintain systems, troubleshoot problems and monitor the measures that were implemented.

Building staff training is essential to maintain the benefits of commissioning and prevent problems. A well-trained staff is capable of operating the building efficiently and maintaining comfortable conditions. In addition to the training included in the commissioning process, building staff can develop their skills through training courses offered by, for example, equipment manufacturers and training organizations.

Preventive maintenance should be redefined to include operational activities to maintain commissioning improvements. Besides the typical preventive maintenance tasks, building staff should check systems for inadequate control strategies and improper schedules since they can cause energy waste, equipment failures, reduction in the equipment's lifespan and poor indoor air quality. Therefore, system setpoints, schedules and parameter checks should be included in the preventive maintenance checklists.

Performance tracking assists building staff to detect and diagnose problems early, before they lead to tenant comfort complaints, high energy costs or unexpected equipment failure. Some of the problems in today's advanced and complex systems may be impossible to detect without performance tracking. Benchmarking, energy use tracking and performance monitoring can be used to track the building's performance. The use of benchmarking allows the building's energy use to be compared with the energy use of other similar buildings. Since the amount of energy used depends on factors such as the weather and building's size, it is common to normalize the use before comparing buildings with each other. More on energy benchmarking and normalization is presented later in this study, in the performance measurement chapter. Where benchmarking compares energy consumption against other buildings, energy use tracking measures the building's energy use over time and helps staff to understand the building's energy consumption patterns. Utility bills and Energy Information Systems (EIS) can be used to track energy use. More advanced performance tracking can be conducted with performance monitoring systems.

In addition to the previous methods mentioned, re-commissioning and continuous commissioning are recommended in ensuring the persistence of commissioning benefits. (PECI 2006a and 2006b)

6.3.3. Barriers

Despite the proven benefits presented in the earlier chapters, commissioning is not a "business as usual" activity (Friedman et. al 2010). The following barriers have been identified in the commissioning literature:

- Lack of awareness (Hagler Bailly Consulting 1998),(Visier 2004), (Friedman et. al 2010)
- Lack of time (Hagler Bailly Consulting 1998), (Visier 2004)
- Too high costs (Visier 2004), (Frank et. al 2007)
- Commissioning is seen as an added cost. Commissioning activities and costs should be included in design, construction and start-up procedures - not something extra. (Hagler Bailly Consulting 1998)
- Budgetary constraints (Hagler Bailly Consulting 1998)
- Difficulty in quantifying non-energy benefits (Hagler Bailly Consulting 1998)
- Difficulty in getting cooperation among all parties (Hagler Bailly Consulting 1998)
- Commissioning focuses on the operation of systems and their interactions, hence, there is a perception that operational improvements may not persist over time. (Friedman et. al 2010)
- Commissioning is a manual, time-consuming task (Frank et. al 2007)
- A lack of technical experts and tools for field optimization, commissioning, and data visualization (Frank et. al 2007)
- Information is lost between design and commissioning. (Frank et. al 2007)

7. Performance measurement

“You can't manage what you don't measure” and “what gets measured gets managed” are often quoted statements that demonstrate the importance of measurement. Measurement provides quantitative information that can be used in effective decision making and improving operation. The principles of performance measurement have been applied in one form or another for several decades in various fields. This chapter presents some of these applications, including business, maintenance and building performance measurement. The business performance measurement part of the chapter introduces the idea of performance measurement where as the rest of chapter concentrates on how performance measurement is applied in the field of maintenance and buildings.

7.1. Business performance measurement

Performance measurement has always been an important part of effective planning and efficient running of a business (Jasar 2004). Performance measurement systems were developed as a means of monitoring and maintaining organisational control and ensuring that organisations achieve their goals and objectives. Performance measurement is utilized for several reasons: to track progress against organisational goals, to identify strong and weak points, to decide on future initiatives and above all to drive improvements. Performance measurement is seen as an integral part of the management processes as it provides feedback based on specifics rather than generalisations and assists with decision making. (Amaratunga & Baldry 2002)

Traditionally business performance has been measured in financial terms, such as turnover, profit, and return on investment. However, these measures, developed from costing and accounting systems, have limitations and they have been criticized for encouraging short term actions rather than longer term planning (Jasar 2004). As a result of criticism, several performance measurement frameworks, that include nonfinancial measures, have been developed over the years. These measurement frameworks, such as the performance measurement matrix (Keegan et al. 1989), the balanced scorecard (Kaplan & Norton 1992), and the performance prism (Neely et al. 2002), provide a more balanced view of business performance. For example, the balanced scorecard has four measurement perspectives; financial, customer, internal business and innovation and learning perspectives as illustrated in figure 7.1.

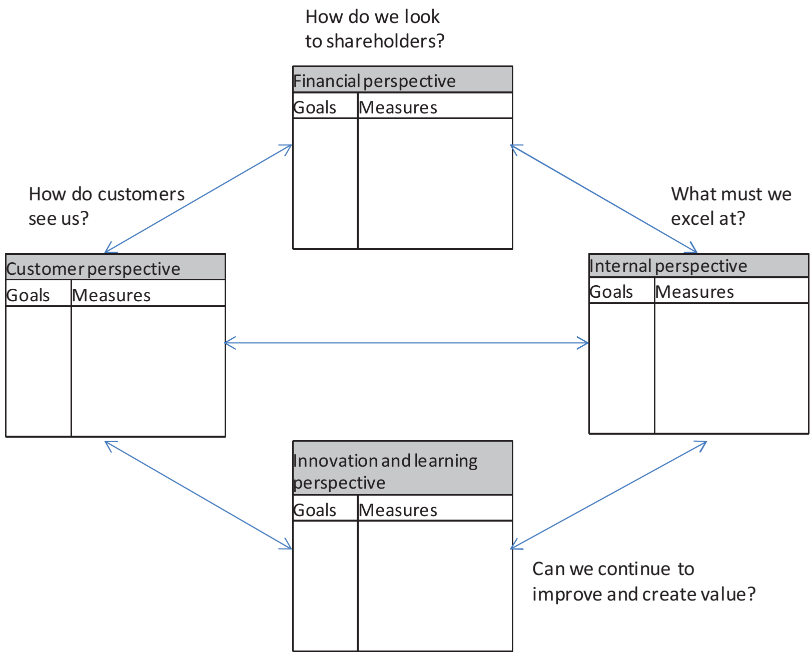


Figure 7.1 Balanced scorecard (Kaplan & Norton 1992)

With the balanced scorecard it is possible to view performance in several areas simultaneously and by this it guards against sub-optimization. Therefore, one area of performance is not improved at the expense of another. (Kaplan & Norton 1992)

7.2. Maintenance performance measurement

This section discusses the performance measurement from the perspective of maintenance. The examination of the subject is not restricted solely to building maintenance. On the contrary, the issue is discussed in general terms including practices from other fields of industry as well (e.g. industrial maintenance).

Maintenance has an important role especially in asset-intensive industries (Tsang 2002), such as the oil and gas, pulp and paper and chemical industries. In these industries, unexpected production breakdowns can have a significant economic consequence and therefore production reliability is a top priority. In addition to reliability, maintenance has an influence on the plant capacity, product quality and production efficiency as well as health, safety and the environment (Parida & Kumar 2006). Thus, tracking the performance of maintenance is a key issue for many organisations.

Parida and Kumar (2009) identify four purposes of maintenance performance measurement. It can be used as:

- A strategic planning tool
- A management reporting tool
- An operational control and monitoring tool
- A change management support tool

Performance measurement provides a tool to translate strategy into measurable and easily understandable objectives, which can be used throughout the organization. The idea is to convert strategic goals into detailed and more meaningful objectives for different levels of the organisation.

Besides being a strategic tool, performance measurement assists with effective management decision making by providing information on the status of the current maintenance operation as well as identifying performance gaps between the current and the desired performance. With performance measurement, maintenance is controlled and monitored and appropriate corrective actions can be taken when performance deviates from the plan.

7.2.1. Maintenance performance measures

An extensive amount of maintenance performance measures can be found in literature. For example, a group working on a standard for key figures in industrial maintenance in Finland easily found more than 200 measures (Komonen 2002). Examples of the key maintenance figures used in industrial maintenance are presented in figure 7.2.

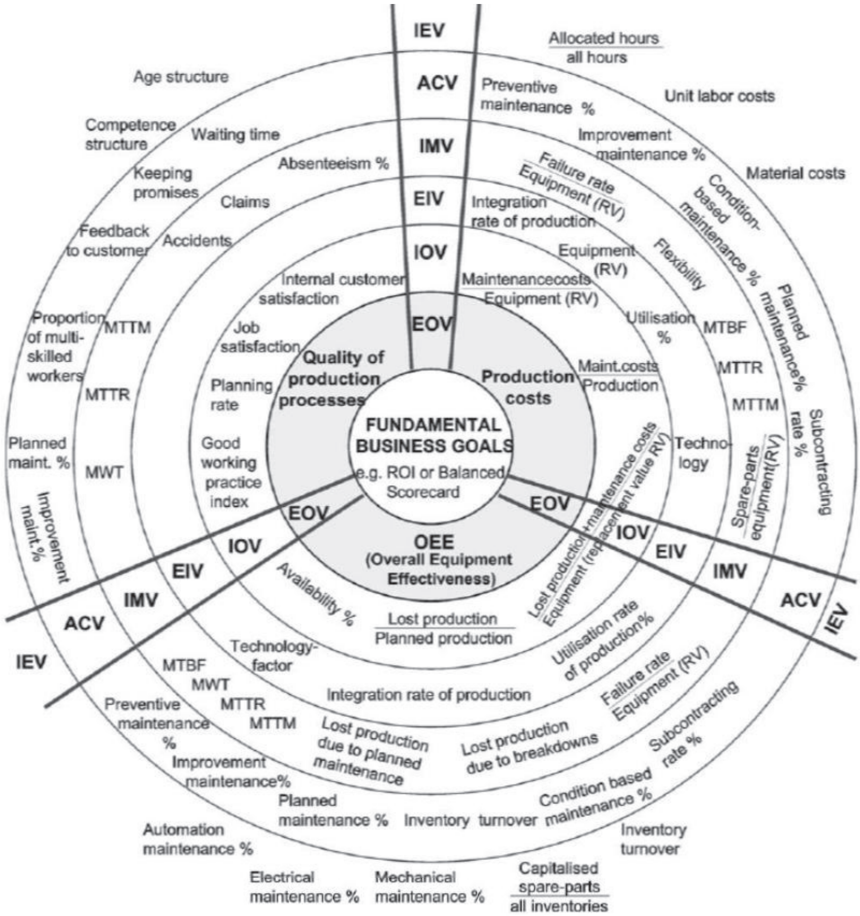


Figure 7.2 Key figures for industrial maintenance (Komonen 2002)

As can be seen from the figure, there are numerous indicators to measure industrial maintenance. These indicators are presented only to give an example of the existing measures in industrial maintenance, they are not specified or discussed further in this thesis. The only exception is the Overall equipment effectiveness (OEE) indicator which is introduced later in this chapter.

Maintenance performance measures can be classified in several ways. Campbell (1995) classifies commonly used measures into three categories on the basis of their focus (Tsang et al 1999):

- Equipment performance; e.g., availability, reliability, overall equipment effectiveness
- Cost performance; e.g., operation and maintenance labour and material costs

- Process performance; e.g., ratio of planned and unplanned work, schedule compliance.

Whereas, Arts et al. (1998) use the time horizon to classify performance measures on three levels; strategic, tactical and operational. Furthermore, a common classification is to divide performance into leading and lagging measures (Muchiri et al. 2011). Leading measures are used in measuring activities that effect future outcomes, such as the percentage of proactive maintenance work. Lagging measures, on the other hand, focus on the results that have been achieved, such as the overall equipment effectiveness which is introduced in the following chapter.

7.2.2. Overall Equipment Effectiveness

In industrial maintenance the Overall equipment effectiveness (OEE) is one of the most important indicators when measuring maintenance performance (Parida & Kumar 2009). It is a measure especially used in total productive maintenance (TPM) philosophy, which aims to maximize equipment efficiency and minimize production down time. According to Nakajima (1989), OEE is based on three performance elements, with each element containing different losses as presented in table 7.1.

Table 7.1 Elements of OEE (adapted from Wudhikarn 2010)

Performance element	Relating losses
Availability	Downtime:
	- Breakdown losses
	- Setup and adjustment losses
Performance	Speed losses:
	- Idling and minor stoppage losses
	- Reduced speed losses
Quality	Defects:
	- Quality defects and rework
	- Startup losses

The first element, availability, measures the total time that the equipment is not operating because of a breakdown, set-up or adjustment, or another reasons for a stoppage (Jonsson & Lesshammar 1999). Availability is calculated using the formula below.

$$A = \frac{loading\ time - downtime}{loading\ time} \tag{7.1}$$

In the formula, loading time is the total time the equipment is available for operational use minus planned or necessary downtime, such as breaks in the production schedule and daily shop floor meetings. Downtime, on the other hand, refers to the losses discussed earlier (breakdowns, set-up, adjustments and other stoppages). (Nakajima 1989)

The performance aspect of overall equipment effectiveness measures the ratio between the actual operating speed of the equipment (the ideal speed minus speed losses, minor stoppages and idling) and the ideal speed (based on the equipment capacity as initially designed) (Jonsson & Lesshammar 1999). Using Nakajima's (1989) formula, performance is calculated as presented below.

$$P = \frac{output \times actual\ cycle\ time}{loading\ time - downtime} \times \frac{ideal\ cycle\ time}{actual\ cycle\ time} \tag{7.2}$$

where output refers to the amount of products produced during the examined period. The ideal cycle time is the time it ideally takes to produce one product and the actual cycle time refers to the time it actually takes to produce one product.

The third element, quality, indicates the proportion of good parts produced compared to the total number of parts produced as presented in formula 7.3. The quality aspect only takes into consideration quality losses that happen in relation to the equipment, not the quality losses that appear downstream (Jonsson & Lesshammar 1999).

$$Q = \frac{number\ of\ good\ products}{input} \tag{7.3}$$

Overall equipment effectiveness is derived by multiplying the three above mentioned factors as shown in equation 7.4.

$$OEE = A \times P \times Q \tag{7.4}$$

OEE is used in industry to measure equipment performance, to indentify development opportunities and to direct improvement efforts (Garza-Reyes et al. 2010). It is not merely a maintenance performance measure, but a measure for the entire production organisation. Maintenance alone cannot address all the losses captured by OEE (Williamson 2004).

7.2.3.From single measures to measurement frameworks

Maintenance is a complex activity consisting of a large number of inputs and outputs and therefore the performance of maintenance should be measured from several perspectives. Many authors recommend the use of holistic performance measurement frameworks with several measures or indicators to evaluate the efficiency and effectiveness of maintenance (e.g., Tsang 1998, Parida & Chattopadhyay 2007, Muchiri et al. 2011)

For instance, the framework of Muchiri et al. (2011) consists of three main sections, maintenance alignment with manufacturing, maintenance effort/process and maintenance results, as presented in figure 7.3.

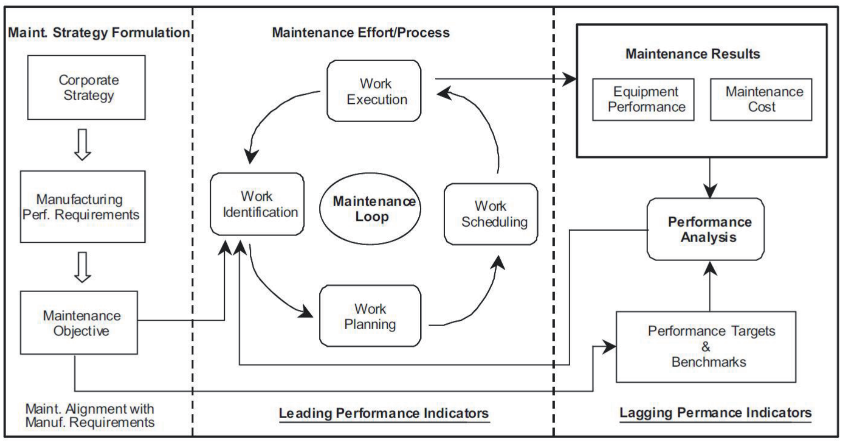


Figure 7.3 The performance measurement framework for the maintenance function (Muchiri et al. 2011)

The aim of the first section is to align maintenance objectives with corporate and manufacturing strategies. After establishing the objectives, maintenance management should set up performance targets and benchmarks to attain the desired maintenance results. Maintenance objectives should also guide maintenance processes so that the desired results can be attained. In the framework, maintenance performance is evaluated using maintenance process (leading) indicators and maintenance results (lagging) indicators. The measures used in the framework are summarized in table 7.2. (Muchiri et al. 2011)

Table 7.2 Summary of the maintenance performance measures (adapted from Muchiri et al. 2011)

	Category	Measures	Units	Description
Maintenance process (leading) indicators	Work identification	Percentage of proactive work	%	Man-hours envidaged for proactive work/Total man-hours available
		Percentage of reactive work	%	Man-hours used for reactive work / Total man-hours available
		Percentage of improvement work	%	Man-hours used for improvement & modification / Total man-hours available
		Work request reponse rate	%	Work requests remaining in 'request' status for < 5 days / Total work requests
	Work planning	Planning intensity	%	Planned work / Total work done
		Quality of planning	%	Percentage of work orders requiring rework due to planning / All WO
		Planning responsiveness	%	Percentage of WO in planning status for < 5 days / All WO
	Work scheduling	Scheduling intensity	%	Scheduled man-hours / Total available man-hours
		Quality of scheduling	%	Percentage of WO with delayed execution due to material or man-power
		Schedule realization rate	%	WO with scheduled date earlier or equal to late finish date / All WO
	Work execution	Schedule compliance	%	Percentage of work orders completed in scheduled period before late finish date
		Mean time to repair (MTTR)	Hours	Total downtime / no. of failures
		Manpower utilization rate	%	Total hours spent on tasks / available hours
		Manpower efficiency	%	Time allocated to tasks / time spent on tasks
		Work order turnover	%	No. of completed tasks / no. Of received tasks
		Backlog size	%	No. of overdue tasks / no. of received tasks
		Quality of execution (rework)	%	Percentage of maintenance work requiring rework
Maintenance results (lagging) indicators	Measures of equipment performance	No. of failures	No.	No. of failures classified by their consequences: operational, non-operational, safety etc.
		Failure / breakdown frequency	No. / unit time	No. of failures per unit time (a measure of reliability)
		MTBF	Hours	Mean Time Between Failure (a measure of reliability)
		Availability	%	MTBF / (MTBF + MTTR) = uptime / (uptime + downtime)
		OEE	%	Availabilty x Performance x Quality
	Measures of cost performance	Direct maintenance cost	$	Total corrective and preventive maintenance cost
		Breakdown severity	%	Breakdown cost / direct maintenance cost
		Maintenance intensity	$ / unit production	% of maintenance cost per unit of products produced in a period
		% maintenance cost component over manufacturing cost	%	% maintenance cost total manufacturing cost
		ERV (Equipment Replacement Value)	%	Maintenance cost / new condition calue
		Maintenance stock turnover	No.	Ratio of cost of materials used from stock within a period
		Percentage cost of personnel	%	Staff cost / total maintenance cost
		Percentage cost of subcontractors	%	Expenditure of subcontracting / total maintenance cost
		Percentage cost of supplies	%	Cost of supplies / total maintenance cost

There are also a number of industry specific performance measurement frameworks and standards which address their unique requirements.

Industries such as the nuclear, oil and gas, railway and process industries have developed maintenance performance measurement frameworks (Parida & Kumar 2009). Although, standards exist to measure maintenance performance, there are still issues that are open for interpretation even in the industry specific guidelines. For example, Airola et al. (2006) illustrated in the field of paper machines that there can be up to 20 percent differences in performance figures using the same data but different calculation standards and guidelines. Thus, clarification and harmonisation of standards and guidelines is still needed so that benchmarking can be performed between different organisations.

7.3. Building performance measurement

The term building performance has several meanings since different actors in the building sector approach it from different perspectives. Investors, for example, tend to focus on economic performance, whereas building occupants are more interested in indoor air quality issues. Numerous guidelines, codes, protocols and standards exist to evaluate specific aspects of building performance, such as energy use or thermal comfort. However, many guidelines provide only a narrow perspective of building performance serving the needs of only a few relevant interest groups. (Cole 1998)

To overcome the single performance aspect problem, several performance measurement frameworks with multiple performance perspectives have been developed. Especially frameworks, such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM), which view building performance from various environmental perspectives, have both become popular during recent years.

Building performance measurement is usually based on physical measurements, the surveyors' observations or on occupancy satisfaction surveys which measure the occupants' perception of the building performance. The measurement data for performance evaluations can be collected manually using portable instruments or automatically utilizing, for example, a building automation system. Manual measurements on a large-scale are, however, laborious and time-consuming and they provide only a snapshot of the building's performance at a specific point in time. Automatically collected measurements, on the other hand, provide the opportunity to monitor and measure the building's performance constantly.

Since the building automation system collects, processes and stores data from various devices and measurement points in the building, it would be rational to utilize it for building performance measurement.

The aim of this part of the chapter is to introduce the wide field of research on building performance measurement and to present in more detail performance measures that can be monitored with a building automation system. The beginning of the section briefly outlines the various building performance measurement perspectives. This is followed by a deeper discussion on three performance themes; energy, thermal comfort and HVAC system. The performance of a building can be assessed from these viewpoints using the data that a building automation system collects.

7.3.1. Performance indicators and frameworks

As mentioned earlier, there is an extensive amount of literature on building performance measurement. In their study Lavy et al. (2010) reviewed the performance measurement literature, identified key performance indicators and classified them into four major categories: financial, physical, functional, and survey-based. The main categories with key performance indicators are summarized in appendix A.

Financial indicators are economic measures that express costs and expenditure of the building. They can be used for both short and long-term planning and provide useful information for all levels of management. Physical indicators illustrate the physical state of the building in terms of appropriateness (how well the building supports the desired function), quality of space (spatial, environmental, and psychological issues), accessibility (site, location, and handicap accessibility), and resource consumption (energy, water, and material). Functional indicators, on the other hand, indicate the functional performance of the building by evaluating aspects related to the organizational or business mission, space, employees, and other supportive facilities. These indicators are mainly intended for senior managers as they assist with long-term goal setting. The last category, survey-based indicators, includes indicators that cannot be quantified or are gathered by using surveys. These indicators are useful especially when it is valuable to know building occupants' reactions and opinions on the subject.

Performance Measurement Protocols for Commercial Buildings guide (ASHRAE 2010), which was developed in collaboration with the American

Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Chartered Institution of Building Service Engineers (CIBSE) and the U.S. Green Building Council (USGBC), provides another example of how building performance is approached from a holistic perspective. The guideline provides "a standardized, consistent set of protocols, for a range of costs/accuracies, to facilitate the appropriate and accurate comparison of measured energy, water and indoor environmental quality (IEQ), thermal comfort, indoor air quality (IAQ), lightning, and acoustics performance of commercial buildings" (ASHRAE 2010). It gives guidance on what to measure, why to measure, how and how often to measure as well as how to compare measurements. In the guide, performance measures are divided into six categories (energy, water, thermal comfort, IAQ, lightning and acoustics) and for every category there are three levels of protocols (basic, intermediate and advanced). Basic protocols include simple and low-cost measures to gain an initial insight of the performance on an annual and whole building level. Intermediate protocols are intended to provide more detailed information on building performance, typically on a monthly frequency and on a major system level. The advanced protocols offer even deeper insights into building performance as they are based on a system or equipment level and are commonly reported on a daily or weekly basis. The basic level performance measures are summarized in table 7.3.

Table 7.3 Basic level performance measures (adapted from ASHRAE 2010)

Category	Descriptive information	Subjective measures	Instrumented measures
Energy use	1. Basic energy-related buildings/ system characteristics		1. Monthly and annual whole-building energy, demand and cost
			2. Annual whole-building energy use index (EUI) and energy cost index (ECI)
Water use	1. Basic water-related buildings/ system characteristics		1. Monthly and annual whole-building water use and cost
			2. Annual total site water use and cost indices
Thermal comfort	1. Basic thermal comfort-related buildings/ system characteristics, including complaint log	1. Occupant survey of thermal comfort and job satisfaction during one-week window or for sample of occupants	1. Spot measurements of thermal comfort -related parameters for problem diagnosis (temperature, relative humidity, mean radiant temperature, air speed)
		2. Operator survey of building characteristics	
Indoor air quality	1. Obtain EPA data to determine outdoor air quality at site	1. Occupant survey of IAQ satisfaction; informal interview during the IAQ evaluation	1. Outdoor air (OA) flow rates at each OA intake
	2. Site assessment to determine basic IAQ-related building/HVAC systems characteristics, including complaint log, to spot potential IAQ problems	2. Interview building manager to gather facility data	2. Spot measurements of temperature and humidity to characterize occupant perceptions of IAQ
Lighting/daylighting	1. Basic lighting-related space characteristics to determine potential problems	1. Occupant survey of lighting satisfaction	1. Spot measurements of illuminance in selected spaces
Acoustics	1. Open office plan, private offices and meeting rooms	1. Occupant survey of acoustic satisfaction	1. Spot measurements of A-weighted sound pressure level (dBa) in occupied spaces
	2. Room finishes		
	3. Location of mechanical equipment, plumbing and outdoor noise sources		

7.3.2. Energy performance

“Energy efficiency is the most cost-effective approach to achieving climate change objectives” has been a frequently used phrase during the last few years. Building energy performance measurement is one of the methods used to improve energy efficiency. It is probably the best defined and most investigated field of building performance measurement (McNeill et al. 2007). The energy performance of buildings can be defined in many ways, for example the European Standard EN 15603 divides energy performance assessment methods into calculated and measured methods (CEN 2008). This paragraph concentrates on measured methods where energy performance is based on the amount of energy actually used in a building.

7.3.2.1. *Energy performance measurement as part of energy management*

Building energy efficiency can be improved and energy use reduced by utilizing long and short term energy management strategies as presented in figure 7.4.

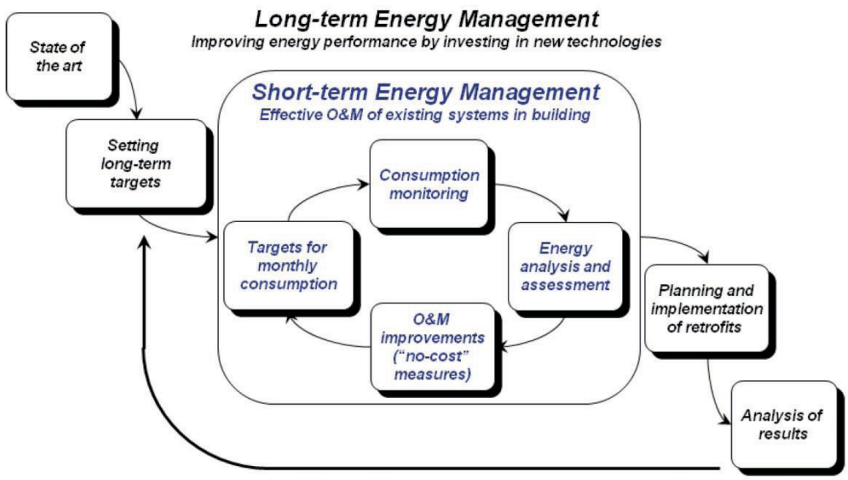


Figure 7.4 Energy management strategies (Zhivov et al. 2009)

Long-term energy management concentrates on energy saving investments whereas short-term activities focus on energy consumption monitoring and optimization of building operation. . Energy performance measurement is an essential part of short-term energy management and is a useful method when determining energy consumption levels, comparing energy usage with design intent or when making comparisons with other buildings, or assessessing opportunities for improvements or evaluating the success of energy efficiency actions.

7.3.2.2. *Energy use metrics*

Energy use metrics recommended in the *Performance Measurement Protocols for Commercial Buildings* guide (ASHRAE 2010) are showed in table 7.4.

Table 7.4 Energy use metrics (adapted from ASHRAE 2010)

Protocol level	Descriptive information	Measures
Basic	1. Basic energy-related buildings/ system characteristics	1. Monthly and annual whole-building energy, demand and cost
		2. Annual whole-building energy use index (EUI) and energy cost index (ECI)
Intermediate	1. Specific energy-related buildings/ system characteristics	1. One year of monthly and weekly energy and demand for whole building
		2. Monthly and weekly energy use and targets for major systems and end uses
Advanced	1. Detailed energy-related buildings/ system characteristics	1. One year of daily and hourly energy and demand for whole building
		2. One year of daily and hourly energy and demand for major systems and end uses

The guide categorises metrics into basic, intermediate and advanced levels depending on the depth of analysis desired. On the basic level, annual whole-building energy use, demand and costs are measured. In the guide, whole-building energy use is the energy imported to the facility plus on-site energy generated from renewable sources minus energy exported from the facility. The annual whole-building energy use index and the energy cost index shown in table 7.4 are calculated as follows:

$$Total\ Energy\ Use\ Index\ (EUI) = \frac{Total\ Annual\ Energy\ Use}{Gross\ Floor\ Area}\ kWh/m^2 \quad (7.5)$$

$$Energy\ Cost\ Index\ (ECI) = \frac{Net\ Annual\ Energy\ Cost}{Gross\ Floor\ Area}\ \$US/m^2 \quad (7.6)$$

The total energy is the energy purchased for the building plus energy generated on site minus energy sold by the facility, whereas the net energy is the sum of the purchased energy minus the sold energy. (AHSRAE 2010)

While the basic level focused on annual energy performance, the intermediate level concentrates on monthly and weekly energy data. Also energy uses of major systems are determined at this level. Sub-metering can be used to measure, for example, HVAC total electric, chiller plant electric or indoor lighting. In addition, the intermediate level includes setting up monthly targets for whole building and major building system energy uses. This can be done, for instance, using regression methods that relate energy use to one or more independent variables, such as weather data. Metrics at the advanced level support a detailed level of analysis, which includes measuring whole building energy use and demand. This can be done on daily or hourly basis as well as modelling or measuring major system end use on an annual basis. Advanced level performance analysis is quite costly since it requires extensive instrumentation and sophisticated tools. (AHSRAE 2010)

Another list of energy performance metrics is proposed in the U.S. Department of Energy's (DOE) *Performance Metrics for Commercial Buildings* guide (Fowler et al. 2010). It provides a set of key metrics that can be used for comparative performance analysis between existing buildings and industry standards. The energy related metrics introduced in the guide are shown in appendix B.

7.3.2.3. *Benchmarking and normalization*

Energy use in buildings varies based on several factors, such as the weather, building type (e.g., school, office, hospital), occupant density, building area and hours of operation. Therefore, building energy use has to be normalized in order to be able to compare buildings with each other. The *Performance Metrics for Commercial Buildings* guide used, for example, building area and the number of occupants to normalize energy performance (Fowler et al. 2010). Weather normalization using heating or cooling degree days is also an often used method. There are tools that are especially designed for benchmarking purposes and take into consideration several normalization and adjustment factors. One of these tools is the U.S. Department of Energy's and the U.S. Environmental Protection Agency's Energy Star rating system which uses, for example, building type, location, building floor area, number of occupants and operating hours as parameters to determine a building's rating (Matson & Piette 2005).

Although energy performance benchmarking provides useful information for energy management purposes, the results of benchmarking should be interpreted carefully. First of all, there can be mistakes in source information, such as building area and energy consumption values. It is not always straightforward to know what areas of the building should be included in the calculations, since building area can be defined in numerous ways. For example, should indoor parking areas or unheated storage areas be included or excluded. Even the finding of building area information on existing buildings can be a laborious task. There can be also difficulties in obtaining the “right” energy consumption figures. For instance, should the user electricity be included in the energy use or not. In addition, buildings can include functions with large energy consumptions, such as server rooms, that may serve several other buildings as well. Including electricity use of such functions can skew the calculation results. Lastly, energy efficiency is a relative term and benchmarking may lead to wrong first impressions. For example, school buildings that are available for evening use may seem to be inefficient compared to schools without evening use. Moving the evening use to a building that is built just for this purpose, is not cost effective and probably will not reduce the overall energy use.

7.3.3. Indoor environmental quality performance

In general, the purpose of energy management measures is to reduce energy use while at the same time improving or maintaining indoor conditions. However, many energy conservation measures, such as reducing operating time of air-handling units, may have a negative effect on indoor environmental quality factors. This should be avoided, since the indoor environment affects health, productivity and comfort of the building’s occupants. Changes in occupant health and productivity can have a substantial financial impact, which may exceed the financial benefits of energy conservation (Fisk 2000). (IPMVP 2002).

The indoor environmental quality consists of several factors as presented in figure 7.5. One of the IEQ factors is thermal comfort which is introduced in more detail in the following paragraphs.

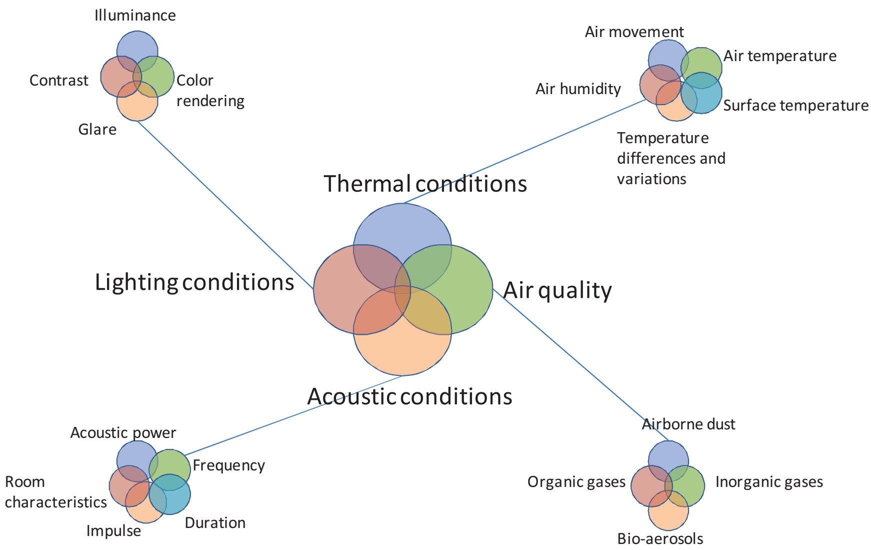


Figure 7.5 Indoor environmental quality factors according to Kauppinen et al. (2009)

7.3.3.1. *Thermal comfort*

The international standard ISO 7730 defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment" (ISO 2005). Thermal comfort requirements vary for different individuals and therefore it is difficult to specify a thermal environment that will satisfy everybody. Thermal comfort depends on six primary factors: an occupant's physical activity (metabolic rate), clothing insulation, air temperature, radiant temperature, air velocity and humidity (ASHRAE 2004).

Since thermal comfort requirements differ from person to person, models have been developed to provide information on thermal condition that a specified percentage of occupants will find comfortable. One of the models to predict occupants' thermal sensation is known as the predicted mean vote (PMV) index. Based on the heat balance of the human body, the PMV predicts the mean value of votes of a large group of people on the following 7-point thermal sensation scale as presented in table 7.5 (ISO 2005).

Table 7.5 Seven-point thermal sensation scale (ISO 2005)

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold

While the PMV predicts the mean value of the thermal votes of people exposed to the same environment, it is also useful to predict the number of people likely to feel uncomfortably warm or cool. For this purposes, a predicted percent dissatisfied (PPD) index can be calculated. The PPD index is related to the PMV as illustrated in figure 7.6. (ISO 2005)

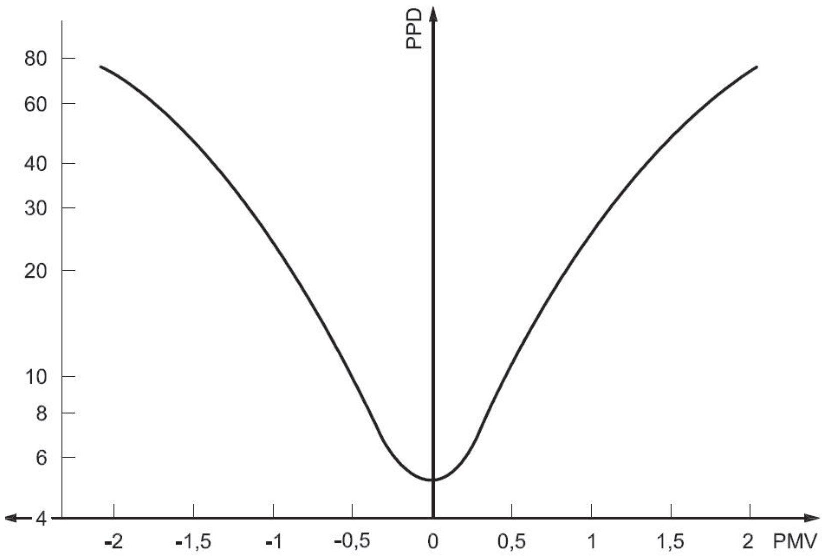


Figure 7.6 PPD as a function of PMV (ISO 2005)

PMV and PPD can be calculated for different combinations of metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity and humidity. An example of different thermal environments with PMV and PPD figures is presented in table 7.6. Many thermal comfort standards use PMV and PPD indices to define acceptable thermal environments, for example, by setting minimum and maximum temperature limits. The way in which standards and guides specify requirements for acceptable thermal environments, is one of the subjects discussed in more detail in the following paragraph.

Table 7.6 Examples of different thermal environments with PMV and PPD indices (ISO 2005)

Run no.	Air temperature °C	Mean radiant temperature °C	Air velocity m/s	RH %	Metabolic rate met	Clothing insulation clo	PMV	PPD
1	22,0	22,0	0,10	60	1,2	0,5	–0,75	17
2	27,0	27,0	0,10	60	1,2	0,5	0,77	17
3	27,0	27,0	0,30	60	1,2	0,5	0,44	9
4	23,5	25,5	0,10	60	1,2	0,5	–0,01	5
5	23,5	25,5	0,30	60	1,2	0,5	–0,55	11
6	19,0	19,0	0,10	40	1,2	1,0	–0,60	13
7	23,5	23,5	0,10	40	1,2	1,0	0,50	10
8	23,5	23,5	0,30	40	1,2	1,0	0,12	5
9	23,0	21,0	0,10	40	1,2	1,0	0,05	5
10	23,0	21,0	0,30	40	1,2	1,0	–0,16	6
11	22,0	22,0	0,10	60	1,6	0,5	0,05	5
12	27,0	27,0	0,10	60	1,6	0,5	1,17	34
13	27,0	27,0	0,30	60	1,6	0,5	0,95	24

7.3.3.2. *Thermal comfort standards and guides*

There are numerous standards, codes and guides that specify minimum requirements or acceptable ranges for thermal conditions. Many of these documents are primarily intended for building and HVAC design professionals to be used for dimensioning systems. However, a few standards and guides also give, in varying degrees of detail, requirements or recommendations for evaluating a building's thermal comfort performance during building operation. This paragraph presents thermal comfort standards and guides by introducing two standards and one national classification. The first standard is the ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy*, which is the primary standard on thermal comfort in the U.S (ASHRAE 2004). The second standard is, in turn, the European standard EN 15251, *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics* (CEN 2007b). This standard gives both requirements and recommendations as well as leaves some issues open to be specified in more detail by national regulations. The introduced national classification is the Finnish Classification of Indoor Environment 2008, which is a voluntary guide prepared by the Finnish Society of Indoor Air Quality and Climate (FiSIAQ 2008).

7.3.3.3. *Thermal comfort classes*

The European standard EN 15251 and the Finnish Classification of Indoor Environment 2008 categorize thermal environments into classes in a relatively similar manner. The EN 15251 standard classifies indoor environment into four categories as presented in table 7.7.

Table 7.7 Description of indoor environment categories (CEN 2007b)

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

On the other hand, the Finnish Classification of Indoor Environment 2008 uses three categories: S1, S2 and S3. The S1 category represents the best indoor environment quality and corresponds to very good thermal conditions, whereas S2 characterizes good indoor conditions and S3 presents satisfactory conditions and an indoor environment quality level which fulfils the building code requirements in Finland.

The EN 15251 standard and the Finnish classifications use different names for the classes, but the basic idea in both categorisations seems to be the same - the thermal environment standards being divided into high, average and moderate quality levels. However, there are differences in thermal comfort requirements for each class (e.g., class II thermal comfort target values are not exactly defined in the same manner as class S2 targets) as will be discovered later in the following section.

7.3.3.4. *Thermal comfort target values*

The ASHRAE Standard 55 describes two methods, the graphical method and the computer model method, for determining comfortable thermal environmental conditions. The graphical method is intended to be used for typical indoor environments, such as for office spaces. In the graphical method, acceptable thermal environmental conditions are illustrated using a figure (Figure 7.7). The figure presents the range of operative temperatures which equal 80% occupant acceptability. In the figure, two comfort zones are shown. One is for 0.5 clo clothing insulation (representing clothing when the outdoor environment is warm) the other for 1.0 clo of insulation (clothing when the outdoor environment is cool).

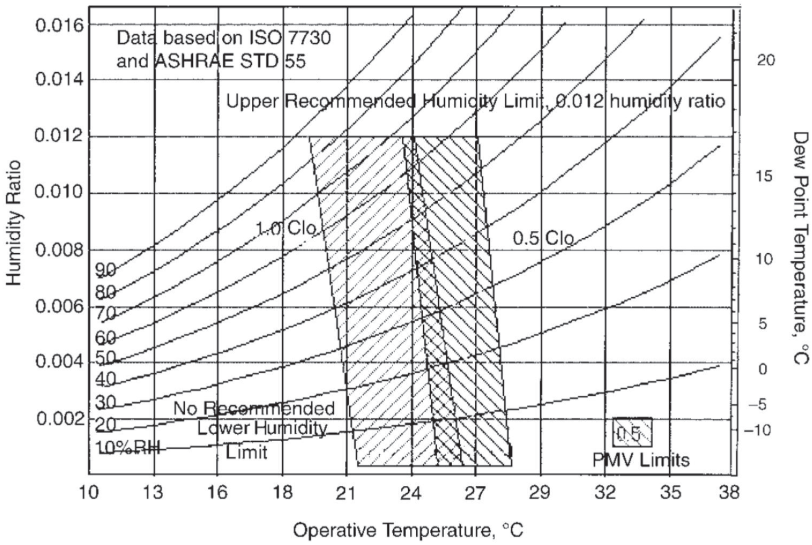


Figure 7.7 Acceptable range of operative temperature and humidity for spaces that meet the criteria (ASHRAE 2004)

The computer model method is for general indoor applications and it uses PMV and PPD indices to define acceptable thermal environments. The range of acceptable PPD and PMV values is presented in the following table (Table 7.8).

Table 7.8 Acceptable thermal environment for general comfort (ASHRAE 2004)

PPD	PMV Range
< 10	-0,5 < PMV < + 0,5

In addition to the above mentioned thermal environment requirements, the ASHRAE Standard 55 sets limits for humidity level, elevated air speed, radiant temperature asymmetry, draft, vertical air temperature difference, floor surface temperature and temperature variations with time.

The EN 15251 standard also uses PMV and PPD indices to define thermal comfort criteria. As in the ASHRAE Standard 55, the PMV and PPD indices can be used directly or, alternatively, the standard provides recommended design indoor operative temperatures for heating and cooling, which are derived from the PMV and PPD indices. Examples of the recommended operative temperatures are presented in table 7.9.

Table 7.9 Examples of recommended design values of the indoor temperature for design of buildings and HVAC systems (CEN 2007b)

Type of building/ space	Category	Operative temperature °C	
		Minimum for heating (winter season), ~ 1,0 clo	Maximum for cooling (summer season), ~ 0,5 clo
Residential buildings: living spaces (bed rooms, drawing room, kitchen etc) Sedentary ~ 1,2 met	I	21,0	25,5
	II	**20,0**	**26,0**
	III	18,0	27,0
Residential buildings: other spaces: storages, halls, etc) Standing-walking ~ 1,6 met	I	18,0	
	II	**16,0**	
	III	14,0	
Single office (cellular office) Sedentary ~ 1,2 met	I	21,0	25,5
	II	**20,0**	**26,0**
	III	19,0	27,0

The Finnish Classification of Indoor Environment 2008, in turn, uses adaptive thermal-comfort criteria to specify thermal environment classes. In the adaptive approach, indoor temperature target values change according to the outdoor temperature. Figure 7.8 presents the operative temperature target value profiles, the acceptable target value deviation ranges as well as the maximum/minimum temperature limitations of the S1 and S2 classes. The outdoor temperature is presented in the figure as 24 hour average values. In the S1 class, the operative temperature should be kept at the target value, but the deviation of +/- 0.5 °C for 95 % of the occupied hours is acceptable. In addition, the S1 class requires that the indoor temperature must be adjustable in each room/apartment within a range of +/- 1.5 °C . The S2 class, on the other hand, specifies that the acceptable deviation is +/- 1 °C for 90 % of the occupied hours. (Hamdy et al. 2011)

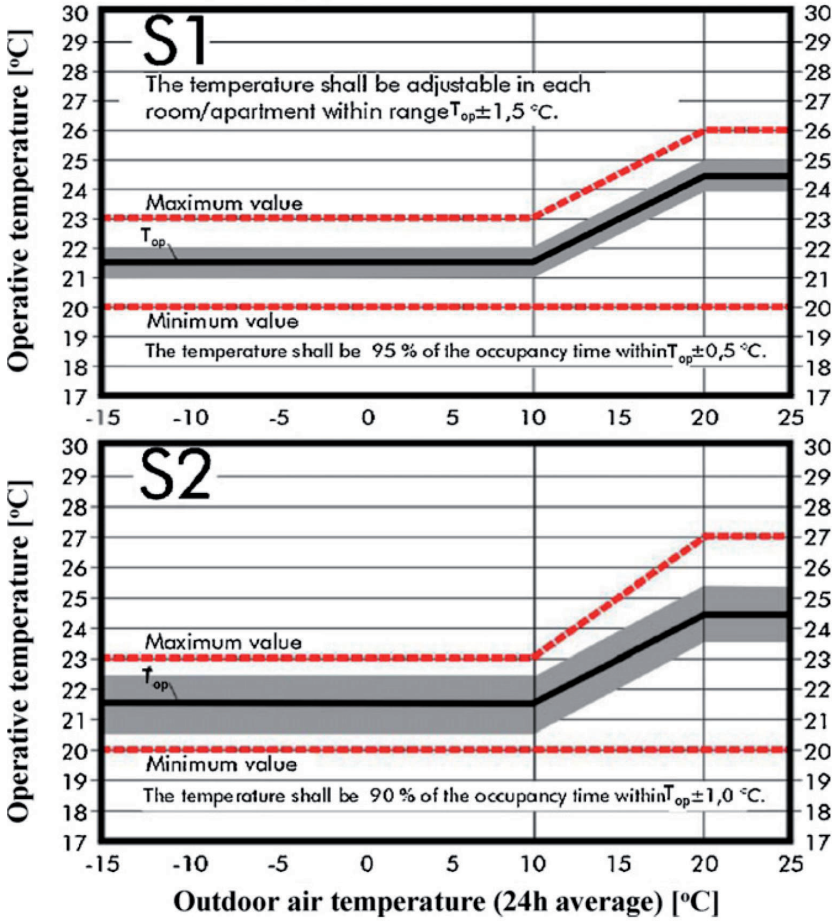


Figure 7.8 Operative temperature target value profiles of S1 and S2 classes (Hamdy et al. 2011)

7.3.3.5. *Evaluation of the thermal comfort*

For validating the thermal environment, the ASHRAE Standard 55 proposes either occupant satisfaction surveys or physical measurements. Occupant satisfaction surveys can be an effective way of assessing thermal environmental conditions, since it is the occupants who in the end experience the environment inside the building. The standard gives guidance on how to perform occupant surveys and what to include, as a minimum, in the occupant questionnaires. For physical measurements, the standard specifies requirements for measuring devices, measurement positions, measuring periods and measuring conditions. In addition, essential mechanical equipment operating conditions, which should be measured concurrently with the environmental data, are defined. These are, for example, air supply rate into the space and room/supply air temperature differential.

In the EN 15251 standard the subject of indoor environment evaluation is discussed more thoroughly than in the ASHRAE standard. The EN 15251 proposes four methods of evaluating the indoor environment on a long term basis:

- Design indicators
- Calculated indicators
- Measured indicators
- Subjective evaluations

The evaluation in each method is performed by assessing the indoor environment of typical rooms representing different zones in the building. In the design method, it is secured that the design is based on the thermal criteria values specified in the standard.

The second method, calculation method, refers to building simulations where four indicators can be used for evaluation, namely, the simple indicator, hourly criteria, degree hours criteria and overall thermal comfort criteria (weighted PMV criteria). In the simple indicator, the building meets the thermal comfort criteria if the rooms representing 95 % of building volume fulfil the criteria requirements. The hourly criteria are based on the number of actual hours or % of time when the criteria is met or not. The degree hours criteria, on the other hand, calculate the degree hours outside the upper or lower boundary of the criteria. In this calculation method, the time during which the criteria exceeds the limits is weighted on the amount of degrees the limit has been exceeded. For example, if the operative temperature limit is exceeded by one hour and during this time the temperature is two degrees higher than allowed, the result would be two degree hours. The overall thermal comfort criteria is similar to degree hours criteria, but in this criteria the time during which the actual PMV exceeds the comfort boundaries is weighted by a factor which is a function of the PPD. Examples of the PPD weighting factors are presented in table 7.10. The allowed temperature range in the example is 23-26 ° C.

Table 7.10 Examples of weighting factors based on temperature difference or PPD for mechanically heated or cooled buildings (CEN 2007b)

Temperature °C		PPD %	Weighting factors	
			wf(°C)	wf(PPD)
Cool	20	47	3	4,7
	21	31	2	3,1
	22	19	1	1,9
Neutral	23	10	0	0
	24	<10	0	0
	25	<10	0	0
	26	10	0	0
Warm	27	19	1	1,9
	28	31	2	3,1
	29	47	3	4,7

While the standard gives guidance for calculating indicators, it does not provide information on indicator target values. For example, what is the maximum acceptable value for degree hours per month or year? It is only stated in the standard that the designed systems may not be able to fulfil the design intent in all rooms during all hours.

The third long term evaluation method, measured indicators, is based on physical measurements. The standard sets requirements for measurement points and instruments as they have to fulfil the EN ISO 7726 standard. To evaluate the measurements, the standard recommends using the same indicators as in the calculated method (simple indicator, hourly criteria, degree hours criteria and overall thermal comfort criteria). In regards to measured indicators, some examples are given for acceptable deviations from the selected criteria. The deviation can be expressed, for example, as an acceptable number of hours outside the criteria based on a yearly evaluation (e.g., 100-150 hours) or the measurements in the rooms representing 95 % of the occupied space are not more than 3 % (or 5 %) of occupied hours a day, a week, a month and a year outside the limits. Thus, the standard provides some guidance for measured indicators on acceptable deviations. However, the acceptable deviation is only expressed in length of time and not in degree days or PPD weighting factors. Neither does the standard set strict requirements for deviations. It only gives examples of acceptable deviations.

The last long term evaluation method is subjective evaluations. The standard provides recommended procedures and questionnaires that can be used in determining occupants' perceptions of the thermal environment.

According to the EN 15251 standard, information on the indoor environment should be included with the energy certificate of the building.

As a result of this, the standard recommends to integrate the complex indoor environment information into a simple overall indicator of indoor environmental quality of the building. It is recommended that the overall indicator gives a comfort “foot-print” for thermal conditions and indoor air quality conditions separately. This can be illustrated as the percentage of time the indoor environment is within the different category (I, II, III, and IV) requirements. An example of such “foot-print” is presented in figure 7.9.

Quality of indoor environment in % of time in four categories				
Percentage	5	7	68	20
Thermal Environment	IV	III	II	I
Percentage	7	7	76	10
Indoor Air Quality	IV	III	II	I

Figure 7.9 Example of classification by ”foot-print” of thermal environment and indoor air quality/ventilation (CEN 2007b)

In concerning indoor environment evaluation, the Finnish Classification of Indoor Environment 2008 refers to the EN 15251 standard. The classification recommends using simulations to calculate a comfort “foot-print” as described in the EN 15251 standard. The classification also sets requirements for measurement procedures and instruments, if the evaluation is performed using physical measurements. In addition, it is stated in the classification that the specified thermal comfort criteria can be applied in construction and maintenance contracts to verify the design target values are met in practice. However, it is noted that there is much research to be done before the procedures are fair for all parties of the agreement. Several factors, such as the outdoor environment and the behaviour of the occupants, can have an effect on the quality of the indoor environment and these issues should be taken into consideration when doing thermal comfort verification procedures and agreements.

7.3.4.HVAC system performance

In addition to collecting data on a building’s energy use and thermal environment, the building automation system gathers a great amount of data on the HVAC systems performance. As the automation system controls and manages the building’s mechanical and electrical equipment, it processes and stores data from various devices. This data can be utilized to evaluate the performance of the HVAC systems.

This section briefly presents the wide range of performance criteria available for the evaluation of HVAC systems. The main interest is in performance criteria which can be measured using building automation systems. To give an example of such criteria, performance requirements for one HVAC system component, namely for an air handling unit, is presented in more detail.

7.3.4.1. *HVAC system standards*

HVAC systems have two main purposes, the first is to maintain good indoor air quality and the second is to provide an acceptable level of occupant comfort and process function (Sugarman 2005). This is achieved by providing an adequate amount of ventilation and controlling the temperature and the air quality of the building. An extensive amount of international and national standards and codes exist to regulate or specify requirements for HVAC systems, such as for system sizing, duct insulation and energy efficiency. There are solely several CEN standards specifying performance criteria for HVAC systems. For example, the European standard EN 13779, *Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems*, provides general guidance on ventilation, air-conditioning and room-conditioning system in order to achieve a comfortable and healthy indoor environment (CEN 2007a). It specifies requirements for indoor environmental quality, ventilation systems and maintenance and safety of operation, among others. Another CEN standard EN 13053, *Ventilation for buildings — Air handling units — Rating and performance for units, components and sections*, specifies requirements, recommendations and testing for ratings and performance of air handling units as well as for specific components and sections of air handling units (CEN 2006a). Whereas, the technical report CEN/TR 14788, *Ventilation for buildings - Design and dimensioning of residential ventilation systems*, assists architects, designers and builders in the design of ventilation systems (CEN 2006b).

However, it is difficult to measure many of the requirements defined in the standards by using a building automation system. The following paragraph presents one of the few standards specifying HVAC system performance criteria which can be evaluated by using building automation measurements.

7.3.4.2. *Performance criteria for air handling units*

The Finnish Standard SFS 5768 sets performance criteria for the control of air conditioning systems (SFS 1993). The requirements specified in the standard are mainly designed to be applied for air conditioning systems of commercial, office and public buildings. The standard sets requirements for air handling units, zone systems and room units. Examples of performance criteria for air handling units are described in tables 7.11 and 7.12. In the specification, the average temperature/pressure means the average temperature/pressure in a cross-section of a duct.

Table 7.11 Control requirements for supply air temperature after the air handling unit (adapted from SFS 1993)

Start up	1. Maximum settling time is 15 minutes with an accuracy of +/- 1 °C of the desired value
Steady state	2. Maximum acceptable average temperature deviation from the set-point is +/- 1 °C
	3. The temperature must be for 90 % of the time within +/- 0,5 °C limits, which are situated symmetrically on the both sides of the average temperature.
	4. Continuous oscillation is not allowed
Setpoint reset	5. Maximum settling time is 10 minutes with an accuracy of +/- 1 °C of the desired value
	6. After the settling time, the maximum acceptable average temperature deviation from the new set-point is +/- 1 °C
	7. The temperature must be for 90 % of the time within +/- 0,5 °C limits, which are situated symmetrically on the both sides of the average temperature.

Table 7.12 Control requirements for duct static pressure (adapted from SFS 1993)

Start-up	1. Maximum settling time is 15 minutes with an accuracy of +/- 10 % of the desired value
Steady state	2. Maximum acceptable average pressure deviation from the set-point is +/- 10 %
	3. The pressure must be for 90 % of the time within +/- 5 % limits, which are situated symmetrically on the both sides of the average pressure.
Setpoint reset	4. Maximum settling time is 10 minutes with an accuracy of +/- 10 % of the desired value
	5. After the settling time, the maximum acceptable average pressure deviation from the new set-point is +/- 10 %
	6. The pressure must be for 90 % of the time within +/- 5 % limits, which are situated symmetrically on the both sides of the average pressure.

8. Building performance visualization and FDD tools

Advanced information systems in building operation and maintenance have concentrated on assessing building and system performance rather than on condition monitoring or prognostics of single equipment. The aim of these tools has been in optimizing building operation, reducing energy costs and improving indoor environmental quality whereas the prevention of breakdowns, the estimation of the remaining useful life of components and the determination of maximum interval between repair has not been of interest. The wide variety of different tools used for assessing building performance will be referred in this chapter as building performance visualization and fault detection and diagnostics tools.

This chapter focuses on building performance visualization and FDD tools. First, the chapter presents different perspectives from which these tools have been approached in the literature. Also recommended features for good tools are presented. In addition, examples of a few commercial tools are provided at the end of the chapter.

8.1. Categorization of the tools

The subject of building performance optimization has been approached from different perspectives over the years. As a result of this, there are various names for the tools used to optimize building performance. Scholars have also described and categorised the tools in different manners.

One of the terms used in this context is fault detection and diagnostics (FDD). Much of the research and development work in this field was conducted during the 90's in two International Energy Agency (IEA) initiated annexes, Annex 25 and Annex 34. The different methods that the fault detection and diagnostics tools use were introduced in chapter four of this study. The FDD tools are often divided into manual and automated tools. Manual tools only assist in fault detection and diagnosis and the identification of the abnormal behaviour and the localization of the fault are left to the user of the tool. Automated tools, on the other hand, use software to automate the different steps of fault detection and diagnostics. However, the distinction between manual and automated FDD tools is not always straightforward, since tools have various levels of automation in their data collection, processing and diagnostics procedures (Friedman & Piette 2001).

Another approach to the subject is building commissioning, which was discussed in more detail in chapter five. Many commissioning tools were developed in Annexes 40 and 47 during the years 2001-2009. Tools exploiting metering and trending software for continuous tracking and performance monitoring were called continuous, monitoring based or ongoing commissioning tools. Many of the tools developed in Annexes 40 and 47 were the same that were introduced during the Annexes 25 and 34 (Visier 2004).

Performance monitoring is also a term used to describe tools similar to the ones presented above. Brambley et al (2005) define performance monitoring as “a process of continuous measurement to support building energy analysis and control”. They also state that performance monitoring tools are intended for manual or visual analysis, in contrast to automated fault detection and diagnostic tools which provide notification when a fault occurs. Thus, there is an analogy with this definition and the definition of manual FDD tools.

In addition, these tools are sometimes referred to as Energy Information Systems (EIS). EIS are software, data acquisition hardware and communication systems that collect, analyze and display building information to aid in reducing energy use and costs in buildings (Motegi et al. 2002). EIS typically process energy consumption data and therefore concentrate on analysing the energy performance of the building. Some EIS offer building level anomaly detection but automated FDD functionalities are not common on the lower levels of energy metering (Granderson et al. 2009).

Furthermore, information dashboard is one of the terms related to building performance visualization. Few (2006) describes information dashboards as single-screen displays presenting the most important information people need to do a job illustrated in a way that allows the users to monitor what’s going on in an instant. Usually information dashboards are applied in the building sector to display energy use figures.

Finally, Lehrer (2009a) uses the term building visualization products to mean tools that have been developed primarily to visually display trend data and to enable historical and normative comparison. Many of these tools visualize building energy and water use in various formats providing tailored interfaces for building owners, operators, and occupants. For example, users can choose whether the energy use is displayed in kilowatt hours, costs or carbon dioxide equivalents. There are noticeable similarities between the products Lehrer (2009a) refers to and energy information systems and information dashboards. All of them are primarily used to assess building energy performance.

As described above, several different terms are used to refer to very similar kinds of tools. There is some overlap between the tools that the terms refer to, yet there are also differences. Common to all of these tools is that they collect, process and visualize data using data acquisition and information techniques beyond the standard building automation. Variations can be found in the degree to the tools assist users in fault detection and diagnostics. Some tools have automated parts of the FDD process whereas others rely on the knowledgeable tool users. Differences can be found also in the data sources the tools use. Some tools concentrate on energy use data where as others utilize data from a variety of data sources including building automation systems, utility meters or separate sensors dedicated to this purpose.

8.2. Recommended features

The literature provides some recommendations for the characteristics of a good performance visualization or FDD tool. One of the studies that investigated this issue was Annex 34 Computer Aided Evaluation of HVAC System Performance. In this study, Visier and Heinemeier (2001) propose that a good tool from the users' point of view ought to have the following qualities:

- Adaptable to the needs of the users, for example different user interfaces for managers and technicians
- Help users, not replace them
- Be easily customizable
- Easy to understand
- Be demonstrated in real buildings to make people more confident
- Do the job it promises to do, for example reduce comfort complaints, energy costs or maintenance costs.

Visier and Heinemeier (2001) also define characteristics of a good user interface. FDD tools should generate alarms when faults are detected, allow easy access to alarm threshold adjustments and provide a synthesis report that is presented first but also offer more detailed information for in depth analysis. In addition, the industrial partners of the Annex emphasized that a good FDD method should fulfil the following features (Gruber 2001):

- Easy to understand and to explain
- Easy to commission
- Easy to use
- Easy to integrate
- Easy to change
- No or very few false alarms
- No disturbance for normal operation
- Robustness
- Cost effective
- Impacts on savings of energy and comfort

In a more recent study, Lehrer and Vasudev (2010) examined the information practices, needs and preferences of building information visualization tool users. The study summarized the key user preferences as follows:

- Displays with a high-level overview information as well as drill-down capabilities
- Ability to filter and generate reports in tabular or graphical form
- Support for normalization and energy benchmarking
- Compatibility with existing building automation systems
- Support for occupant interaction

8.3. Examples of tools

To provide an overview of the capabilities that the current building performance visualization and fault detection and diagnostics tools offer, four tools are described in more detail in the following paragraphs. The product descriptions are based on research reports, seminar presentations as well as material available on companies' web pages. It should be taken into consideration that especially the material provided by the companies can give a biased appearance of the products since these materials are often written to market products and therefore emphasize their positive aspects (Granderson et al. 2009).

8.3.1.BuildingEQ

The BEQ tool was developed in connection with the European Commission sponsored project Building EQ - tools and methods for linking Energy Performance of Buildings Directive (EPBD) and continuous commissioning during 2007-2009. The project aimed at strengthening the implementation of the EPBD by linking the certification process with commissioning and optimisation of building performance. (Building EQ 2011)

The BEQ tool includes the following features (Mazzarella et al. 2009):

- Data handling
- Data visualization
- Model based analysis

In order to evaluate building performance, the BEQ tool requires what is called a minimum data set. The necessary data needed is shown in table 8.1. This data can be acquired by a building automation system or a separate data logger. (Mazzarella et al. 2009)

Table 8.1 Minimal data set of measured data (Neumann & Jacob 2010)

item	Measured value	unit	min. time resolution	remarks
consumption	total consumption of fuels	kWh	h	e.g. gas, oil, biomass
	total consumption of district heat	kWh	h	
	total consumption of district cold	kWh	h	
	total consumption of electricity	kWh	h	
	total consumption of water	m^3	h	
weather	outdoor air temperature	°C	h	own weather station or from weather data provider
	outdoor rel. humidity	%	h	see above
	global irradiation	W/m^2	h	see above
indoor conditions	indoor temperature	°C	h	choose one or more reference zones for that measurement
	indoor relative humidity	°C	h	see above
system	Flow / return Temperatures of main water circuits	°C	h	main heat/cold distribution. "Main" in this context refers to the distribution in the building and not to a primary distribution such as a district heating system.
	supply and exhaust air temperature of main AHUs	°C	h	
	supply and exhaust air relative humidity of main AHUs	%	h	
	Control signals of drives (pumps, fans)	0/1 or 0-100%		

The tool uses time series, scatter and carpet plots to visualize the measured data, as presented in figures 8.1, 8.2 and 8.3. These visualizations support the tool user to undertake manual fault detection and diagnosis.

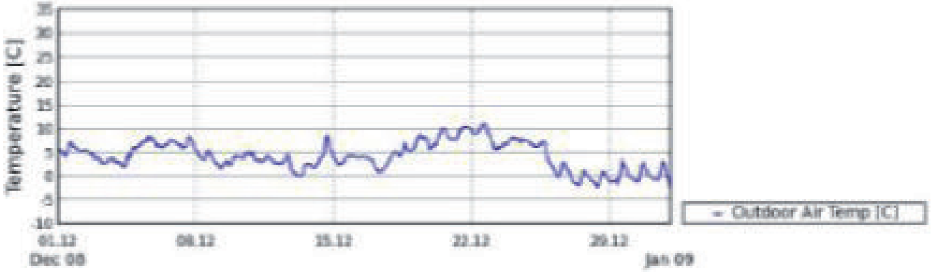


Figure 8.1 Time series plot (Mazzarella et al. 2009)

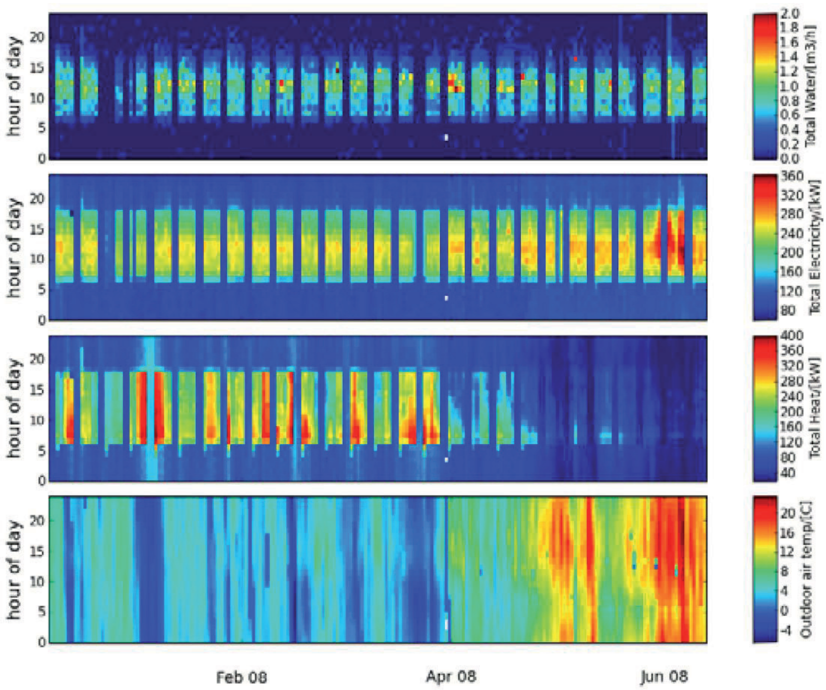


Figure 8.2 Carpet plot (Mazzarella et al. 2009)

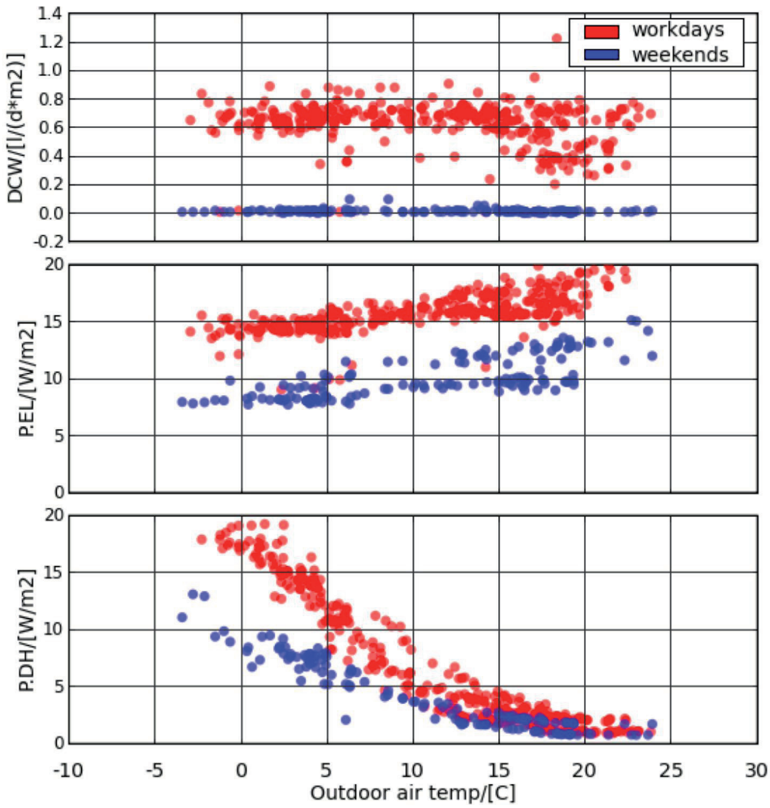


Figure 8.3 Scatter plot (Mazzarella et al. 2009)

In addition to visualization, the tool utilizes a simplified model of the building to identify faults. The model is based on CEN-standards and includes three components; building zone, air handling unit and system component. A simplified structure of the model is presented in figure 8.4.

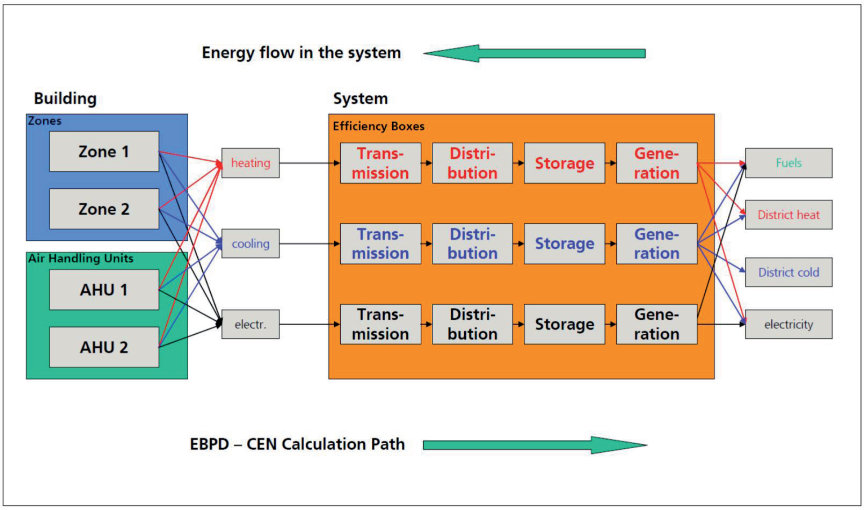


Figure 8.4 Simplified scheme of the overall system model (Neumann & Jacob 2010)

The model is used to compare measured data to the model prediction to discover faults and optimization potentials, as illustrated in figure 8.5.

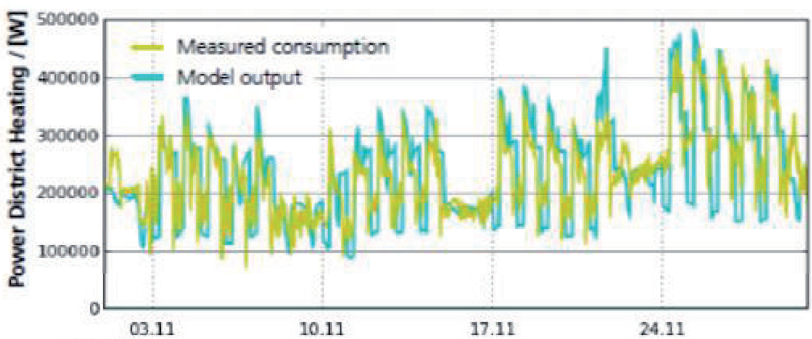


Figure 8.5 Measured heat consumption vs. model output (Neumann & Jacob 2010)

8.3.2. Enforma Building Diagnostics

Enforma Building Diagnostics software is a product of the Architectural Energy Corporation which is an engineering and consulting company operating in the U.S. The Enforma software was one of the first diagnostic tools available on the market (commercialized in 1996) and, at first, it was intended for short-term performance analysis using data loggers and data imported from a variety of sources, including building automation systems (Friedman & Piette 2001). Later on, the Enforma was developed to an internet- based application to be used for continuous performance monitoring and to work in conjunction with Tridium Niagara, which is a software framework capable of communicating with diverse devices regardless of manufacturer or communication protocol. As part of the continuous monitoring, the measurement data used for diagnostics is first collected and stored in Tridium Niagara controllers and then downloaded into a server were the Enforma software resides (Eardley 2006).

8.3.2.1. *Fault detection and diagnostics rules*

The Enforma software uses a rule-based fault detection approach to identify abnormal operation of an air handling unit. Fault detection is performed comparing measurement data to a set of logical rules that describe the function of a properly operating air handling unit (AHU). There are altogether 59 performance assessment rules and they are divided into seven AHU operating modes as follows:

1. Heating, minimum outside air
2. Cooling with outside air
3. 100% outside air and mechanical cooling
4. Minimum outside air and mechanical cooling
5. 100% outside air, no mechanical cooling
6. Minimum outside air, no mechanical cooling
7. Unknown

Three examples of fault detection rules used in the heating mode are shown in table 8.2.

Table 8.2 Fault detection rules in the heating mode (adapted from Bushby et al. 2001)

Rule	Rule Expression (true implies existence of a fault)
1	$Tsa < Tma + \Delta Tsf - \varepsilon t$
2	For $\lvert Tra - Toa \rvert \geq \Delta Tmin$: $\lvert Qoa/Qsa - (Qoa/Qsa)min \rvert > \varepsilon f$
3	$\lvert uhc - 1 \rvert \leq \varepsilon hc$ and $Tsa,s - Tsa \geq \varepsilon t$

where
Tsa = supply air temperature
Tma = mixed air temperature
Tra = return air temperature
Toa = outdoor air temperature
Tsa,s = supply air temperature set point
ΔTsf = temperature rise across the supply fan

$\Delta Tmin$ = threshold on the minimum temperature difference between the return and outdoor air

Qoa/Qsa = outdoor air fraction = $(Tma - Tra)/(Toa - Tra)$

$(Qoa/Qsa)min$ = threshold on the minimum outdoor air fraction

uhc = normalized heating coil valve control signal [0,1] with $uhc = 0$ indicating the valve is closed and $uhc = 1$ indicating it is 100 % open

εt = threshold parameter accounting for errors in temperature measurements

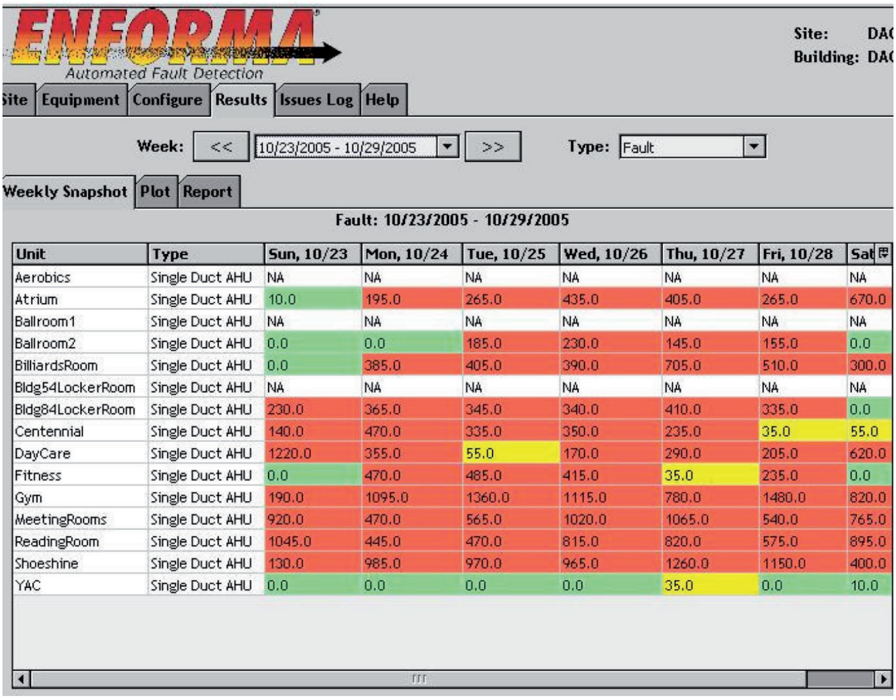
εf = threshold parameter accounting for errors related to airflows (function of uncertainties in temperature measurements)

εhc = threshold parameter for the heating coil valve control signal

Rule one verifies that the air temperature rises across the heating coil. Rule two checks that the mixed air damper is in the minimum outside air position by comparing several AHU temperature measurements with each other. The rule three notifies if the supply air temperature setpoint cannot be achieved. (Eardley 2006)

8.3.2.2. *Data visualization*

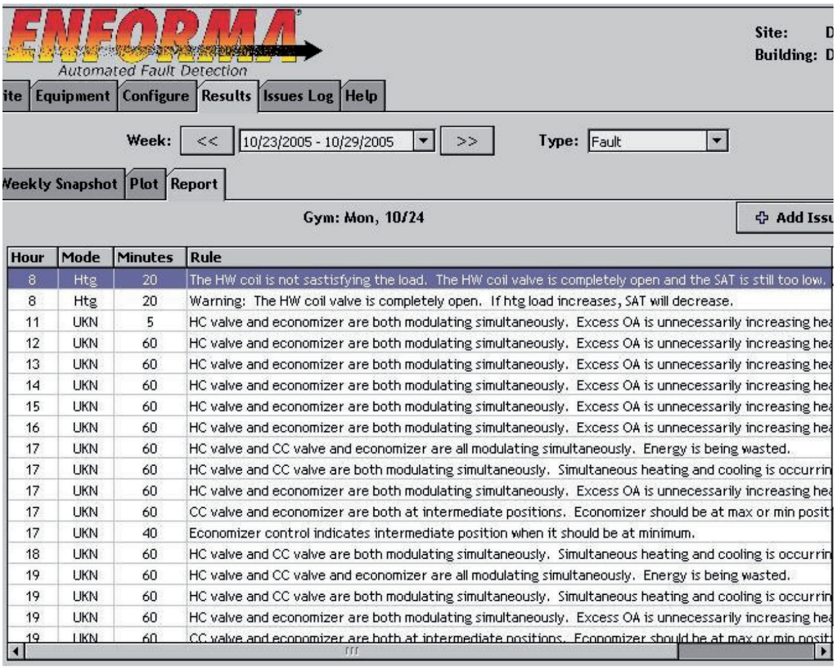
The Enforma software provides three displays to analyse the performance of air handling units. The overall performance is assessed from a weekly snapshot view, as shown in figure 8.6. The green colour in the snapshot indicates that there are no faults, whereas the yellow shows that there are few faults and the red indicates that there are many faults. The numbers in the cells express the time in minutes that the AHU in question has operated in fault conditions. In addition, the marking NA indicates that there are insufficient amount of control points for fault detection analysis.



Unit	Type	Sun, 10/23	Mon, 10/24	Tue, 10/25	Wed, 10/26	Thu, 10/27	Fri, 10/28	Sat
Aerobics	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Atrium	Single Duct AHU	10.0	195.0	265.0	435.0	405.0	265.0	670.0
Ballroom1	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Ballroom2	Single Duct AHU	0.0	0.0	185.0	230.0	145.0	155.0	0.0
BilliardsRoom	Single Duct AHU	0.0	385.0	405.0	390.0	705.0	510.0	300.0
Bldg54LockerRoom	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Bldg84LockerRoom	Single Duct AHU	230.0	365.0	345.0	340.0	410.0	335.0	0.0
Centennial	Single Duct AHU	140.0	470.0	335.0	350.0	235.0	35.0	55.0
DayCare	Single Duct AHU	1220.0	355.0	55.0	170.0	290.0	205.0	620.0
Fitness	Single Duct AHU	0.0	470.0	485.0	415.0	35.0	235.0	0.0
Gym	Single Duct AHU	190.0	1095.0	1360.0	1115.0	780.0	1480.0	820.0
MeetingRooms	Single Duct AHU	920.0	470.0	565.0	1020.0	1065.0	540.0	765.0
ReadingRoom	Single Duct AHU	1045.0	445.0	470.0	815.0	820.0	575.0	895.0
Shoeshine	Single Duct AHU	130.0	985.0	970.0	965.0	1260.0	1150.0	400.0
YAC	Single Duct AHU	0.0	0.0	0.0	0.0	35.0	0.0	10.0

Figure 8.6 FDD tool results showing detected faults (Eardley 2006)

To receive more detailed information regarding the faults, the Enforma software provides daily fault detection reports (figure 8.7) and time-series plots (figure 8.8). The daily report presents information on the hour the fault was present (hour column), the operation mode of the AHU (mode column) and the duration of the fault (minutes column) as well as it shows the rule that has identified the fault (rule column).



Hour	Mode	Minutes	Rule
8	Htg	20	The HW coil is not sastisfying the load. The HW coil valve is completely open and the SAT is still too low.
8	Htg	20	Warning: The HW coil valve is completely open. If htg load increases, SAT will decrease.
11	UKN	5	HC valve and economizer are both modulating simultaneously. Excess OA is unnecessarily increasing hea
12	UKN	60	HC valve and economizer are both modulating simultaneously. Excess OA is unnecessarily increasing hea
13	UKN	60	HC valve and economizer are both modulating simultaneously. Excess OA is unnecessarily increasing hea
14	UKN	60	HC valve and economizer are both modulating simultaneously. Excess OA is unnecessarily increasing hea
15	UKN	60	HC valve and economizer are both modulating simultaneously. Excess OA is unnecessarily increasing hea
16	UKN	60	HC valve and economizer are both modulating simultaneously. Excess OA is unnecessarily increasing hea
17	UKN	60	HC valve and CC valve and economizer are all modulating simultaneously. Energy is being wasted.
17	UKN	60	HC valve and CC valve are both modulating simultaneously. Simultaneous heating and cooling is occurrin
17	UKN	60	HC valve and economizer are both modulating simultaneously. Excess OA is unnecessarily increasing hea
17	UKN	60	CC valve and economizer are both at intermediate positions. Economizer should be at max or min posit
17	UKN	40	Economizer control indicates intermediate position when it should be at minimum.
18	UKN	60	HC valve and CC valve are both modulating simultaneously. Simultaneous heating and cooling is occurrin
19	UKN	60	HC valve and CC valve and economizer are all modulating simultaneously. Energy is being wasted.
19	UKN	60	HC valve and CC valve are both modulating simultaneously. Simultaneous heating and cooling is occurrin
19	UKN	60	HC valve and economizer are both modulating simultaneously. Excess OA is unnecessarily increasing hea
19	UKN	60	CC valve and economizer are both at intermediate positions. Economizer should be at max or min posit

Figure 8.7 Summary of detected faults (Eardley 2006)

Time-series plots, such as shown in figure 8.8, assist in confirming the faults and help finding causes for the faults. The users can plot one or more measurement points for any period of time that has been monitored by the Enforma. (Eardley 2006)

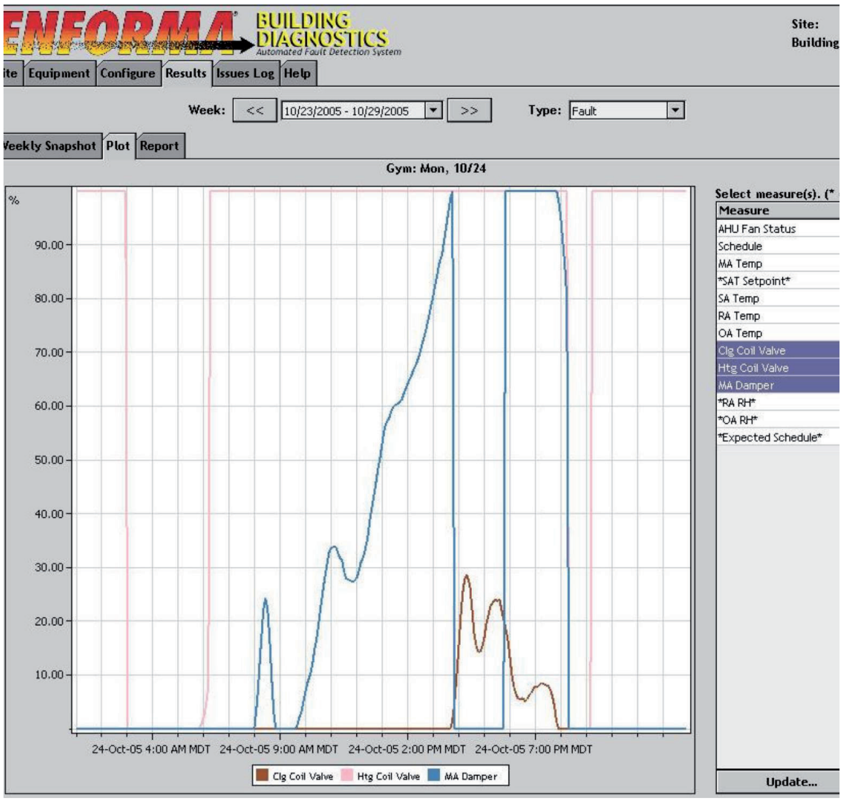


Figure 8.8 Graphical representation of detected fault (Eardley 2006)

8.3.3. Taloinfo

A Finnish building services consulting company known as Granlund has developed a building performance reporting tool called Taloinfo. The tool collects real-time data from various sources, such as building automation, access control, energy metering and maintenance management systems, and visualizes the data to assist in tracking building conditions and energy uses. The structure of the tool is illustrated in figure 8.9. (Mazzarella et al. 2009)

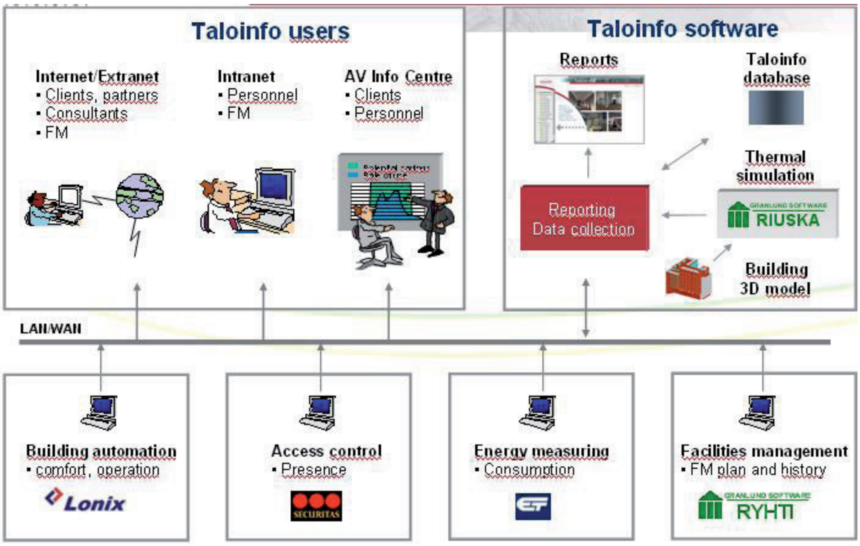


Figure 8.9 The structure of the Taloinfo tool (Hänninen 2004)

Taloinfo offers several different user interfaces for analysing information. There are simple and easy to understand displays for non-technical users and more detailed reports for expert users. Examples of the interfaces are shown in figures 8.10 and 8.11. (Mazzarella et al. 2009)

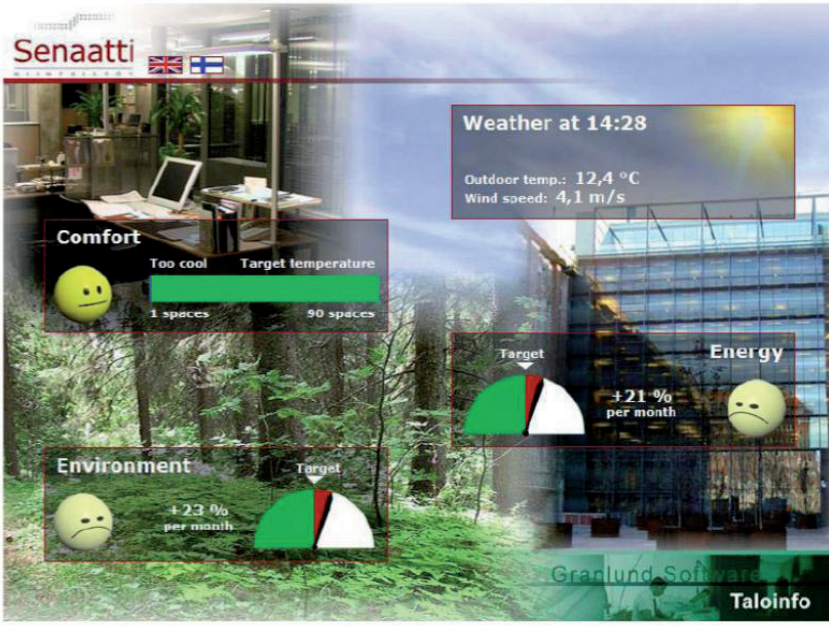


Figure 8.10 Interface for non-technical users (Mazzarella et al. 2009)

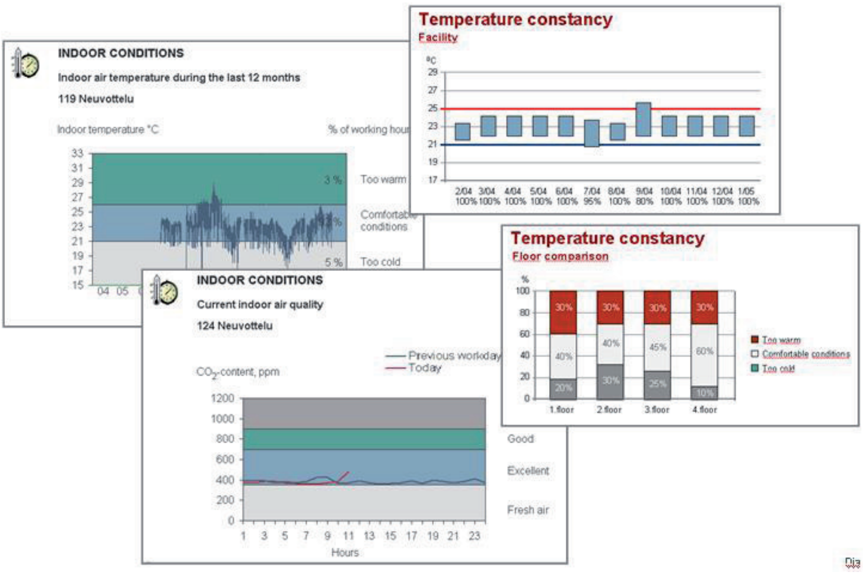


Figure 8.11 Indoor condition related reports for expert users (Mazzarella et al. 2009)

The tool also utilizes building information models to provide three-dimensional graphical interfaces. 3D displays are used, for example, to visualize room temperatures and indoor air quality figures as shown in figure 8.12.

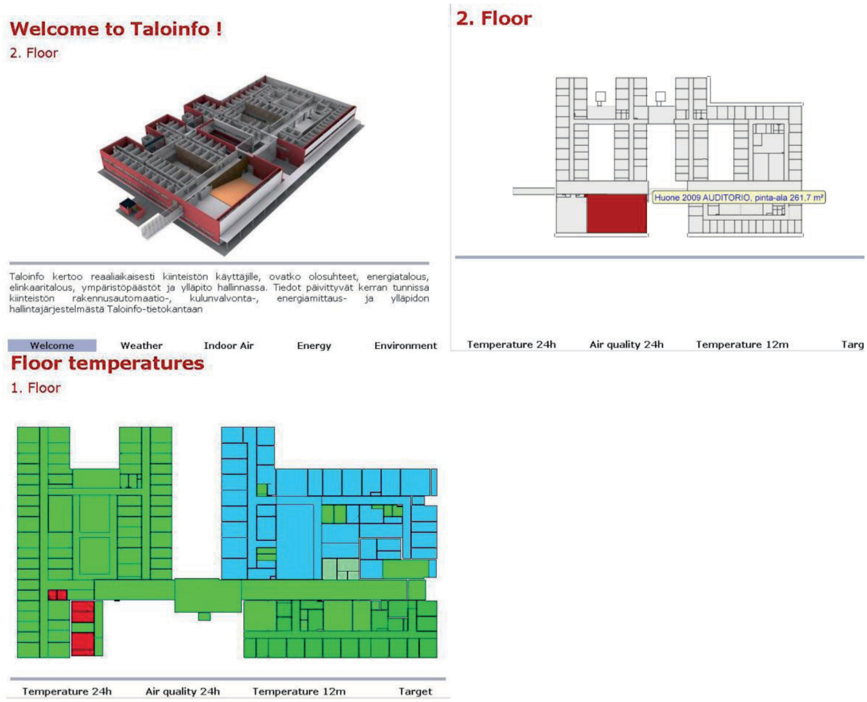


Figure 8.12 Visualization of 3D building maps and performance maps (Mazzarella et al. 2009)

8.3.4. Building Dashboard

Lucid Design Group's Building Dashboard is an interactive website and a kiosk display that provides real-time information feedback to teach, inspire behavioural change and save energy and water resources in buildings. Building Dashboard is primarily intended to be used by building occupants, visitors and the public to view energy and water use information on touchscreen displays. (Lucid Design 2011)

The Building Dashboard can be integrated with building automation systems, energy management systems, data loggers and utility meters to gather metering data (figure 8.13). The collected data is processed and stored in a database to record a building's energy and water use. The Building Dashboard transforms this data into information that is approachable for non-technical audiences. (Building Dashboard 2006)

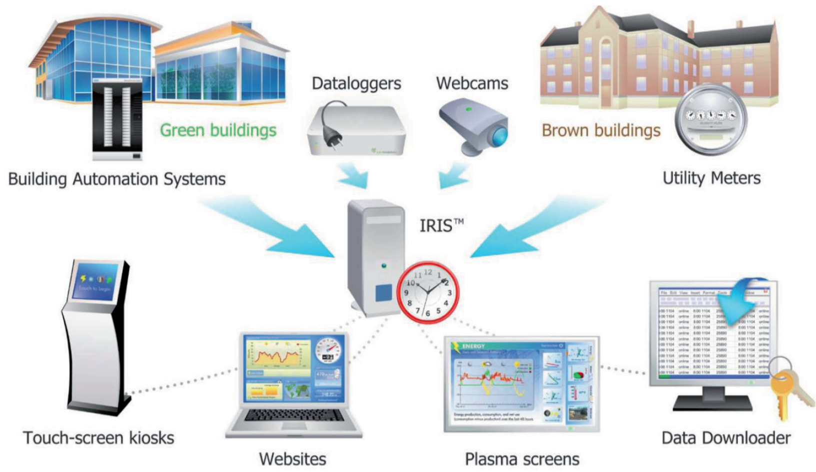


Figure 8.13 The structure of the Building dashboard (Building Dashboard 2006)

The Building Dashboard offers a variety of different types of displays to visualize building performance. For example, users can view real-time and historical consumption data, compare consumption tp other buildings and look at consumption per person or per square foot. Users can also choose in what unit the usage should be expressed in, such as in dollars spent or pounds of carbon dioxide emitted. Examples of the Building Dashboard displays are presented in the below figures (figures 8.14 and 8.15). (Lucid Design 2011)

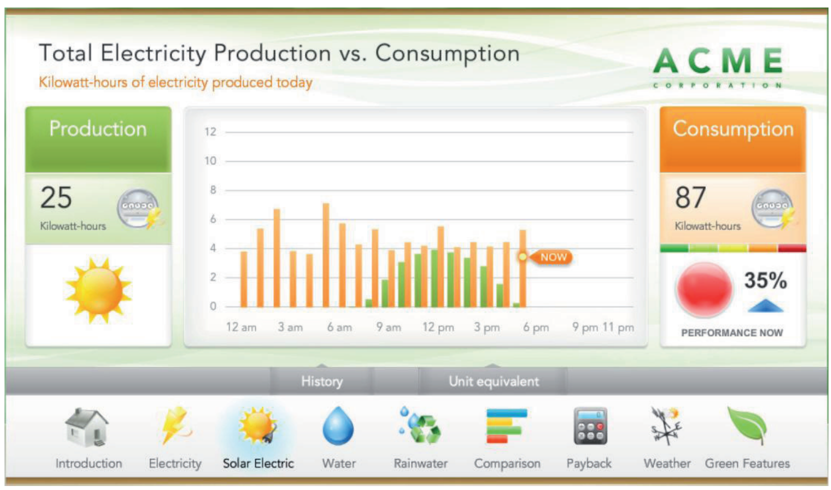


Figure 8.14 Comparison of solar generation and total electrical consumption (Lehrer 2009b)

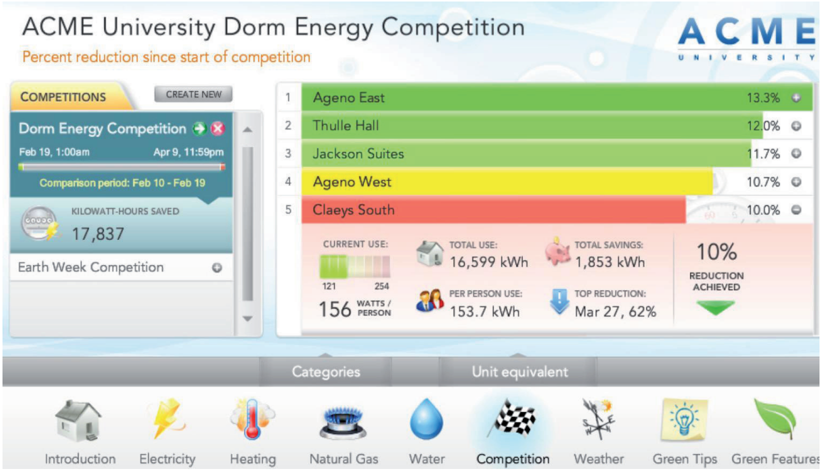


Figure 8.15 Comparing energy consumptions (Lehrer 2009b)

9. Information and automation system adoption and use

In today's global competition, information systems have become critical to the success of many organizations. By investing in information systems organisations aim at improving their performance, cutting down costs and achieving competitive advantage. Information systems are used, for example, to improve communication between people, to automate various manual tasks and to process large amounts of data into information that can be utilized in decision making. As an enabler and a driver of change, information systems have reduced the need for human labour, increased productivity and shortened distances (Nance 1996).

However, the benefits associated with information systems are not always achieved and only a few information technology projects are completed with all requirements fulfilled. According to the Standish Group Chaos statistics, which is commonly cited by information system authors (e.g., Schultzea & Boland 2000, Briggs et al. 2003, Legris et al. 2003), only 30 percent of information technology projects are completed on time, on budget, with required features and functions (The Standish Group 2009). Fortune & Peters (2005) describe several information systems that failed in one way or another. For example, some systems never worked and others were never made operational since they were not accepted by users.

The importance of information systems to organisations and the high number of failed information technology projects have attracted the attention of both practitioners and scholars. This has led to a significant amount of studies and numerous theories and models concerning information systems. In addition to technological viewpoints, the subject has been approached from many other perspectives including project management, success factors, technology acceptance, usability and user satisfaction. Over the years, research in the field has accumulated to the extent that it has been characterized as fragmented (Larsen 2003) and somewhat chaotic (Marple 2000).

To gain an overview of the research field, basic theories concerning information system success, acceptance and user satisfaction are presented in this chapter. However, before introducing these theories, an outline of information systems and their relationship with organisations is illustrated.

In addition, the end of the chapter discusses the utilization of automation systems. The purpose of this chapter is to provide a theoretical framework for the usage evaluation which is conducted later in this study.

9.1. Information systems and organisations

Technology is rarely a solution by itself (Alter 2002). To achieve the benefits associated with information systems, organisations usually need to do something differently, for example, change organisational structures or ways of working. In addition, no matter how sophisticated the information systems are, they still are dependent on people to make them work (Boddy et al. 2004). Humans are needed to enter data into the systems and to exploit the results they provide. Therefore information systems should be seen as a part of a wider organisational context. Leavitt (1965) describes organisations by four interdependent variables illustrated in figure 9.1

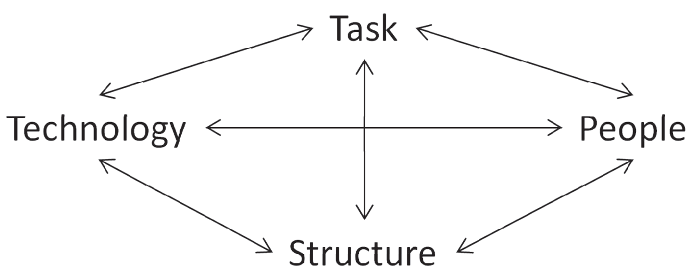


Figure 9.1 The Leavitt "Diamond" (Keen 1981)

A change in any point of the diamond will impact some, or all, of the others (Smith et al. 1992). Therefore, a change in the technology component will affect people, tasks and structure components within the organisation. Thus, in addition to technological challenges, information systems also raise organisational challenges. The latter tends to be underestimated by software engineers when implementing new systems (Hertzum 2002). However, many empirical studies have addressed the fact that organisational issues are the most critical issues when it comes to successfully implementating a new information system (Ahn & Skudlark 1997).

9.2. Information system success

Researchers have attempted to identify information system success factors and have also tried to develop success measurement methods for several years. Unfortunately, they have not found a single factor or measure to be used in information success evaluation. On the contrary, there are nearly as many solutions as there are studies. For example, DeLone and McLean (1992) found approximately 100 information success measures in the 180 studies they reviewed. However, this is understandable since information system success has many dimensions and success criteria depend on the stakeholder's perspective. Information system developers, project managers, end users and investment decision makers all have different definitions of success. For a project manager, a successful information system may be one that is completed on time and under budget, with required features and functions. Where as for the end user, a successful system may be one that enhances his or her job performance and is easy to use.

In information system success studies, the main area of interest has been on the impact of the system either at an organization or individual level (Koivisto 2009). Success at the organisational level has been traditionally evaluated using financial measures, such as the return on investment (ROI), net present value (NPV), the internal rate of return (IRR) and the payback period (Martinsons et al., 1999). However, while the costs associated with information systems are quite easily determined, the benefits of the systems are more difficult to recognize. The challenge is to isolate the effects of an information system from the other effects which influence organisational performance (DeLone & McLean 1992). Besides, traditional financial measures do not take into consideration intangible benefits, such as improved customer service or a higher degree of competitiveness (Martinsons et al., 1999). More advanced methods for the evaluation of information system success at the organisational level have been suggested by, for example, Parker et al. (1988), Martinsons et al. (1999) and Mills and Mercken (2004).

At the individual level, information system success has often been evaluated with user satisfaction. User satisfaction is seen as a meaningful surrogate measure, since it is difficult to evaluate the impact of an information system on individual users, such as productivity benefits or improved decision making (Ives et al. 1983). In addition, user satisfaction provides an end-users' view of the information system instead of viewing the system only from a technical perspective, such as measuring data accuracy or system reliability. However, there is some degree of controversy in the literature as to whether user satisfaction is an adequate measure of information system success or not (Marble 2000). According to Gelderman (1998) user satisfaction is the most appropriate measure for information system success available whereas Wixom and Todd (2005) point out that user satisfaction is a weak predictor of system use. The user satisfaction subject is further discussed later in this chapter, including factors affecting user satisfaction as well as different satisfaction measurement methods.

9.2.1. The DeLone and McLean model of success

DeLone and McLean (1992) synthesized the previously described diverse information system success aspects into an information system success model. They organised information system success measures into six categories; system quality, information quality, use, user satisfaction, individual impact and organisational impact. The six categories of the model and the measures belonging to these dimensions are described in table 9.1.

Table 9.1 Categories and measures of the DeLone and McLean model (DeLone and McLean 1992)

Category	System quality	Information quality	Use	User Satisfaction	Individual impact	Organisational impact
Description	Measures of the information processing system itself	Measures of information system output	Recipient consumption of the output of an information system	Recipient response to the use of the output of an information system	The effect of information on the behaviour of the recipient	The effect of information on organisational performance
Measures	Data accuracy	Importance	Amount of use/ duration of use	Satisfaction with specifics	Information understanding	Range and scope of application
	Data currency	Relevance	Number of inquiries	Overall satisfaction	Learning	Number of critical applications
	Database contents	Usefulness	Amount of connect time	Single-item measure	Accurate interpretation	Operating cost reductions
	Ease of use	Informativeness	Number of functions used	Multi-item measure	Information awareness	Staff reduction
	Ease of learning	Usableness	Number of records accessed	Difference between information needed and received	Information recall	Overall productivity gains
	Convenience of access	Understandability	Frequency of access	Enjoyment	Problem identification	Increased revenues
	Human factors	Readability	Frequency of report requests	Software satisfaction	Decision quality	Increased sales
	Realization of user requirements	Clarity	Number of reports generated	Decision-making satisfaction	Improved decision analysis	Increased market share
	Usefulness of system features and functions	Format	Charges for system use		Correctness of decision	Increased profits
	System accuracy	Appearance	Regularity of use		Time to make decision	Return on investment
	System flexibility	Content	Direct vs. chauffeured use		Confidence in decision	Return on assets
	System reliability	Accuracy	Binary use: Use vs. nonuse		Decision-making participation	Ratio of net income to operating expenses
	System sophistication	Precision	Actual vs. reported use		Improved individual productivity	Cost/benefit ratio
	Integration of systems	Conciseness	Use for intended purpose		Change in decision	Stock price
	System effieciency	Sufficiency	Appropriate use		Causes management action	Increased work volume
	Resource utilization	Completeness	Type of information used		Task performance	Product quality
	Response time	Reliability	Purpose of use		Quality of plans	Contribution to achieving goals
	Turnaround time	Currency	Levels of use: general vs. specific		Individual power or influence	Service effectiveness
		Timeliness	Recurring use		Personal valuation of information system	
		Uniqueness	Institutionalization/routinization of use		Willingness to pay for information	
		Comparability	Report acceptance			
		Quantitativeness	Percentage used vs. opprotunity for use			
		Freedom from bias	Voluntariness of use			
			Motivation to use			

DeLone and McLean proposed that these six categories were interrelated rather than independent. Their model, as presented figure 9.2, suggests that information is first created and that the information is affected by system and information quality. After this, users experience the output of the information system and are either satisfied or dissatisfied with the system or its information. Next, the use of the system impacts the user's work processes, and these individual impacts collectively result in organisational impacts. (DeLone & McLean 2003)

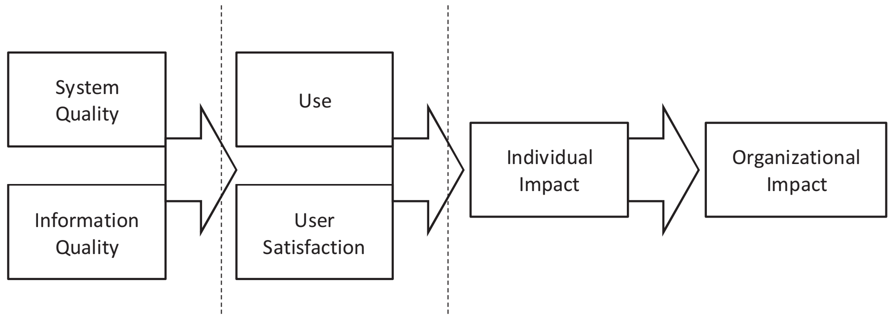


Figure 9.2 Success model (DeLone & McLean 2003)

The DeLone and McLean model of success has been used in numerous studies. Ten years after the publication of the model, DeLone and McLean (2003) found nearly 300 articles referring to their framework. In the same study DeLone and McLean made minor modifications to their original model and, for example, added service quality to the beginning of the process.

9.3. Technology acceptance

Explaining user acceptance of new technology is one of the most investigated topics of information system research. Several theories and models, with roots in information systems, psychology and sociology, have been developed to understand why users accept or reject information technology (Venkatesh et al. 2003). User acceptance is seen as essential, since information systems cannot provide the intended benefits if they are not used. The capability to predict and explain user acceptance has great practical value and the theories can be used in both system design and implementation. Two models, which are considered to be some of the most distinguished models in the information system field, are introduced briefly below.

9.3.1. The technology acceptance model

The technology Acceptance Model (TAM), illustrated in figure 9.3, is used to predict whether or not individuals will accept and use a particular information system (Davis 1989, Davis et al. 1989). TAM uses social psychology theories as the basis for specifying the causal linkages between the key beliefs: perceived usefulness and perceived ease of use, and users' attitudes; intentions and actual use of the system (Davis et al. 1989). Whereas earlier social psychology studies provided general models on user behaviour, TAM is specifically focused on explaining computer usage behaviour.

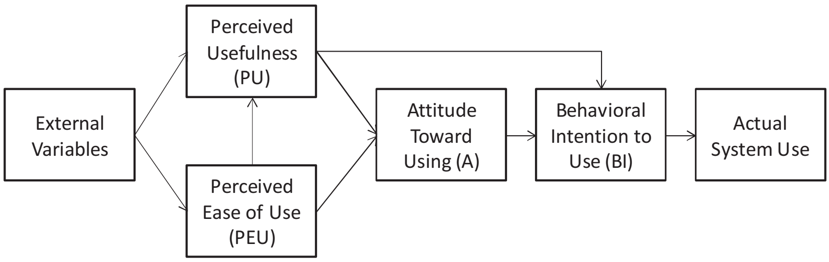


Figure 9.3 Technology Acceptance Model (TAM) (Davis et al. 1989)

TAM posits that technology acceptance primarily depends on two variables, perceived usefulness (PU) and perceived ease of use (PEU). Davis (1989) defines perceived usefulness as "the degree to which a person believes that using a particular system would enhance his or her job performance." It is assumed that the more people who think a system will help them to perform their job better; the more likely they are to use it. Perceived ease of use, on the other hand, refers to "the degree to which a person believes that using a particular system would be free of effort." Individuals have to allocate effort between alternative demands, and therefore are likely to prefer systems that are easier to use. In the model, it is recognized that PU and PEU are influenced by various external factors, such as system design characteristics, nature of the development or implementation process and organizational structure (Davis et al. 1989). However, these variables are not the primary interest of the model. Instead, the model concentrates on PU and PEU and proposes that they are determinants of attitudes towards using a system which predict behavioural intention shown to be a predictor of actual system use (Koivisto 2009). Davis's (1989) studies showed that higher degree of PU and PEU led to a higher level of actual system use and that PU had a significantly greater correlation with usage than PEU. The studies thus indicated, that users were primarily driven by the usefulness of the system and secondarily by the ease of use.

9.3.2. Unified theory of acceptance and use of technology

Another model to explain users' intentions to accept an information system is the Unified Theory of Acceptance and Use of Technology (UTAUT). Venkatesh et al. (2003) developed the theory by reviewing eight earlier acceptance models and integrating elements across these models to build a unified model as presented in figure 9.4.

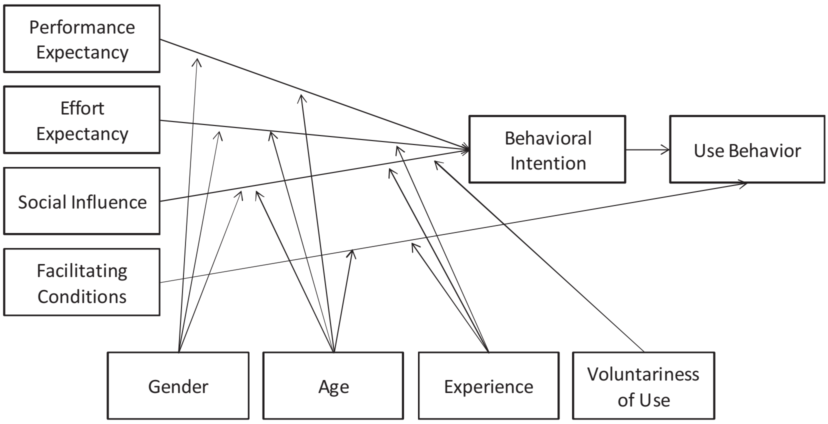


Figure 9.4 Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al. 2003)

According to the model, four constructs (performance expectancy, effort expectancy, social influence, and facilitating conditions) are direct determinants of user acceptance and usage behaviour. The four constructs are described in more detail in table 9.2. In the model, gender, age, experience and voluntariness of use are proposed to moderate the impact of the four constructs on usage intention and behavior. UTAUT was found to explain as much as 70 percent of the variance in usage intent (Venkatesh et al. 2003).

Table 9.2 UTAUT constructs (Venkatesh et al. 2003)

Construct	Definition
Performance expectancy	the degree to which an individual believes that using the system will help him or her to attain gains in job performance
Effort expectancy	the degree of ease associated with the use of the system
Social influence	the degree to which an individual perceives that important others believe he or she should use the new system
Facilitating condititions	the degree to which an individual believes that an organizational and technical infrastructure exists to support use of the system

9.4. User satisfaction

As earlier noted in this chapter, user satisfaction evaluation is widely used to measure information system success. Even though it is an indirect measure of success, it is still a meaningful measure due to its applicability and ease of use. If users are not satisfied with an information system, they are unlikely to use it and therefore the benefits associated with the system are not realized. (Zviran & Erlich 2003)

9.4.1. Factors affecting user satisfaction

In a meta-analysis study consisting of 45 publications, Mahmood et al. (2000) identified that factors affecting user satisfaction fell into three major categories: perceived benefits and convenience, user background and involvement and organizational attitude and support. They also recognized nine variables that can be divided into one of each of the above-mentioned categories as illustrated in figure 9.5.

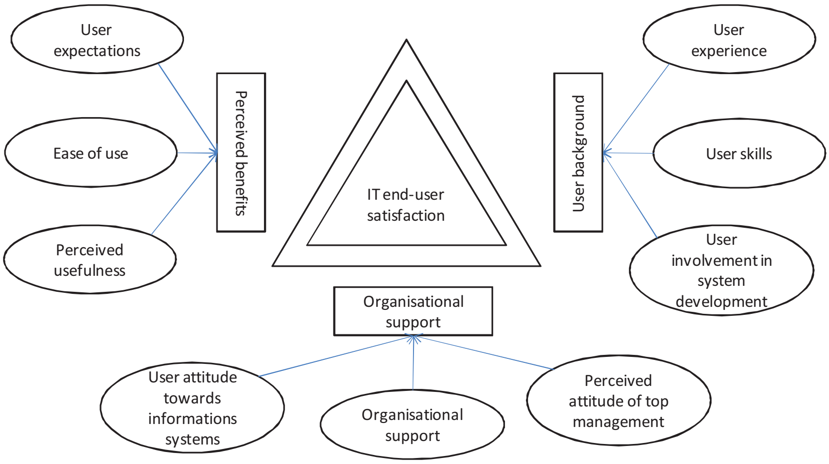


Figure 9.5 Factors affecting end-user satisfaction (Mahmood et al. 2000)

In addition to identifying the nine variables that affect user satisfaction, Mahmood et al. (2000) provided information on the effects and significance of the variables on user satisfaction. They found positive support for the influence of all nine variables on information system user satisfaction but the influence each variable had varied to some degree. The most significant factors were user involvement in systems development, perceived usefulness, user experience, organizational support and user attitude toward the information system. The nine variables and their influence on user satisfaction are presented in table 9.3.

Table 9.3 Variables and their influence on user satisfaction (Mahmood et al. 2000)

Variable	Influence on user satisfaction
Perceived usefulness	A positive relationship between perceived usefulness and end-user satisfaction
Ease of use	A positive relationship between ease of use and end-user satisfaction
User expectations	Subjects with high expectations will have higher user satisfaction scores than subjects with moderate (realistic) expectations
User experience	A positive relationship between the number of years of personal experience with computers and user satisfaction
User skills	A positive relationship between (self-reported) computer skills and user satisfaction
User involment in system development	A positive relationship between user involvement in system development and end-user satisfaction
User attitude towards information system	A positive relationship between organizational support (training) and end-user satisfaction
Organizational support	A positive relationship between end-user's perception of top management support and end-user satisfaction
Perceived attitude of top management	A positive relationship between attitude toward information systems and user satisfaction

9.4.2. Measuring user satisfaction

There are numerous tools and questionnaires available to measure user satisfaction. Some studies have employed single-question measures to determine user satisfaction, for example by asking the overall satisfaction rate with the system. However, single-question measures have been criticized as unreliable. In addition, they are unable to provide further information about the areas of dissatisfaction. (Zviran & Erlich 2003)

Besides the single-question measure, several multiple-item measures for user satisfaction exist. They measure various factors that may affect user satisfaction, such as the features of the information system, documentation and training. One of the most distinguished measurement tools is formulated by Ives et al. (1983). Their measurement instrument consists of 13 questions as follows (Baroudi & Orlikowski 1988):

1. Relationship with the Electronic Data Processing staff
2. Processing of requests for changes to existing systems
3. Degree of Electronic Data Processing training provided to users
4. Users' understanding of systems
5. Users' feelings of participation
6. Attitude of the Electronic Data Processing staff
7. Reliability of output information
8. Relevancy of output information (to intended function)

9. Accuracy of output information
10. Precision of output information
11. Communication with the Electronic Data Processing staff
12. Time required for new systems development
13. Completeness of the output information

9.5. Utilization of automation systems

In today's competitive global market, efficient, high quality and flexible production are some of the methods for industrial companies to achieve competitive advantage. In order to attain this, companies invest in production technology such as in automation systems. Since automation is capable of improving the production and thus the profitability of the business, there is a general impression that automation systems are utilized efficiently in the industrial sector. Especially in large scale process plants with 24/7 manned control rooms, automation systems are a vital tool in running and monitoring the production process. However, hardly any scholarly studies have discussed the utilization of industrial automation systems. Many studies examine only the technical aspects of automation or the new methodologies developed. Some studies include a description of the implementation of the new technology developed during the research project. Yet, these studies usually provide information only on the early days of the implementation and not on the issues regarding how the system is used in the long run.

The utilization of industrial automation systems has been discussed briefly in the study by Veldman et al. (2011) who investigated the use of condition-based maintenance technology in the process industry in the Netherlands. As a part of their study, they observed that in each case company the maintenance personnel used highly automated systems for process control. Kallela's (1996) research findings in the Finnish process industry also support this impression that automation systems are utilized a great deal by the operators and the engineers who monitor and control processes. However, Kallela argues that automation systems could provide better support for control of disturbances, transitional situations as well as forecasting.

Automation systems are used in an entirely different way in the building sector. In several connections it has been noted that current building automation systems are underutilized (for example Friedman & Piette

2001, Webster 2005, Piikkilä 2008). The building automation system users do not necessarily have a technical background or the in-depth training which is required for efficient utilization of the system. In addition, the users may be too busy with other maintenance duties, such as taking care of occupant complaints and hence, will not have the time to use the automation system. According to Webster (2005) building automation is primarily used to address faults and complaints as well as for scheduling and manual control of equipment but more advanced analysis features are left unused.

Petze (1996) discusses the reasons why industrial and building automation systems are so different. He argues that industrial automation systems are better accepted since industrial automation has a clearly measurable impact on the process that produces the revenue for the company. He also notes that the decision makers in the industrial sector have a technical background and are familiar with the production process since it affects the profitability of the business. However, decision makers in the building sector usually have a financial background and therefore may view automation systems as an expense without understanding the benefits associated with the automation. These factors can lead to buying the automation system with the lowest investment cost as well as devoting insufficient resources to the commissioning of the system and the training of the users.

THE NEW SOLUTION

10. Performance monitoring and management systems (PEMMS)

This chapter presents the novel solution constructed in the research project. The solution is based on the state-of-the-art review and on the lessons learned from the earlier studies. The recommendations for good performance visualization or FDD tools (presented in chapter eight) were taken into consideration in the development work. The chapter begins with the description of the methods used to transform building automation data into performance metrics. This is followed by the presentation of the web-based system for continuous building performance measurement, which is called in this study performance monitoring and management system (PEMMS). After this, the principles behind visualizing the performance metrics are introduced. The chapter ends with a discussion on the applications of the system, limitations, challenges, development targets and future possibilities of the system.

10.1. Transforming building automation data into performance metrics

Building automation data is transformed into performance metrics by comparing actual measurements to predetermined targets. Each performance target is based on either of the following principles:

- Target values are generally seen as representing good performance, such as targets derived from building standards or guides
- Target values represent good performance for the building or the equipment in question, such as targets presenting optimal operation or targets that can be achieved according to the equipment manufacturer

Performance targets can include one or two target values. For instance, the heat recovery efficiency sub-measure has one target value (e.g., 75 %), whereas the indoor conditions metric has two target values, acceptable minimum and maximum temperatures (e.g., min. 20 °C and max. 23 °C). If there is one target value for the performance metric, the metric is calculated by dividing the actual measurement by the target value. In a situation where there are two target values, the metric is calculated by counting the time during which the actual measurements are inside the minimum and maximum target values (as in the indoor conditions metric) or outside the optimal starting and ending times (as in AHU time schedule efficiency sub-measure) and dividing this time by the total measurement time. The results are multiplied by 100 to convert metrics into percentage format. A more detailed description of the calculation methods is provided in the paragraphs below.

The comparison of actual measurements with target values enables performance metrics to be presented in a 0-100 percentage scale where 100 percent signifies the best performance possible. The method used to transform the building automation data into performance metrics is summarized in figure 10.1.

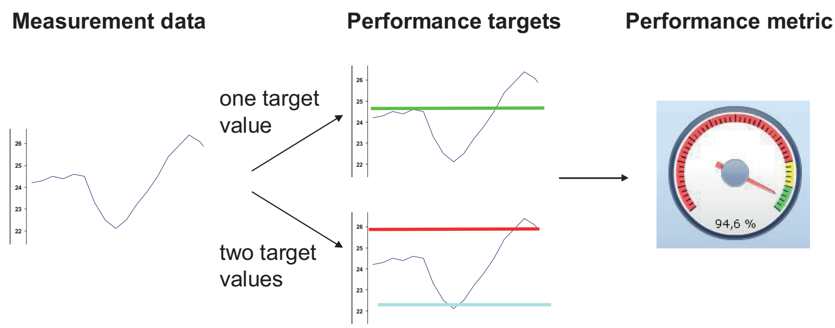


Figure 10.1 Methods of transforming automation data into performance metrics

The performance metrics are divided into three categories; energy, indoor conditions and HVAC system metrics.

10.1.1. Energy performance metric

As was mentioned earlier in this study, buildings contribute a significant portion of the world's carbon emissions. One of the methods used to reduce building energy use and carbon emissions is energy performance monitoring. It assists, for example, with assessing opportunities for improvement and evaluating the success of energy efficiency actions. Therefore it is natural that energy performance is selected as one of the performance categories.

However, in contrast to the energy performance metrics presented in the state-of-the-art review, which concentrated on energy use measures, the energy performance metrics proposed in this study measure the factors that affect energy use in buildings. The measured factors are AHU time schedule efficiency and heat recovery efficiency. The energy performance metric is calculated as an average of these two sub-measures. The reason for choosing a different perspective to energy performance is that energy meters are not always connected to a building automation system and current tools are often concentrated on displaying energy use figures rather than providing information on the cause of the energy use anomalies.

Energy use data can be acquired and displayed in many different ways, using a building automation system is only one way of doing this. Traditionally building automation systems are tconcentrated on monitoring and controlling building systems and often other tools are used for visualizing energy consumption figures. Since energy use data is not always available on a building automation system, it does not meet the design criterion for this study, transforming building automation data into performance metrics.

Although there are numerous tools on the market which display energy use, such as presented in the studies by Motegi et al. (2002), Granderson et al. (2009) and NBI (2009), they rarely assist in locating the cause of the abnormal energy use. Instead, these tools typically visualize energy use in various ways, such as through the use of bar charts, time-series graphs and scatter plots as illustrated in figure 10.2. Finding the cause of the abnormal deviation is in these cases left to the user of the tool.

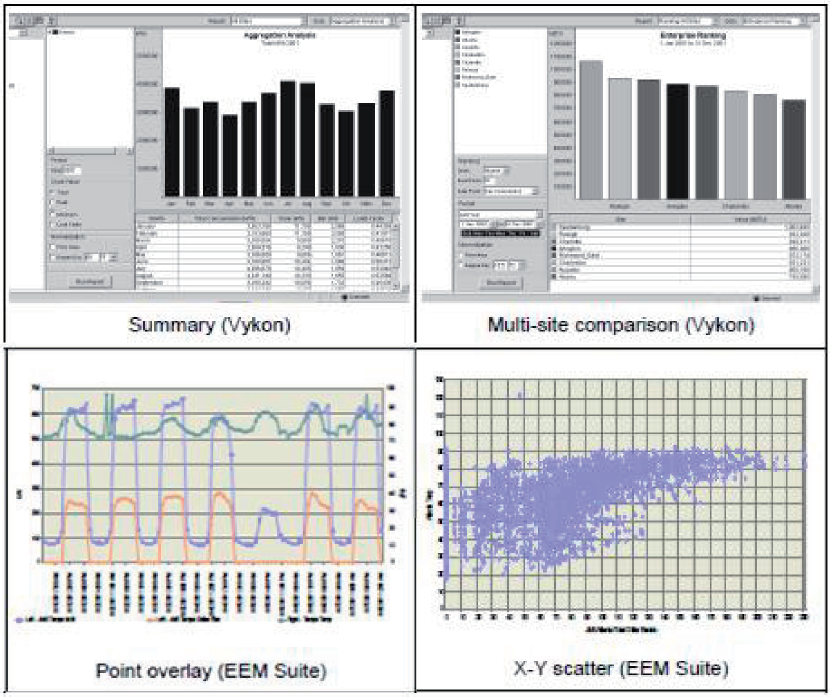


Figure 10.2 Energy use visualization examples (adapted from Motegi et al. 2002)

There can of course be several reasons for the anomaly in the building energy use but as was presented in the commissioning chapter (chapter six) energy savings in buildings are usually gained by correcting operational and control deficiencies in HVAC systems, such adjusting setpoints and changing time schedules or parameter settings. By measuring these factors that affect energy use in buildings, tool users would receive more detailed information than the ordinary energy use display provides. A building automation system controls many of these factors and thus they are available to be transformed into performance metrics. From the many factors possible, AHU time schedule efficiency and heat recovery efficiency were chosen to be included in the energy performance metrics. The methods used for presenting these factors as sub-measures are described below.

10.1.1.1. *AHU time schedule efficiency*

The purpose of the AHU time schedule efficiency sub-measure is to ensure that air handling units are operated only when needed. There is a need for this, since sometimes air handling units can be left operating unnecessarily. For example, air handling unit time schedules may be changed to meet a special need in the building (e.g., an after-hours event) and if the schedules are forgotten in this setting and never changed back to original settings then problems may occur. In addition, air handling units can be overridden manually, for instance during maintenance procedures, and left in a running position by accident.

To prevent this kind of situation the sub-measure compares the actual AHU time schedule to a so-called optimal time schedule. The optimal time schedule represents a time schedule that corresponds as well as possible with the use of the building so that air handling units are not running unnecessary but on the other hand comfortable indoor conditions are achieved when the spaces are occupied. The optimal time schedule for each AHU is determined together with the users' and the operators' of the building.

The AHU time schedule efficiency sub-measure has two target values, as the optimal time schedule can have an optimal starting and ending time. The sub-measure is calculated by counting the time during which the actual time schedule exceeds the optimal time schedule and dividing this time by the total measurement time. To present the sub-measure in percentage format, where 100 % signifies the best performance possible, the result is then subtracted from 1 and multiplied by 100 as illustrated in the formula 10.1.

$$AHU\ time\ schedule\ efficiency = \left(1 - \frac{Time\ exceeding\ optimal\ schedule}{Total\ measurement\ time}\right) \times 100\ \% \qquad (10.1)$$

An example of the AHU time schedule efficiency sub-measure calculations is presented below. In the table 1 equals "true" and 0 equals "false".

Table 10.1 AHU time schedule calculation example

Measurements	Optimal time schedule	Actual time schedule	Time exceeding optimal
1	0	0	0
2	0	1	1
3	1	1	0
4	1	1	0
5	1	1	0
6	0	1	1
7	0	1	1
8	0	0	0
9	0	0	0
10	0	0	0
	Amount of measurements exceeding optimal		3
	Total amount of measurements		10
	Metric result (calculated with formula 10.1)		70 %

As a consequence of the calculation method, the sub-measure cannot show a better result than 100 % even if the actual AHU time schedule is shorter than the optimal time schedule. If an AHU could be operated for a shorter time than the optimal time schedule shows, the optimal time schedule should be changed to match this shorter running time.

10.1.1.2. *Heat recovery efficiency*

The heat recovery efficiency of a ventilation system has a significant impact on the energy use of buildings in cold climates. The heat recovery efficiency sub-measure proposed here assures that the heat recovery unit achieves the thermal efficiency the equipment manufacturer promises for it. The best possible thermal efficiency is not always achieved due to, manufacturing failures, poor installation or degradation during operation.

The heat recovery efficiency sub-measure compares the actual heat recovery efficiency to the target heat recovery efficiency, which is the efficiency promised by the equipment manufacturer. The efficiency ratio used in the calculations is the supply-air side temperature ratio which is defined in the European Standard EN 308 as (CEN 1997):

$$\eta_t = \frac{t_{22} - t_{21}}{t_{11} - t_{21}} \tag{10.2}$$

where

t_{21} = supply air inlet
t_{22} = supply air outlet
t_{11} = exhaust air inlet

The sub-measure is calculated by dividing the actual heat recovery efficiency (calculated as shown in formula 10.2) by the target efficiency and then multiplying the result by 100 to give a percentage figure as follows

$$Heat\ recovery\ efficiency = \frac{Actual\ efficiency}{Target\ efficiency} \times 100\ \% \tag{10.3}$$

The sub-measure is calculated only during the heating period, which is defined in Finland by the Ministry of Environment as the season when the outdoor temperature is under +12 °C (YM 2003). Although the actual efficiency could be better than the target efficiency, the metric result is limited to 100 % to avoid figures better than 100.

It should also be noted, that the target efficiency promised by the equipment manufacturer might not be reached since the actual operating environment can be different from the environment where the target efficiency was measured. Equipment manufactures usually measure the heat recovery efficiency in a test environment with certain parameters (e.g., outdoor temperature and exhaust and supply air flows). If the actual operating environment is different, the target efficiency may not be reached although the heat recovery unit functions as it should.

10.1.2. Indoor conditions metric

The indoor conditions metric is intended to ensure that comfortable indoor conditions are maintained in the building and that energy conservation measures are not performed at the expense of indoor environmental quality. The metric measures the thermal comfort factor of the IEQ and is constructed by applying the temperature target values presented in the Finnish Classification of Indoor Environment 2008, which was described in more detail in chapter 7.3.3. The target values can be chosen from S1, S2 or S3 classes depending on how strict the temperature limits are wanted for the metric.

Since in the classification the indoor temperature target values change as a function of the outdoor temperature, both indoor as well as outdoor temperature data is needed for the metric calculations. For each indoor temperature measurement an outdoor temperature must be determined as this defines the target values for the indoor temperature measurement in question. The metric is calculated by counting the time during which the actual measurements are inside the minimum and maximum target values and dividing this time by the total measurement time. The result is then multiplied by 100 to present the metric in percentage format. The indoor conditions metric calculations are presented in formula 10.4.

$$Indoor\ conditions = \frac{Time\ inside\ boundaries}{Total\ measurement\ time} \times 100\ \% \qquad (10.4)$$

For example, the indoor conditions metric using S2 class targets is calculated as illustrated in table 10.2.

Table 10.2 Indoor condition calculation example

Measurement	Indoor temperature	Outdoor temperature	Min target	Max target	Inside min/max limits
1	22,1	8	20	23	yes
2	22,1	9	20	23	yes
3	22,9	12	20	23,8	yes
4	23,8	14	20	24,6	yes
5	25,6	16	20	25,4	no
6	25,7	16	20	25,4	no
7	26,5	18	20	26,2	no
8	26,8	19	20	26,6	no
9	26,1	17	20	25,8	no
10	25,5	15	20	25	no
		Measurements inside limits			4
		Total amount of measurements			10
		Metric result (calculated with formula 10.4)			**40 %**

However, for rooms and apartments where the indoor temperature is adjustable by the occupant the indoor temperature is also compared to the temperature setpoint value. The acceptable deviation from the temperature setpoint is +/- 0.5 °C for S1 class and +/- 1.0 °C for S2 and S3 classes. In this case the indoor conditions metric is calculated by counting the time during which the actual measurements are inside the allowed deviations from temperature setpoints or within the minimum and maximum boundaries and then dividing this time by the total measurement time.

The indoor conditions metric is calculated only for the hours the building is in operation. To determine this time, occupancy sensor data or air handling unit time schedules can be used. Both of these can be obtained from a building automation system. Occupancy sensors provide more accurate information regarding the building use whereas time schedules may be based on building operators' best guesses of the building use.

10.1.3. HVAC system metric

The main function of HVAC systems is to create and maintain a comfortable indoor environment for building occupants. Poor HVAC system performance can lead to indoor environmental quality problems and occupant complaints. HVAC system performance is therefore an essential part of the performance metrics proposed in this study.

Earlier tools developed in this field have focused on examining HVAC system performance from the fault detection and diagnostics perspective. For example, the tools presented in Annexes 34 (Dexter & Pakanen 2001), 40 (Visier 2004) and 47 (Neumann et al. 2010) as well as in the *Comparative Guide to Emerging Diagnostic Tools for Large Commercial HVAC Systems* (Friedman & Piette 2001) have diagnosed HVAC system performance using models, statistical methods and knowledge-based methods. These tools have visualised HVAC system performance in various ways, such as in time series, scatter and carpet plots. However, the use of performance metrics has been rare in this field. In the few studies found, Kärki and Hyvärinen (1997) present different performance requirements for air handling units, Kärki and Karjalainen (1999) illustrate how performance factors could be used to evaluate AHU performance and Choinière (2008) describes an on-going commissioning tool that utilizes HVAC performance metrics as part of the used fault detection and diagnostics method.

The HVAC system metric is constructed by applying the principles of overall equipment effectiveness (OEE) metric as well as the control loop performance criteria for air handling units described by Kärki and Hyvärinen (1997) and defined in the Finnish Standard SFS 5768 (SFS 1993). The HVAC system metric consists of three sub-measures; availability, temperature and pressure. The HVAC system metric is calculated as a product of the three sub-measures as shown in equation X.

$$HVAC\ system\ metric = Availability \times \Pr essure \times Temperature \qquad (10.5)$$

The sub-measures of the metric correspond partly with the performance elements of the overall equipment effectiveness. The availability sub-measure presented in this study is closely related to the availability used in the OEE calculations. The pressure sub-measure, on the other hand, could be seen as representing the performance element of the OEE. The performance element compares the actual operating speed of the equipment to the ideal speed whereas the pressure sub-measure compares actual duct static pressure to the setpoint pressure (the “ideal” pressure). If the duct static pressure is seen as a measure describing the speed of production (the amount of air supplied to the spaces), there is an analogy between the performance element and the pressure sub-measure. There is also a similar analogy between the quality element of the OEE and the temperature sub-measure. The quality element indicates the proportion of good parts produced compared to the total number of parts produced whereas the temperature sub-measure compares actual supply air temperature to the setpoint temperature (the “quality requirement” for temperature). If the setpoint air temperature is achieved, the quality of the supply air meets its requirements and thus it presents the good parts produced according to the OEE definition.

The idea of the HVAC system metric is to help assess the overall performance of air handling units. The sub-measures of the metric are presented below.

10.1.3.1. *Availability*

To be able to provide comfortable indoor conditions the air handling units have to operate at least during occupied hours. The idea of the availability sub-measure is to secure this by comparing the actual air handling unit running signal to the air handling unit time schedule. In the measure, it is assumed that the time schedule corresponds with the use of the building. Availability is calculated using the formula 10.6.

$$Availability = \frac{Actual\ running\ time\ during\ the\ time\ schedule}{Total\ time\ of\ the\ time\ schedule} \tag{10.6}$$

The measure degrades as a result of air handling unit stoppages which originate from, for example, breakdowns and maintenance work.

10.1.3.2. *Pressure*

One of the functions of air handling units is to supply the right amount of air to the building. This function is measured with the pressure sub-measure, which compares the actual duct static pressure to the target value which is applied from the Finnish Standard SFS 5768 (SFS 1993). In the pressure sub-measure calculations, a deviation of +/- 5 % is allowed from the pressure setpoint. The measure is calculated by counting the time during which the actual measurements are inside the allowed deviation and dividing this time by the total measurement time. Again, the division result is then multiplied by 100 to present the metric in percentage format as presented in below

$$\Pr essure = \frac{Time\ inside\ boundaries}{Total\ measurement\ time} \times 100\ \% \tag{10.7}$$

The measure is calculated only during AHU operation and it can be calculated for both supply and exhaust air. To combine these measures a pressure sub-measure for an AHU is calculated as an average of the supply and exhaust air measures. The pressure sub-measure describes how well the air handling unit is performing against design. The measure helps to detect undersized AHUs as well as poor turning, such as oscillation and droop.

10.1.3.3. *Temperature*

In addition to providing the right amount of air, an AHU should provide an adequate air temperature to the spaces. The temperature sub-measure follows the design principles of the pressure sub-measure. The measure applies target values defined in the standard SFS 5768. The allowed temperature deviation from the setpoint is +/- 0.5 °C. The measure is calculated by counting the time during which the actual measurements are inside the allowed deviation, dividing this time by the total measurement time and multiplying the result by 100.

$$Temperature = \frac{Time\ inside\ boundaries}{Total\ measurement\ time} \times 100\ \% \tag{10.8}$$

The measure is calculated only during AHU operation. The temperature sub-measure assists in the same manner as did the pressure sub-measure in detecting undersized AHUs as well as poor tuning, such as oscillation and droop.

10.2. System architecture

The system architecture of PEMMS is shown in figure 10.3. PEMMS uses a building automation system to collect and store all the data points needed for the metric calculations at a 10-minute interval. The data is first saved as trend logs in controllers and then collected to a database server located in the building for long-term storage. This server is connected through the internet to a central server that polls and stores data from several buildings. Finally, the data is transferred to another server which includes an application to visualize the data in performance metrics on a web page. The calculations needed to transform building automation data into performance metrics are performed in the controllers, the database located in the building as well as by the visualization application.

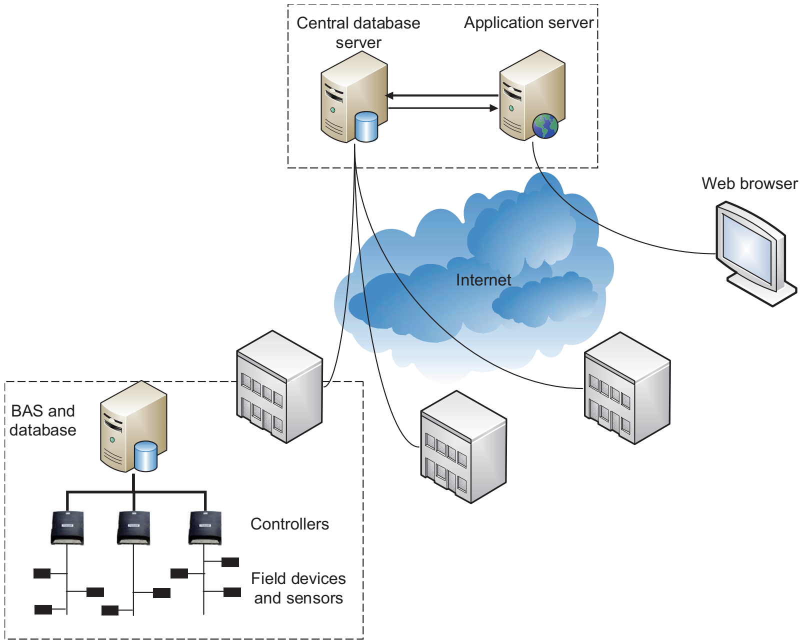


Figure 10.3 PEMMS architecture

The system is constructed by using hardware and software already available on the market. The key components of the system are the Tridium Niagara automation and integration products and SAP Crystal Dashboard Design business intelligence software.

The Tridium Niagara Framework is more than a traditional control system as it is capable of integrating various systems and devices of numerous different manufacturers into a unified platform using a common framework. The systems that the Niagara manages can be accessed easily over the internet using a standard web browser. The data collected by the Niagara can be stored in several different databases, such as in a Microsoft SQL server. (Tridium 2011)

The SAP Crystal Dashboard Design software was used in designing the performance metric reports, connecting the building automation data to the reports as well as to publish the reports on the internet. The software assists in designing reports by providing, for example, a rich library of ready-to-use visualization components, such as charts, maps and bars. It is also capable of creating reports based on numerous different data sources. In addition, the software offers several options for publishing, saving and exporting the reports, such as web, Microsoft Office and Adobe PDF. (SAP 2011)

10.3. Visualization of the metrics

The performance metrics provided by the PEMMS can be accessed by a regular web browser. In addition to an internet connection, the user is required to have a username and a password to login into the system. The front page of the system gives a holistic view of a building's performance as shown in figure 10.4. The idea of the front page is to provide a fast and intuitive picture of the current and past performances. As the performance is presented in a percentage format, it is easily understandable by technical as well as non-technical users.

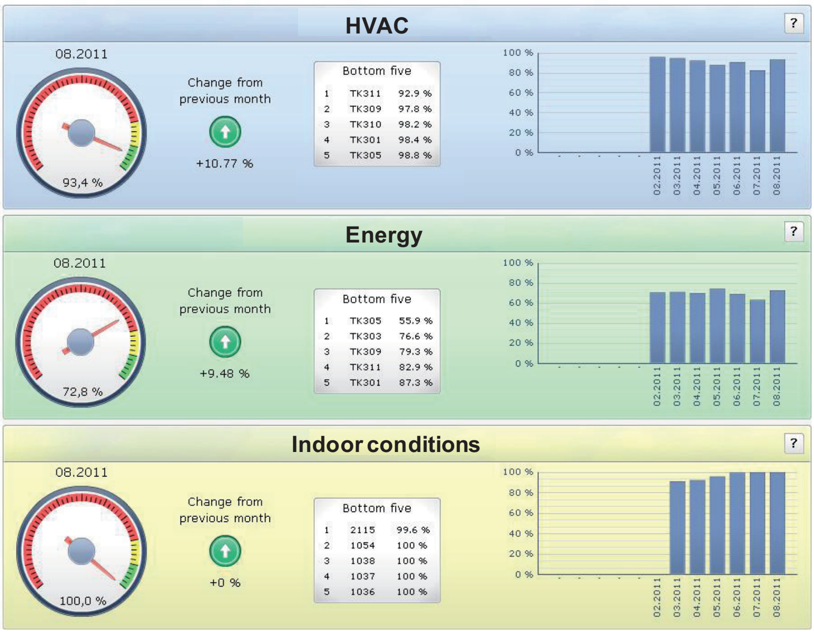


Figure 10.4 Front page of PEMMS

The percentage values presented on the front page describe the performance of the whole building. The energy and HVAC system metrics are calculated for all AHUs linked to the PEMMS and the percentage value shown on the front page is calculated as an average value of these AHU metrics. Similarly, the indoor conditions metric is calculated for all spaces linked to the PEMMS and the front page percentage presents the average value of these space-specific indoor conditions metrics. Gauges on the front page are used to present the current state (the performance of the present month) of each performance category. On the right side of the gauges, the current state is compared to the performance of the previous month. The five currently worst performing AHUs and spaces are presented in the middle of the page and the performance history of twelve previous months is illustrated on the right side of the page. Descriptions of the performance categories as well as the calculation formulas on which the metrics are based can be viewed by clicking the question marks located on the upper right corner of each performance category.

PEMMS also offers drill-down capabilities to view detailed information behind each metric. In addition to the front page, there are two levels of performance reports providing information on metrics and sub-measures of each AHU and space as well as on the actual measurement data as illustrated in figure 10.5.

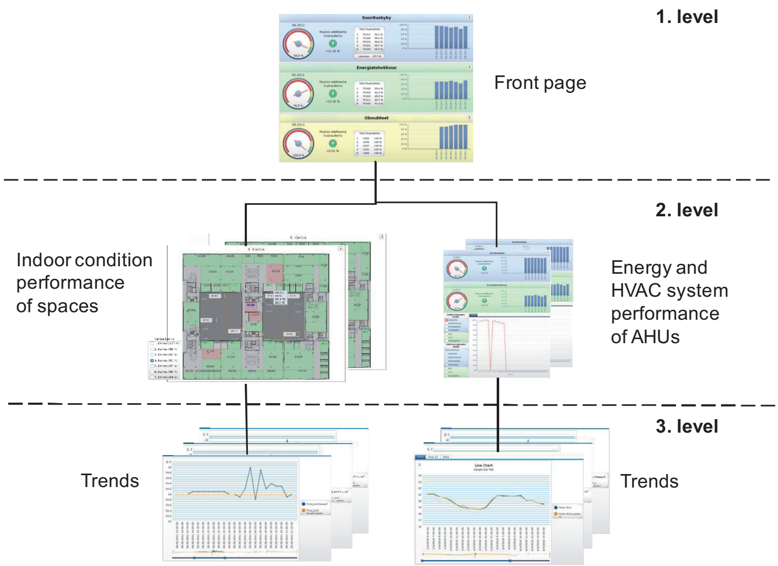


Figure 10.5 Reporting hierarchy

On the second level of reporting, the users can view indoor conditions metrics of each space linked to the system on a colour coded floor plan where red means poor performance, yellow means satisfactory performance and green means good performance. Thus, the colours provide an instant overall view of the thermal comfort on each floor. The indoor conditions metrics are presented as monthly summaries on the floor plan and the users can freely select the month they want to view. On the second level, it is also possible to view energy and HVAC system metrics and sub-measures of each AHU. The AHU-specific reports display energy and HVAC system metrics on a monthly basis in a similar fashion as to what is presented on the front page. In addition, AHU-specific reports provide information on sub-measures by displaying them as time series plots. The sub-measures presented on the plots are daily averages of the measures. On the AHU-specific reports, users can choose which month's metrics are to be viewed and which sub-measures are to be displayed on the chart.

The actual measurement data, on which the sub-measures and metrics are based, is available on the third level of reporting and is to be used for in-depth analysis. The data is visualized using time series plots and the users can determine which data points are to be plotted. The displayed time period is selectable but only one week of data can be presented at a time.

10.4. Discussion

There are several opportunities as well as limitations and challenges associated with the solution presented in this chapter. These issues are discussed in the following paragraphs.

10.4.1. Applications of the system

As described above, the PEMMS turns building automation data into a set of performance metrics which approach building performance from three perspectives: energy, indoor conditions and HVAC system performance. The PEMMS visualizes the metrics in a manner that is easy and intuitive to understand, even for a non-technical user. The system provides high-level performance reports which enable the overall building performance to be assessed at a glance. In addition, the system offers information that is detailed enough to help the user to find the causes of degradation. As the name of the PEMMS suggests, it is intended to be utilized as both a building performance management and performance monitoring tools as described in more detail below.

10.4.1.1. *Performance management*

Presenting the building performance information in a percentage format provides the opportunity to use PEMMS in building operation and maintenance management. As the performance metrics are displayed in a 0-100 percentage format, they can be easily used to set goals and to follow them. The PEMMS can be utilized throughout the operation and maintenance organization to translate management targets into easily understandable objectives. Everyone in the operation and maintenance organisation, from top management to building operators, can use the

PEMMS to track current performance and compare it to target values or historical performance as well as to identify improvement opportunities. Even non-technical users can use the system and observe the actual performance of their buildings. The technical persons, on the other hand, can utilize the system in finding the reasons behind degraded performance.

In addition, the performance metrics defined in this study could be included in the operation and maintenance contracts. Instead of defining how the operation and maintenance work should be conducted, performance metrics could be used to specify the end result of the work, such as the availability of the systems or the quality of the indoor environment. By measuring the outcomes instead of inputs or processes, the suppliers would be given the freedom to find innovative ways to meet the contract requirements. The PEMMS could then be used to measure how well the performance requirements specified in the contract are actually met in operation.

10.4.1.2. *Performance monitoring*

Besides being a management tool for the entire operation and maintenance organisation, the PEMSS is suitable for building performance monitoring. With monitoring it is referred to the daily, weekly or monthly tasks aiming at optimizing building operation, reducing energy costs and improving indoor environmental quality. Building performance monitoring is work which is mainly conducted on the operative level of the organisation by, for example, maintenance men, custodians and facility managers. The main focus of the earlier building performance visualization and FDD tools has been in providing information to these persons who are responsible for the building operation.

With the help of PEMMS, evaluating a building's performance is less demanding and time-consuming than it would be using a building automation system. The front page of the PEMMS shows the overall building performance and the worst performing equipment and spaces. Thus, the detailed performance analysis and troubleshooting can be focused on the problem areas noticed on the front page. The system user can utilize the AHU or space-specific performance reports as well as the trend reports to find the cause of the performance degradation. However, the PEMMS does not include automated fault detection and diagnostics features, and therefore the localization of the fault is left to the user.

Using PEMMS, building performance degradation can be detected before it leads to occupant complaints or increased energy costs. For example, the HVAC system performance metric can be used to prevent occupant discomfort. If the air handling unit is not running or capable of providing the right amount of air or the correct air temperature, there is a risk that comfortable indoor conditions will not be achieved.

The PEMMS can be utilized to detect several different performance anomalies and faults. For example, in two pilot buildings where the PEMMS was developed to the system as described in this study, the following problems could be noticed:

- Unnecessary AHU operation
- Heat recoveries not reaching their target values
- Too warm or cold spaces
- Poor turning of air temperature and pressure of air handling units
- Malfunctioned sensors

10.4.2. Taking the prior literature into account in the development work

At the beginning of the chapter, it was stated that the PEMMS is based on the state-of-the-art review and on the lessons learned from the earlier studies. The issues that were taken into account when developing the construct are discussed in more detail in this section.

First of all, the PEMMS fulfils many of the characteristics of a good performance visualization tool as outlined in chapter eight. The PEMMS is, for instance, adaptable to the needs of its users, easy to understand, easy to use and provides a synthesis report that is presented first but also offers more detailed information for in depth analysis. The PEMMS also tries to address some of the challenges related to fault detection and diagnostic tools since it is easy and fast to install. As the PEMMS utilizes the existing building automation measurements, no additional sensors and equipment is needed to implement the system. In addition, the system does not require teaching data in contrast to process history -based fault detection and diagnostic tools which need a large amount of history data. This is possible because the performance metrics are based on predetermined performance targets rather than on certain faults identified from the history data.

The indoor condition and HVAC performance metrics are derived from the building performance standards and guides presented in chapter seven, for example, the indoor condition metrics applies the temperature target values presented in the Finnish Classification of Indoor Environment 2008. On the other hand, the energy performance metric is based on the findings of commissioning studies. The energy performance metric measures some of the factors that are used to gain energy savings in commissioning projects.

The beginning of chapter seven presented how performance measurement is used to manage business. However, this management aspect has not been considered in the field of building performance visualization and fault detection and diagnostics tools. The previous tools such as described in the studies of Dexter & Pakanen (2001), Friedman & Piette (2001), Visier (2004), Neumann et al. (2010) and in chapter eight of this study have focused on monitoring and optimizing building operation and have not provided information for management purposes.

10.4.3. Exploitability

The PEMMS is designed in a manner that makes it easy to utilize in various buildings in Finland regardless of the building system technology. However, the solution has some limitations and requirements. The starting point for the PEMMS is that the building has a building automation and a mechanical ventilation system. If this is the case, then many of the proposed performance metrics can be applied. The indoor conditions performance metric requires only indoor temperature data from the building and this can be read from the temperature sensors located in the spaces or in the exhaust air ducts. In addition, measurements needed for the energy performance metric can be found in a typical non-residential building. The older buildings might not have air heat recoveries but the newer ones normally have, at least for the larger AHUs. Furthermore, the HVAC system metric can usually be calculated for the building. However, only availability and temperature sub-measures can be calculated for constant volume air handling units.

The current PEMMS uses the Tridium Niagara framework to collect and store measurement data from the building systems. Nevertheless, the PEMMS is not dependent on this framework and other building automation systems can also be used for the same purposes. Since almost all building automation vendors store the measurement data in a different manner, a different data acquisition method has to be constructed for each vendor.

The principles of transforming building automation data into performance metrics are simple and can be easily used to construct new performance metrics, for instance metrics describing the performance of heating or cooling systems. The extension of applying PEMMS to new performance perspectives and measures is currently in progress.

10.4.4. Limitations

Building performance measurement is a multifaceted and complex issue which has been approached in this thesis from three perspectives (energy, indoor conditions and HVAC system), each including one or more performance measures utilizing building automation data. By focusing on building automation and the data it provides, several building performance aspects have been left outside this study. In addition, each of the three performance categories presented in this study could include several other performance measures. Merely by using the building automation data, performance measures such as CO_2 or heating system performance could be added to the existing performance aspects.

10.4.5. Measurement quality

Several aspects contribute to the measurement quality and thus the performance metrics quality. Haves et al. (2006) provide an extensive list of factors that affect measurement quality.

> *"The quality of any measurement is determined by the attributes of the sensor, any signal conditioning present, the infrastructure of the data acquisition system, the analog-to-digital converter, the wiring connecting them, any calibration corrections that are applied, the installation technique and field conditions. Accuracy, precision, linearity, drift or stability over time, dynamic or rate of response, range, turn-down, sample or scan rate, resolution, signal-to-noise ratio, engineering unit conversion and math functionality, data storage and retrieval frequency are all relevant to defining the quality of the measurement system and its components."*

As was noted in the fault detection, diagnostics and prognostics chapter, there is typically a lack of adequate sensors to monitor the performance of HVAC systems. To keep the system costs down only a small number of sensors, which can also be of poor quality, are used in HVAC applications. Thus, there can be errors in the figures that the PEMMS provides and there might also be occasionally the need to verify the building automation measurements with field measurements.

It should also be noted that the indoor environmental quality aspect of the building performance is to some extent a subjective measure. Therefore, a good measurement quality or even good indoor environment fulfilling the highest IEQ standard requirements may not necessarily guarantee that the user of the building is satisfied with the quality of the indoor environment.

10.4.6. Calculation methods

The PEMMS displays the performance metrics in a percentage format. This is achieved by comparing the actual measurements with predetermined targets, such as values derived from building standards or guides. Presenting the information in this manner as relative figures has both advantages and disadvantages. Ratios make the information easier to understand for persons with no background on the subject. For example, presenting the indoor air CO_2 level as an absolute figure in parts per millions does not tell anything if it is not known what the CO_2 should be. Whereas by comparing the actual CO_2 to the normal level of CO_2 and presenting the result in relative figures is much more understandable. On the other hand, relative figures offer the opportunity to manipulate information. Because of this, it is essential to know which figures are compared with each other. For instance, the indoor conditions performance metric could give poor figures if the actual indoor environment is compared to S1 requirements but excellent figures when comparing to S3 requirements.

There are numerous ways to construct a performance metric hierarchy. The set of performance metrics proposed in this study has three hierarchy levels. Energy and HVAC system sub-measures are combined into AHU level metrics and these as well as space level indoor conditions metrics are furthermore combined into building level metrics. The higher level metrics are calculated as an average of the sub-measures or metrics on the level immediately below. The only exception is the HVAC metric which is obtained by multiplying the availability, pressure and temperature sub-measures by each other. This is performed to follow the design principles of the overall equipment effectiveness (OEE) metric. By choosing the multiplication method, the HVAC metrics shows lower figures than it would show using the average method. However, this can be seen as a good thing, since the stricter requirements show performance anomalies earlier and in doing so prevent possible indoor environmental quality problems. There are also disadvantages with the average method as it hides few poor metrics if the other metrics are at a good level. For example, the indoor conditions metric may show good figures on the building level but from the tens or hundreds of rooms in the building a couple can still have really poor indoor conditions figures. To prevent this problem, the PEMMS displays the worst five performing spaces on the building level performance report.

All the performance sub-measures and metrics have equal weight in the calculations. Yet, they could be assigned weight according to their estimated importance. For instance, in the case of energy performance metrics, larger AHUs could have a higher weight than the smaller ones since they have a greater effect on the energy use. Assigning relative weight to different metrics is a complex issue and is one of the matters that need further investigation. Although the performance metrics have not been assigned a weight, the used calculation methods have made them unequal. The multiplication used in the HVAC system metric gives the metrics poorer figures than it would get using the average method. In addition, metrics that have one target value, such as the heat recovery efficiency sub-measure, will probably get poorer figures than the metrics with two target values. The calculation method for two target values counts only the time during which the actual measurements are inside or outside the acceptable limits but does not take into consideration for how long it was outside of the limit. However, the calculation method for one target value considers this aspect as the actual measurement is divided by the target value.

10.4.7. Benchmarking

The PEMMS is designed to be used for single building monitoring and management. Therefore it does not support benchmarking in the best possible way. From a single building's point of view it does not make any difference how the target values have been assigned to the performance metrics. The target values only describe the state that is wanted to be reached in this specific building. The targets can be based on values that generally represent good performance or on values that represent good performance in this specific building. However, the meaning of the target values is totally different when buildings are compared to each other. At least the following issues should be taken into consideration before benchmarking.

The comparison of HVAC system metric with other air handling units and buildings can be seen as comparing “apples with apples” since the target values for the metric sub-measures are the same for all AHUs. However, there are issues that require a closer investigation. The availability sub-measure compares the actual AHU running signal to the AHU time schedule. Thus, it is harder to achieve high scores on availability for AHUs operating 24 hours a day compared to AHUs that only run from 8 a.m. to 4 p.m. In addition to this, since the pressure sub-measure target value is defined in percentage form (+/- 5 %), the target is more difficult to achieve in small AHUs compared to larger ones. For example, if the duct static pressure setpoint is 50 Pa, the allowed deviation is +/- 2.5 Pa whereas for the setpoint of 200 Pa, the allowed deviation is +/- 10 Pa.

The indoor conditions metric, on the other hand, compares the actual indoor temperature with the requirements specified in the indoor environment classes S1, S2 or S3 depending on how strict the temperature limits are needed for the metric. Therefore, to benchmark the indoor conditions metric it should be known which indoor environment class is used in the indoor condition calculations.

The third performance category, energy performance, provides information only on how well the optimal target values are reached for each AHU. The target values, the optimal time schedule and the heat recovery efficiency, are equipment-specific and therefore benchmarking of the energy performance metric is difficult.

10.4.8. Future implications

As several countries have set ambitious targets for energy efficiency and the reduction of greenhouse gas emissions, it is inevitable that the energy use of buildings has also got to be reduced. To reach the goals of low and zero energy buildings, innovative technology and building design is needed. At least equally important is to ensure that the buildings are operated efficiently and that the energy efficiency is not achieved at the cost of indoor environmental quality. To respond to these challenges, tools such as the PEMMS are needed. The current features and capabilities of the PEMMS have been introduced in this chapter. In addition to these, the PEMMS offers numerous development opportunities.

The PEMMS is primarily intended to provide building performance information to the operation and maintenance organisations. In addition to these organisations, several others could benefit from the information that PEMMS offers. One of the end-user groups could be building occupants. For instance, by providing feed-back information on the building energy performance, the occupants could learn to use building systems more efficiently. PEMMS could also provide valuable feedback to building and HVAC system design on the actual building performance. With this information, design practices as well as the accuracy of simulation tools could be improved. The third group who could utilize PEMMS information is equipment manufacturers. As PEMMS is capable of collecting performance data from various building systems, the data could be transformed into information that is useful for the manufactures and their product development teams. However, interest in this kind of performance information utilization was not found in the field of frequency converters (Wacklin 2010).

At the moment, the PEMMS does not provide automated fault detection and diagnostics functionalities. The current version of PEMMS leaves troubleshooting to the user of the system. However, automating some parts of the fault detection and diagnostics process could be performed quite easily. For example, an automatic notification could be sent to the user of the system when performance metric figures reach certain alarm thresholds. In addition, more advanced automated fault detection methods have been tested during the development of the PEMMS. As part of his master's thesis Kukkonen (2008) developed knowledge based fault detection methods to analyse the energy performance of air handling units. However, similar challenges as reported in the FDD literature were confronted during this development work. The greatest challenges were associated with the measurement quality and the detection sensitivity. As a consequence of this, only manual FDD is possible with the current PEMMS.

The current PEMMS is an extension of the traditional building automation system. Nonetheless, these features could be embedded in a building automation system. If the building automation sector follows the development path of the industrial automation systems, the future building automation system will have information management and visualization capabilities that enable reporting similar to the PEMMS. For instance, current process automation systems already include features such as control loop monitoring, condition monitoring, performance reporting and high definition data management and visualization (ABB 2011, Metso 2011).

There is a lack of standardization in the field of building performance measurement. The number of performance metrics that could be measured is innumerable. There is little consensus regarding how to evaluate or report measured building performance. Since there is no standardization in this field, organisations and companies are developing their own solutions for performance measurement. This makes it difficult for the building owners to decide which performance measurement solution they should choose for their building as well as complicates the comparison between buildings. At the moment, there is very little experience in terms of evaluating and reporting measured building performance and therefore it is evident that it takes time to find consensus in this field.

As the current PEMMS measures building performance from three perspectives (energy, indoor conditions and HVAC), the question remains whether the system takes into account the essential building performance aspects or are some substantial performance aspects still missing? In addition, another unanswered question is whether these three performance metrics can assist in gaining a better overall understanding of the building's performance or will some other performance aspects suffer at the expense of these metrics? For example, if a building operation and maintenance organisation concentrates on these performance metrics, will it lead to a sub-optimal situation where some other performance perspectives will decrease? These questions can be answered only by gaining experiences with the use of the PEMMS and by assessing the building performance from a wider perspective.

11. Evaluation of the use of PEMMS

In this chapter, the PEMMS is evaluated from the users' perspective. The intention of the chapter is to provide information on how the PEMMS is actually used and what challenges the users have confronted. The chapter begins by introducing the research methods and materials used in this part of the study. This is followed by a presentation on the feedback gained from the users. The chapter ends with a discussion regarding the results, including major findings, future implications and an evaluation of the research process.

11.1. Methods and materials

This section explains the steps involved in the use evaluation carried out in this research. The section describes the used research method and the research materials. It also introduces the data collection and analysis methods.

11.1.1. Research method

In this study, the users' perceptions regarding the use of PEMMS are explored using semi-structured interviews. In the semi-structured interview method, the interviewer has a list of predetermined questions to be asked of the respondents. The predetermined questions only guide the discussion while at the same time giving the opportunity for the interviewer to explore particular themes or responses further (Tuomi & Sarajärvi 2002). On the other hand, the list of questions ensures that the same basic lines of inquiry are conducted with each interviewee (Patton 2002).

Interviews are a suitable method for exploratory studies where one does not exactly know what one is looking for (Nielsen 1993). During the discussions with the respondents, the interviewer can adjust the questions in an attempt to find unexpected information. The interview allows the researcher to find out what is in someone else's mind and what his or her perspective on the studied phenomenon is (Patton 2002). These two factors were the primary reasons for choosing the interview method, specifically the semi-structured interview, for this research. The method is used in this chapter to get an insight of the users' experiences and opinions of the

PEMMS and especially to gain an in-depth understanding of the challenges associated with use of the system.

There are both advantages as well as weaknesses associated with the interview method. The benefit of the interview is the ability for the interviewer to rephrase, explain, clarify or correct questions if necessary. During the discussion the interviewer can also act as an observer and not only record verbal responses but also make notes of body language. (Tuomi & Sarajärvi 2002)

The disadvantage with interviewing is the fact that especially when doing face-to-face interviews it becomes an enormously time-consuming task as it requires preparation, travelling to the interview locations and transcribing as well as analysing the interviews (Gillham 2000). In addition, interviews can be understood and interpreted in different ways depending on the interviewer. In qualitative research, the researcher is the instrument for collecting and analysing data and therefore the research results are subjective (Kaplan & Maxwell 2005).

11.1.2. Selection of data sources

Several versions of the PEMMS have been created during the development process. The different versions of the PEMMS vary to such a degree that only the users of the system version described in chapter 10 were selected for the interviews. This system version was used in three buildings in the Helsinki region in Finland. Two of them were office buildings and one was a commercial building. All the PEMMS users in these three buildings were asked to participate in the study. However, two of users declined because of busy work schedules.

Background information on all ten persons participating in the interviews is presented in table 11.1. The interviewees are classified into three categories according to their role in the studied buildings: owner, user and service provider. This categorisation follows the classification of the building operation and maintenance actors as was described in chapter three. In addition to the role of the interviewee, the table represents information on the respondents' responsibilities and the time period he or she has had the access to the PEMMS. The duration of access is calculated from when the user received a username and password to PEMMS until the time when the user was interviewed.

Table 11.1 Background information of the interviewees

	Role	Title	Duration of access
1.	Owner	HVAC specialist	39 weeks
2.	Owner/user	Head of corporate real estate management	6 weeks
3.	Owner/user	Facility manager	6 weeks
4.	Service provider	Facility manager	30 weeks
5.	Service provider	Customer service manager	29 weeks
6.	Service provider	Customer service manager	29 weeks
7.	Service provider	Energy consultant	8 weeks
8.	Service provider	Energy consultant	7 weeks
9.	Service provider	Service man	6 weeks
10.	Service provider	Service man	4 weeks

11.1.3. Data collection

The one-to-one interviews were conducted between May and July 2011. The interviews took place at each of the interviewees' workplace and they were held in Finnish. Each interview lasted from 30 minutes to two hours. The intention was to organise the interviews so that the interviewees would have the possibility to use the PEMMS during the discussions. The aim with this was to remind the user of the capabilities and challenges of the system as well as to provide the interviewer with the possibility to observe the use of the system. The PEMMS was available in nine of the ten interviews. All the interviews were conducted by the author of the study.

At the beginning of the interviews, the interviewees were informed about the purpose of the study as well as the anonymity and the confidentiality practices. Permission for tape recording was asked before the actual interview started. After the introduction to the subject, the interviews followed the semi-structured interview guide presented in table 11.2. The guide provided an outline for the interview but allowed the interviewer to explore and ask further questions that were seen as significant to the aim of the study.

Table 11.2 Interview guide, part 1/2

		Questions	Information system theory	Other theories
Backgroung information	1.	Tell about your role and responsibilities in the building w here the PEMMS is in use.		
	2.	What information systems associated to building operation and maintenance do you use in your w ork? How often do you use these system?	Mahmood et al. (2000) model: user experience and skills	
	3.	What deficiencies do you see in these systems? What kind of information w ould you need in your w ork?		
Implementation	4.	Why did you acquire PEMMS? What kind of expectations did you have for the system? (only presented to persons w ho participate in the purchase decision making)		
	5.	Have you participated to the development or the implementation of PEMMS?	Mahmood et al. (2000) model: user involment in system development	
	6.	In w hat w ays has the implementation/use of the PEMMS been supported or motivated?	Unified Theory of Acceptance and Use of Technology: facilitating conditions	Maintenance personnel at operational level argue that maintenance budgets are below the needs and top management at the strategic level criticize the inefficiency of the maintenance organisation (Lee & Scott 2009), chapter 3
			Mahmood et al. (2000) model: organisational support	
	7.	What did you think about the training and the instructions?	Unified Theory of Acceptance and Use of Technology: facilitating conditions	Building automation system users do not necessarily have a technical background or the in-depth training w hich is required in efficient utilization of the system (Webster 2005), chapter 9
			Mahmood et al. (2000) model: organisational support	

Table 11.2 Interview guide, part 2/2

		Questions	Information system theory	Other theories
Use	8.	Have you use the PEMMS? How often have you used it? Has the use been mandatory or voluntary?	DeLone and McLean model: use	Operators are too busy responding to comfort complaints, performing routine maintenance and troubleshooting problems to track building performance (Friedman et al. 2003b), chapter 6
				Advanced features of BAS are not used, training and documentation is inadequate, user lack time to use the BAS (Webster 2005), chapter 9
	9.	For what purposes have you used the PEMMS?		
	10.	What is your overall impression of the PEMMS and satisfaction with the system?	DeLone and McLean model: user satisfaction	
	11.	Has the system been useful in your work?	Technology Acceptance Model: perceived usefulness	
	12.	What do you think about the information quality or the interface of the system?	DeLone and McLean model: system and information quality	
	13.	How would you describe the difficultness or easiness of use of the system?	Technology Acceptance Model: perceived ease of use	
	14.	What kind of changes has there been in working procedures/organisations/management practices that stemmed from the use of PEMMS?	Leavitt diamond	
	15.	What kind of benefits has the system provided?	DeLone and McLean model: individual/organisational impact	Benefits will not be realized if the building staff are not able use their control systems to correct problems, are too busy with other duties or lack resources to obtain help from control contractors (Katipamula et al. 2003), chapter 5
				Commissioning benefits (Pietiläinen et al. 2007), chapter 6
				Fault detection and diagnostics benefits (Hyvärinen & Kärki 1996), chapter 5
	16.	What challenges do you see in the use of the system?		Commissioning barriers (Hagler Bailly Consulting 1998),(Visier 2004), (Frank et. al 2007), (Friedman et. al 2010), chapter 6
				Fault detection and diagnostics challenges (Katipamula & Brambley 2005b), (Dexter & Pakanen 2001), (Brambley et al. 2005a), (Norford et al. 2002), (Schein & Bushby 2005), (Hirvonen & Ventä 2009), chapter 5
	17.	What would you improve in the system?		
	18.	Do you intend to use the system in the future?		
	19.	Do you intend to purchase similar kind of systems in the future? (only presented to persons who participate in the purchase decision making)		

The guide was based on the state-of-the-art review and the link between the questions and the theoretical background is shown in the table. The aim of the guide was to help gain a holistic picture of the use of the PEMMS and to find the challenges associated with the system use. Before the first interview, the guide was evaluated by an expert specialised in usability research and based on his comments minor changes were made to the guide.

All the interviews were tape recorded and field notes were taken during the discussions to ease the data analysis. Right after each interview, the recordings were listened to several times in order to find the essential issues. The field notes were then supplemented with these findings. The interviews were therefore not transcribed verbatim, only the key findings and statements were written down.

11.1.4. Data analysis

The interview data was analysed using content analysis to identify emerging themes. Content analysis is a systematic and objective method of examining messages and their characteristics (Neuendorf 2002). According to Tuomi & Sarajärvi (2002), the method aims at creating a clear verbal description of the studied phenomenon. Content analysis is used to reduce the volume of raw data, to identify themes and patterns and organise the information into a compact form without losing any information content. There are several procedural suggestions for content analysis but no systematic rules exist. However, the used analysis approach should be systematic and transparent. The research approach used in the analysis was abductive, meaning that the analysis was a continuous interplay between the theory and the empirical data. Thus, the findings were based on both prior theory and the empirical research.

The data analysis started with a review of the field notes to develop an initial coding scheme. In case of unclear field notes, the interview tapes were listened tp again to supplement the notes. The coding was used to identify themes arising from the interview data. In parallel with this, a semi-structured interview guide was used to discover linkages between the theory and the interview data. The emerging themes that were not discussed in the state-of-the-art review led to a search for new theories supporting these findings. Finally, the identified themes were grouped under four categories as presented in table 11.3. This categorization formed the basis for presenting the interview results. Direct quotations were used to report the results and to provide sufficient descriptions of the phenomena. To accomplish this, the interview tapes were listened to once again.

Table 11.3 Identified themes

	Categories			
	Implementation of the system	**Frequency and purpose of use**	**Positive experiences**	**Challenges and proposals for improvement**
Themes	- Participation to the development work	- Amount of use	- Usability of the system	- Lack of time
	- Training	- Purpose of use	- Identified capabilities of the system	- Easier access to the information
	- Other organisational support	- Benefits gained from use		- Lack of trust
		- Intentions of future use		- Improvements to the interface
		- Purchasing intentions		- New features

11.2. Results

This chapter presents the results of the interviews. The results are introduced in the following paragraphs under four categories; implementation of the system, frequency and purpose of use, positive experiences and challenges and proposals for improvement.

11.2.1. Implementation of the system

During the implementation of the PEMMS, approximately one hour training session to the use of the system was organised in each of the three buildings. All the interviewees, apart from one, had participated in this session. The training included an introduction to the system and an outline of the system features and capabilities. After the session, usernames and passwords were sent to the users by email so that they could familiarize themselves with the system. Most of the interviewees thought that this kind of short introduction to the system use was sufficient and that the best way to learn is by doing.

> *"In my opinion the training was sufficient at this point... you cannot learn so much at one time...it is easier if you familiarize yourself with the system, then you can ask more and understand better what it is about."*

> *"I thought that it (the training) was good...it is good that the training is short so that too much information is not given...usually you learn*

by doing…I believe that everyone can figure out themselves how the system works in detail."

"The system is extremely clear. The only thing that is needed is to go through what the terms mean"

However, two interviewees would have also wanted written training materials, such as instructions, manuals or hand-outs. As one of them stated:

"…some kind of manual, what the system enables and how you find it. You cannot remember everything after the training."

In addition to the system training, no other organisational support was mentioned during the interviews. None of the interviewees participated in the development of the PEMMS.

11.2.2. Frequency and purpose of use

All the interviewees had used the PEMMS one to three times. The use of the system was voluntary and words, such as testing or experimenting, were used in describing the system usage.

"I have only tested it (the PEMMS) a few times"

"I have just familiarized myself with it (the PEMMS)."

In one of the buildings where the PEMMS had been in use for only a short time (the interviewees had received the access to the system for 4 to 8 weeks before the interview), the aim was to test the system for a short period and then make decisions regarding how the system will be utilized in the future. However, in the other two buildings where the PEMMS was introduced several months ago (the interviewees had received access to the system 29 to 39 weeks before the interview), the system had remained in test use and was not taken into operative use.

During the use of the system, few abnormal performance values had been noticed. However, no actions had been carried out to find the causes for these anomalies. For example, one of the interviewees said:

”I viewed the HVAC performance metrics, why is there good and poor air handling units? I took a glance at the spaces as well, how they are performing. It gave me good information. It was quite warm in there... the reason is not known...it has not yet been sorted out. It would require going to the site.”

As the use of the system was limited to testing, no actual benefits were gained with the help of the system. No faults were corrected or energy efficiency or indoor conditions improved.

Observations during the interviews supported the fact that the PEMMS had been used only a few times by the interviewees. Most of the users did not fully remember where each report was located or what would happen when pressing on some of the icons. The two energy consultants interviewed were an exception to this. Although the consultants had used the PEMMS two or three times, they used the system in a routine manner. Both of them had even found performance metric calculation errors which had not been noticed by the system developers.

All the interviewees believed that they would use the PEMMS in the future. However, it was not clear how often they would use it. Two of the interviewees said that they will probably use the system once or twice a month whereas the others stated something more undefined and could not specify more clearly their future use. As one of the latter ones answered:

”I suppose I will use it...I have a link to it on my computer. From there I can find it.”

Four of the interviewees were in a position to make investment decisions and to them the last question “Do you intend to purchase similar kind of systems in the future?” was presented. One of the decision makers was so satisfied with the PEMMS that he was ready to order the system for other buildings as well. Two other interviewees wanted to gather more experience with these kinds of systems and one said that he presumably will not invest more in these systems in the future.

11.2.3. Positive experiences

The end user feedback was very positive concerning the usability of the PEMMS. The interviewees were satisfied with the system interface and described it as:

“In my opinion this makes common sense. You can quickly see if everything is fine and if not then you can search what might be the problem behind it.“

“I think that this is clear... this front page. There is no unnecessary information on the front page. You can see certain things at a glance”

”In my opinion this is very easy (to use). And then this is also very clear. This is not too complicated... even a stupid can understand this. You don’t need to be a technical expert to understand this.”

All the interviewees, regardless of their position in the operation and maintenance organisation, thought that they could utilize PEMMS as a part of their work. The interviewees identified that the system provides several capabilities. In their opinion the system could be used for monitoring building performance, optimizing operation, detecting faults before they affect indoor conditions and assessing the impacts of corrective measures on building performance.

“The more devices in the building the better this (the PEMMS) services is…when there is a large number of devices, it is difficult to see the overall performance...some things can go unnoticed, there may not be alarms but still the process does not work optimally…this (the PEMMS) definitely assists...you can drill down to see what is wrong.”

“This is a monitoring application”

“The history information is good. If something is creating problems all the time and if actions are taken to fix it, you can easily see what kind of affect it has on performance …The system provides advantages if you can predict things and you don’t need to hurry only after someone comes to complain. This would be good customer service…This is a tool of the future for maintenance men. It is about predicting things…”

11.2.4. Challenges and proposals for improvement

Many of the PEMMS users stated that they lacked time to use the system. In today's hectic work environment with numerous information systems it can be hard to find time for a new system, such as PEMMS. It was also mentioned that even the existing systems are not fully utilized or used at all. For example, one of the interviewees pointed out that:

> *"The Computerized Maintenance Management Systems are often not updated...all the documents are not included...this is very common."*

On the other hand, it was noted that the lack of time cannot be an obstacle to the use of PEMMS since the system provides a quick overview of the building's performance. It takes only a few seconds to view the front page of the system to check whether something is wrong with the building.

In order to be used in the hectic work environment, many interviewees suggested that easier access should be provided to receive performance metric information. Although the PEMMS can be accessed by a web browser and the front page of the system provides a fast picture of the building's performance, the users perceived that the information was not easy enough to obtain. Since the interviewees had only used the system a few times, they had difficulties in remembering the web site address, usernames as well as passwords. The interviewees stated that the performance reports should be accessible from those applications that they would otherwise use in their daily work, such as email or the Computerized Maintenance Management System (CMMS). At least the front page performance metrics should be accessible via these applications so that they could be quickly viewed while performing other work tasks. Another proposal was to receive notifications of poorly performing devices via email to avoid unnecessary logins to the system. Currently the user may login to the system to see that everything is well in the building but by receiving performance alarms the system would only be used in abnormal situations. The idea would be to devote time to the system only in situations when the performance differs from the expected.

> *"Alarm limits, you would get alarms to email stating that the performance has dropped under 50 percent or whatever the limit is."*

> *"The thing that would be needed and would be efficient is reporting once a month to email...it would be handy, you wouldn't need to login to the system."*

“If the system had an alarm feature… stating that something is wrong now…without login in to the system”

In addition to system access difficulties, some of the interviewees did not fully trust the PEMMS. The performance metric idea was new to the users and they did not entirely understand what the metrics meant and what they could enable.

”I have just familiarized with the system and all these (calculation principles) have not entirely opened up to me.”

“It (the PEMMS) could be useful when you start to understand how the system functions and you begin to trust it.”

Another issue affecting the trust was the system’s limited capability to measure building performance. As discussed in the previous chapter the PEMMS has several limitations and some of these were also noticed by the interviewees. The limitations that the users identified were associated with indoor condition measurements and PEMMS inability to take into account exceptional process operating modes. Although the indoor air temperature shown by the automation system or the PEMMS seems to be on a good level, it does not guarantee that the building occupants are satisfied with it.

”The outdoor temperature determines how people perceive indoor conditions…there are those people that think 22 °C is cold…we cannot go and say that this temperature is good.”

”It is not able to interpret all, in all possible ways…for example does the night cooling or heating work as it is supposed to”

Few proposals were given to improve the interface and the usability of the PEMMS. Most of these were connected to trending. The interviewees commented that this part of the reporting should be made more user-friendly.

”I would see that there is much to improve with the trending features…when I open this trend page, it does not tell me anything…some of the features were such that I did not even notice that something had happened.”

“Then the trending could be more user-friendly...the possibility to display more plots at a time...the x-axis could scale automatically”

Some new features were suggested to the system during the interviews. They were for example:

”Question marks could include information about the air handling units, such as the size of the unit”

“Floor plan pictures could show which areas each air handling unit serves”

“The system was sometimes slow to use. Could it be faster?”

“When you click a trend, could it be opened in another window?”

“Could the indoor air temperature be viewed from an energy efficiency perspective in the floor plan reports?”

11.3. Discussion of the results

This section outlines and explains the results of the interviews. The results are also related to previous theories. The section ends with a discussion on the future implications as well as on the reliability and validity of the research method.

11.3.1. Present use of the system

The PEMMS was in test use in each of the studied buildings. The idea of presenting building performance as performance metrics was new to the users and they wanted to gain experiences with the system. In one of the buildings where the system was just taken into use, the aim was to test the use of the system and then make decisions on how to utilize it in the future. Thus, it was understandable that the system was not utilized more thoroughly in this case. However, the PEMMS had stayed in test use in the other buildings as well, although the users had received access to the system several months ago.

Despite the fact that, there were no significant differences in the frequency of use (varied between one to three times), there were probably differences in the thoroughness of use. For instance, the interviewed energy consultants were able to discover errors with the performance metric calculations, though they had only used the PEMMS a few times.

The users had not utilized the PEMMS more frequently although they were satisfied with the system in general. The users identified the capabilities of the system and thought that the user interface of the system was easy to use and suitable for non-technical users as well. The users also recognised several useful features of the system, such as the ability to see the overall performance of the building at a glance and the possibility drill-down into detailed information if necessary. All the interviewees also thought that they could utilize PEMMS as part of their work in either building performance monitoring or management.

Since the use of PEMMS was limited to testing and experimenting, no actual benefits were gained with the help of the system. When comparing the results of the interviews with the DeLone and McLean model of success presented in chapter nine, it should be noticed that the success of PEMMS was limited to good user satisfaction. Although the users were satisfied with the system, it did not lead to any individual or organisational impacts. It is not unusual that information systems are under-utilized or left unused. As discussed in chapter five, despite the benefits of fault detection and diagnostics systems they have not been adopted by the building sector at large. In addition, the beginning of chapter nine provided examples of failed information systems and the end of the same chapter described why building automation systems are not fully utilized. Furthermore, one of the interviewees mentioned that computerized maintenance management systems can be left unused.

11.3.2. Challenges and proposals for improvement

The fact that the PEMMS was used relatively little has certainly had an effect on the identified challenges and proposals for improvement that the users mentioned during the interviews. An in-depth analysis of the systems usage is difficult to make based on just one to three instances of use. On the other hand, the feedback from the interviewees which presented their first impressions of the system can be valuable as well. The same kind of challenges came up in almost every discussion. The main challenges were associated with accessibility, trust and management practices. The first two challenges were directly mentioned by the interviewees themselves but the third was more based on the author’s interpretations and prior studies. All three challenges with proposals for improvement are discussed in detail in the following paragraphs.

11.3.2.1. *Information accessibility*

Many of the interviewees wished that the performance metric information could be easier to access. In today's hectic work environment, information should be accessible as convenient and fast as possible. The interviewees were struggling to manage with numerous information systems and therefore had problems within finding the PEMMS and authenticating to it.

The fact that the interviewees highlighted the importance of accessibility was not surprising. Numerous information science studies have shown that accessibility is the factor that influences most when selecting information sources (Allen 1977, O'Reilly 1982, Rice & Shook 1988). Information seekers tend to choose information sources that are obtained with the least effort. However, there are various interpretations of the accessibility concept. Bronstein (2010) found five meanings for accessibility in her study and of these three were also supported by earlier studies. The three elements were ease of use, time saving and physical proximity. With ease of use she meant user friendly and easy to use interfaces, with time saving the time spent accessing the information needed and with physical proximity the convenience of accessing information. To the PEMMS users the most challenging accessibility element was physical proximity as they had difficulties in remembering the PEMMS web site address and usernames as well as passwords.

To overcome the accessibility difficulties the users proposed that the performance reports or at least the front page of the PEMMS should be accessible from those applications that they would otherwise use in their daily work, such as email or the Computerized Maintenance Management System (CMMS). Another suggestion was to receive performance alarms of poorly performing devices so that time could be devoted to building performance issues only when the performance deviates from the expected. These wishes are in line with the findings of prior studies as the users would like to obtain information as easily as possible.

Probably because the interview questions concentrated around PEMMS, the interviewees suggested that the PEMMS should resolve the difficulties with accessibility. However, the problem could be solved with organisational procedures as well. For instance, one person in the operation and maintenance organisation could be responsible for the use of the

PEMMS and he or she could print performance reports for weekly or monthly meetings as well as inform the necessary people in case of anomalies. All the parties would receive performance information in a convenient way and response to performance deviations would be secured.

Although the importance of information accessibility is known is the field of information science, it has been overlooked in the context of building performance visualisation and fault detection and diagnostics tools. Many of these tools, such as the tools described in the studies of Friedman and Piette (2001), Motegi and Piette (2003) and Granderson et al. (2009), have aimed at providing building performance information on a web page. The challenge so far has been in creating a system that collects performance data, processes it into information and presents the information on the web. In this setting, challenges have been confronted, for instance, with data acquisition and quality (Brambley et. al 2005a, Granderson et al. 2009, Lehrer and Vasudev 2010 and Neumann & Jacob 2010). However, the findings of this study suggest that the system users may not be satisfied with a web portal dedicated to displaying performance information. The users do not want a new system as they are struggling to manage with numerous existing ones. Instead, the users would like to receive information as easily as possible preferably to applications that they would otherwise use in their daily work.

11.3.2.2. *Trust to the system*

All the interviewees did not fully trust the PEMMS. To some of the users, the whole concept of performance measurement was new and others did not entirely understand what the metrics meant. In addition, some users commented that the system had only limited capabilities in terms of assessing building performance. The system was not able to take account of all operating modes or able to measure all aspects of building performance. As mentioned in chapter five, a similar lack of trust has been one of the reasons why only a few solutions based on intelligent algorithms, such as artificial intelligence and neural networks, have proceeded to commercial products (Hirvonen & Ventä 2009). These solutions are often neglected in practice since they are seldom transparent or well understood in field use.

The users did not themselves suggest any methods to solve the lack of trust challenge. However, the challenge could certainly be addressed by educating the PEMMS users and by improving the performance measurement features of PEMMS. Training and education could provide a deeper understanding of the possibilities and capabilities of performance measurement. On the other hand, the limitations of the PEMMS could be reduced by developing the system further to take into consideration other aspects of building performance.

11.3.2.3. *Management practices*

Although the accessibility of the PEMMS could be improved to meet the users' requirements, it still would not guarantee that the performance reports provided by the system would be utilized in improving building performance. Turning information into actions and improvements requires management practices that support the performance measurement philosophy. PEMMS is only one part of a larger entity which aims at improving building performance.

Signs of above mentioned management practices could not be observed in the studied buildings. The PEMMS was used only for test purposes to see how the system works and therefore there were no changes in managerial practices or in ways of working. However, to achieve better building performance, the working procedures should change as well. The PEMMS itself does not improve building performance, it only enables the improvements. A similar lack of management practices supporting performance improvements has been reported in the field of building performance visualization and fault detection and diagnostics tools. Although, most of the studies in this field have focused on technical aspects some have also described managerial and organisational challenges. For instance, Katipamula et al. (2003) stated that the benefits of fault detection and diagnostics tools will not be realized if the building staff are not able to use their control systems to correct problems, are too busy with other duties or lack resources to obtain help from control contractors. In addition, Neumann and Jacob (2010) reported of organisational problems in implementing ongoing commissioning tools. According to them, ongoing commissioning approach requires a dedicated team, clarification of responsibilities and an action management plan to gain achievements. The importance of managerial practices and organisational issues were also emphasized in information system literature. The beginning of chapter 8 discussed how a change in technology will affect people, task and structures in the organisation. Later in the same chapter Venkatesh et al. (2003) described the importance of organisational infrastructure to the acceptance of information systems and Mahmood et al. (2000) explained how organizational attitude and support affect user satisfaction.

In order to achieve improvements in building performance, the same management practices that are utilized in other fields of performance management could be used. For instance, management methods used in energy performance measurement could provide a good starting point since there is a long history of conducting energy performance measures. The management principles and the lessons learned in energy performance management could now be applied to other fields of building performance. There are several guides that discuss implementing energy performance management practices and one of them is by the Office of Energy Efficiency of Natural Resources Canada (NRCan 2003). According to the guide, a successful energy management program requires:

- The management's understanding and commitment
- Company policies, directives and organization
- Program responsibilities
- Procedures and systems
- Project selection and focus
- Approved budget
- Approved investment criteria
- Training
- Integrated information systems
- Reports on savings achieved
- Motivation
- Marketing

As can be seen by looking at the above list, only a few of the elements of success are related to technology. Yet, the technology part is important since it enables the whole management program.

It is stated in the same guide that results can be achieved only if the whole organisation, from the board of directors, the president, senior management, operational staff and administration, is committed to the program (NRCan 2003). Considering this, tools such as the PEMMS, which provides information to all levels of the operation and maintenance organisation, could have better possibilities to succeed than tools meant merely for operative use. The prior building performance visualisation and fault detection and diagnostics tools have used various visualisation methods, such as time series, scatter and carpet plots, to provide performance information for technical users on the operative level of the organisation whereas the PEMMS displays the performance information in an easily understandable format that can be utilized by the whole organisation in both building performance management and monitoring. As everyone in the operation and maintenance organisation can use PEMMS as part of their work, it provides excellent support for a building performance management program.

11.3.3. Future implications

Although the PEMMS was considered to have several positive features, it was used for testing and experimental purposes. In order to be accepted as part of everyday work, the challenges described in the previous paragraph should be addressed. Some of the challenges were proposed to be solved with technological solutions and others with education, procedures and management practices. The suggested technological solutions are such that they can be constructed by using existing information technology. Therefore, the challenges associated with technological developments are quite easily answered. However, the challenges that require changes to working methods are more difficult to answer and will take a longer period to be solved. Although one could take example from other areas of performance management, accomplishing changes in the field of building operation and maintenance can be especially difficult since, as was noted at the beginning of the study, the maintenance of buildings has been considered to be the "Cinderella" of the building industry. Achieving changes can also be challenging because building performance measurement and tools, such as the PEMMS, are not necessary for the functioning of the building as they aim at optimizing operation and predicting faults. In order to attain the required changes, close co-operation is needed with the users of the PEMMS

11.3.4. Evaluation of the research

In this part of the thesis, qualitative research methods were used to investigate the users' opinions of the solution. In qualitative research, there are no common criteria to evaluate the quality of the research (Patton 2002). Validity and reliability, as they are understood in quantitative research, are not suitable for evaluating qualitative research (Eskola & Suoranta 2000). According to Eskola and Suoranta (2000) the starting point for the evaluation is to acknowledge the subjectivity of the qualitative research and admit that the researcher is a central tool in his or her research. Due to the subjectivity, the research process and the practices of transforming data into results and findings should be carefully reported. In addition, the researcher should report his or her background and role in the research so that others can consider the potential influence on the study results. (Kaplan & Maxwell 2005).

This chapter has aimed at providing sufficient information for the reader to follow the different steps of the qualitative research process used in this study. The chapter began with an introduction and a justification of the research method. This was followed by a presentation on the data sources and their background. In addition, the data collection and analysis procedures were described in detail so that the logic of turning data into research findings could be followed. Finally, direct quotations were used in reporting to link the interview data into results.

The author of this thesis was responsible for all the steps in the qualitative research process. He worked for the Finnish building services company where the research was conducted and led the development of the PEMMS. The author had lead the PEMMS training session in all the three studied buildings and he knew eight of the interviewees beforehand. Since many of the interviewees knew the author, they may have told things that they would not have said to a stranger. On the other hand, the interviewees may have given replies that they ought to give because they did not want to insult the author and his development work, namely the PEMMS.

Mäkelä (1990) represents another method of evaluating qualitative research. He argues that qualitative analysis can be evaluated using four criteria; the significance of the data and the social and cultural context of it, the sufficiency of the data, the scope of the analysis and the assessability and repeatability of the analysis. The first criterion tries to answer the question: “Why is the data significant and worth analyzing?”. In this study, only persons with access rights to the PEMMS version presented in the chapter 10 were asked to participate to the interviews. Thus, the selected interviewees were potential users of the system and able to describe their use experiences. The second criterion evaluates the sufficiency of the research data. According to Mäkelä (1990) there are no exact measures for assessing the sufficiency of data. However, he states that it has become a tradition to continue the data gathering until additional data samples do not provide new perspectives to the studied phenomenon. Although only ten persons were interviewed during this study, there were several similar themes that recurred throughout the interviews. This suggests that some level of saturation of data was reached in the interviews. The third criterion evaluates whether the analysis is based on incidental extracts or thorough analysis. To avoid the former, the interviews were listened and read through several times. In addition, support for the interview findings was searched from the prior literature. The last criterion is related to the transparency of the research process. According to Mäkelä (1990), the assessability means that the reader is capable of following the interpretations of the researcher and the repeatability that applying the same categorisation and interpretation principles another researcher would come to the same research results. To improve the transparency of this study, the different steps of the research process were described thoroughly. Also, direct quotations were used so that the reader either accept the researcher's interpretations or challenge them.

In addition to the previous criteria, the confirmability of the qualitative research can be evaluated (Eskola & Suoranta 2000). Confirmability refers to the degree of which the research results are confirmed by previous studies. In this study, all the main findings were confirmed to some degree by other studies. The contributions of this study are in that some of the findings were not confirmed with studies on the same field rather than on another field of science.

12. Conclusions

This chapter, the final chapter of the study, addresses the research questions presented at the beginning of the dissertation. The chapter also summarizes the research results as well as compares them with previous studies. The chapter as well as the study ends with an evaluation of the research findings and makes suggestions for future research and development.

12.1. The solution for continuous building performance measurement

The first research question was stated as: “What kind of solution for continuous building performance measurement transforms building automation data into a set of performance metrics describing building performance from multiple perspectives?”

12.1.1. Outline of the solution

The first question was addressed in chapter 10 by constructing a performance monitoring and management system that utilizes automation data from real buildings. The solution was based on the state-of-the-art review and on the lessons learned from the earlier studies as described in chapter 10.4.2. The constructed solution is capable of:

- Presenting building performance from energy, indoor conditions and HVAC system perspectives.
- Visualizing the performance metrics in a manner that is easy and intuitive to understand also for non-technical users
- Providing high-level performance reports which enable the overall building performance to be assessed at a glance
- Offering drill-down capabilities to view detailed information behind each metric
- Providing information that can be utilized by the whole building operation and maintenance organisation in both building performance management and monitoring

12.1.2. Methods for transforming automation data into performance metrics

The beginning of chapter 10 introduced the methods of transforming building automation data into building performance metrics. The basic idea behind the transformation is that actual building automation measurements are compared with predetermined performance targets. Each performance target is based on either of the following principles:

- Target values are generally seen as representing good performance, such as targets derived from building standards or guides
- Target values represent good performance for the building or the equipment in question, such as targets presenting optimal operation or targets that can be achieved according to the equipment manufacturer

The performance targets can include one or two target values. If there is one target value for the performance metric, the metric is calculated by dividing the actual measurement by the target value. In the case of two target values, the metric is calculated by counting the time during which the actual measurements are inside the minimum and maximum target values or outside the optimal starting and ending times and dividing this time by the total measurement time. The results of the divisions are multiplied by 100 to convert metrics into percentage format. The comparison between actual measurements and target values enables performance metrics to be presented on a 0-100 percentage scale where 100 percent signifies the best performance possible. With these principles, the solution transformed automation data into energy, indoor conditions and HVAC system performance metrics. However, the same principles can be used in creating new performance metrics as well, for instance metrics describing the performance of heating and cooling systems.

Similar principles of transforming building automation data into performance metrics with multiple performance perspectives were not found in prior literature. Very few previous studies have examined the use of performance metrics in terms of continuous building performance measurement. The use of performance metrics has been rare in the field of fault detection and diagnostics tools, whilst the energy performance monitoring tools have solely concentrated on measuring and displaying energy use data. In the few studies found, Kärki and Hyvärinen (1997) presented different performance requirements for air handling units and Kärki and Karjalainen (1999) illustrated how performance factors could be used in the evaluation of AHU performance. Findings of these two studies were applied in the construction of the HVAC performance metric for the solution. In addition to the two previously mentioned studies, Choinière (2008) presented an on-going commissioning tool that utilized HVAC performance metrics as part of a used fault detection and diagnostics method. The tool he described calculated performance indices for air handling equipment, room control devices, heating circuits, cooling circuits, lighting devices and energy meters. These indices where then analysed by expert rules or the user of the system, who evaluated whether the devices worked at maximum performance. However, all the calculation methods for different indices were not fully described in the study and therefore one could not entirely understand what each performance indicator meant.

12.1.3. Building performance management and monitoring

As the solution described in this study presents the performance information in 0-100 percentage format, it can be utilized by the whole building operation and maintenance organisation in both building performance management and performance monitoring. Anyone in the operation and maintenance organisation, from top management to building operators, can use the solution to track current performance and compare it to target values or historical performances as well as to identify improvement opportunities. Even the non-technical users can use the system to observe the actual performance of their buildings. A more technical person, on the other hand, could utilize the system in monitoring building performance and optimizing building operation.

The previous studies in the field of building performance visualization and fault detection and diagnostics have focused on performance monitoring and have not taken the management aspect into account. The fault detection and diagnostics tools described in the literature (Dexter & Pakanen 2001, Friedman & Piette 2001, Visier 2004, Neumann et al. 2010) or in chapter eight of this study have visualised HVAC system performance in various ways, such as using time series, scatter and carpet plots. The tools have displayed the information in a format that has required at least some technical knowhow from its users. Many of the tools have been made to be used by maintenance men, technicians, or engineers to monitor and optimize building operation. Thus, they have been suitable for performance monitoring but not for performance management.

In addition to visualizing building performance using time series, scatter and carpet plots, some tools, especially those which are intended to be used by building occupants, have also used methods of displaying building performance. One example is smileys, which was used by the TaloInfo tool described in chapter eight. Smileys present information in a format that can be understood by non-technical users as well. However, smileys are not at their best in defining management targets. Figures and percentage values are better for this purpose.

The importance of performance management was emphasized in the energy management guide by the Office of Energy Efficiency of Natural Resources Canada (NRCan 2003). According to the guide, energy performance improvements can be achieved only if the whole organisation, from the board of directors, the president, senior management, operational staff and administration, is committed to the program. Thus, tools such as the solution in this study, which provides information for all levels of the operation and maintenance organisation, could have better possibilities to succeed than tools meant merely for operative use.

12.1.4. Challenges associated with the technical and methodological aspects

The end of chapter 10 discussed the challenges related to the solution. The challenges were associated with technical and methodological aspects of the solution. Table 12.1 summarizes the discussion.

Table 12.1 Summary of the solution challenges

Exploitability	
	- In order to display performance metrics, the solution has certain technical requirements for the building systems
Limitations	
	- By focusing on the building automation data several building performance aspects have been left outside the scope of the solution - The current three performance categories include only few performance measures
Measurement quality	
	- Performance measures may include errors, since only a small number of sensors, which can also be of poor quality, are used in HVAC applications - Indoor conditions aspect of the building performance is to some extend a subjective measure
Calculation methods	
	- Relative figures offer the opportunity to manipulate information - Finding the optimal way to construct a performance metric hierarchy
Benchmarking	
	- The solution does not support benchmarking in the best possible way

12.2. Experiences and challenges associated with the use of the solution

The other research question was determined as: "What are the experiences and especially the challenges associated with the use of this solution?"

The question was addressed in chapter 11 by interviewing ten users of the solution in three buildings. The interviews were semi-structured meaning that the interviewer had a list of predetermined questions to be asked of the respondents. This list of questions was based on the state-of-the-art review and especially addressed information system adoption and use theory. The interviews were analysed using content analysis to identify emerging themes from the interview data.

12.2.1. Current use of the solution

The solution was in test use in each of the studied buildings. In one of the buildings, the testing period had just begun and the users wanted to gain experiences with the solution before making decisions of the future use. However, the solution had stayed in test use in the other building as well, although the users had received access to the solution for several months ago.

The solution was not taken into operative use, despite the fact that the users were satisfied with the solution on a general level. The users thought that the user interface was easy to use and suitable for non-technical users as well. The interviewees had also recognised several useful features of the solution, such as the ability see the overall performance of the building at a glance and the possibility to drill-down into detailed information if necessary. In addition, all the interviewees believed that they could utilize the solution as part of their work in either building performance monitoring or management.

12.2.2. Challenges with the use of the solution

The main challenges with the use of the solution were related to accessibility, trust and management practices.

Although the solution provided the performance reports on a web page, the users were not satisfied with the accessibility of the performance information. Many of the interviewees were of the opinion that in today's hectic work environment, information should be accessible as convenient and fast as possible. Therefore, they proposed that the performance reports or at least the front page of the solution should be accessible from those applications that they would otherwise use in their daily work, such as email or the Computerized Maintenance Management System (CMMS). Another suggestion was to receive performance alarms from poorly performing devices so that time would be devoted to building performance issues only when the performance deviates from the expected. There are several information science studies (for example Allen 1977, O'Reilly 1982, Rice & Shook 1988) that support the finding on the significance of information accessibility. According to these studies, information seekers tend to choose information sources that can be obtained with the least effort. However, the studies that deal with building performance visualisation and fault detection and diagnostics tools have overlooked the importance of information accessibility. Many of the tools, such as described in the studies of Friedman and Piette (2001), Motegi and Piette (2003) and Granderson et al. (2009), aim at providing building performance information on a web page whereas the findings of the interviews suggest that the users may not be satisfied with this. They would rather receive information as easily as possible and preferably via applications that they would otherwise use in their daily work.

The second challenge was related to a lack of trust. All the interviewees did not fully trust the solution, since they did not entirely understand what the performance metrics meant or because the solution had limitations in regards to assessing building performance. Similar challenges have been confronted in regards to intelligent algorithms, such as artificial intelligence and neural networks (Hirvonen & Ventä 2009). Solutions using intelligent algorithms are often neglected in practice since they are seldom transparent or well understood in field use.

The third challenge was associated with management practices. The solution is currently used only for test purposes to see how the system works and therefore there are no changes in managerial practices or in ways of working. No management practices were observed that would support the performance information turning into actual actions and improvements. A similar lack of management practices supporting performance improvements has been reported in the field of building performance visualization and fault detection and diagnostics tools. Katipamula et al. (2003) stated that the benefits of fault detection and diagnostics tools will not be realized if the building staff are not able to use their control systems to correct problems, or if they are too busy with other duties or there is a lack of resources to obtain help from control contractors. In addition, Neumann and Jacob (2010) reported organisational problems in regards to implementing ongoing commissioning tools. According to them, an ongoing commissioning approach requires a dedicated team, clarification of responsibilities and an action management plan to gain achievements. The importance of managerial practices and organisational issues are also emphasized in information system literature. For instance, Leavitt (1965) describes how a change in technology will affect people, tasks and structures within an organisation, Alter (2002) states that technology is rarely a solution by itself and Bobby et al. (2004) note that no matter how sophisticated the information systems, they still are dependent on people to make them work. In addition, Venkatesh et al. (2003) describe the importance of organisational infrastructure when information systems are being introduced and Mahmood et al. (2000) explain how organizational attitudes and support affect user satisfaction.

12.3. Evaluation of the study

The main research approach used in this study was constructive research, which aims at solving real world problems through constructions.

According to Kasanen et al. (1993) constructions are something profoundly different than what existed before. They also state that an important characteristic of constructions is that the usability must be demonstrated through implementation of the solution.

The same general evaluation criteria used in any scientific research can be utilized to evaluate a constructive study. The research topic has to be relevant and have potential for both practical and theoretical contribution. The study has to prove that the researcher is familiar with the (potential) ex ante -theories of the research area. The research design has to be clear and fruitful and the study should be conducted so that it is credible. The study should also provide a new theoretical contribution and the research should be clearly and economically reported. In addition to these standard evaluation criteria, two additional criteria exist for constructive research. First, the result of the constructive study should be feasible, meaning that it is simple and easy to use. Secondly, the study should be conducted within close involvement and co-operation between the researcher and practitioners in a team-like manner. (Lukka 2000)

The relevance of this dissertation was emphasized in the introductory part of the study. The problem field this research addresses is the building energy efficiency requirements, building performance problems and especially the tools intended for continuous building performance monitoring. The state-of-the-art review demonstrated that the researcher had familiarized himself with the prior theories. Based on the state-of-the-art review and on the lessons learned from the earlier studies, a new solution was constructed. The solution was thoroughly described and critically analysed in chapter 10. The solution was developed with the practitioners in the field as the research was conducted in a Finnish building services company together with its customers. The solution is a commercialized product that utilizes data from real buildings. The practicality in terms of users experiences with the solution were examined in chapter 11 through the means of interviews. The results of the interviews indicated that the solution was considered to be simple and easy to use. Despite these positive experiences, the solution was used only for testing purposes and not taken into operative use. The findings of the research were linked to prior theoretical knowledge as illustrated in chapter 12. The study provided both practical and theoretical contributions as outlined in chapter 1.5.

Several actions were taken to ensure that the research meets the criteria of a scientific research. First, the research proceeded in stages, starting with the background of the research and state-of-the-art review and then proceeded to the introduction and evaluation of the new solution. This ended with a comparison between the research results and the information gained from prior literature. This provided the possibility to follow the steps of the development process as well as to see how the study was linked to previous studies. The study also described the used research methods and procedures so that the readers would gain an understanding of how the research was conducted. In addition, the findings of the study were critically analysed describing both the advantages and limitation of the solution. Furthermore, the study was written in a style that would make it easy to follow and understand. Finally, the research results will be published and evaluated by the academic community.

In addition to the evaluation criteria of Lukka (2000), Kasanen et al. (1993) state that the validity of a construct can be tested by market tests. The method is based on the concept of innovation diffusion, in which the constructions are viewed as competing in the market with other solutions. The weak market test is passed when a manager is willing to apply the construction to his or her actual decision-making. The semi-strong market test is passed if the construct is widely adopted by companies and the strong market test requires the business units applying the construction produce better results than those which are not using it. According to Kasanen et al. (1993), the market test is relatively strict and not all constructs will pass even the weakest test. When comparing user experiences of the solution with the market test requirements, it should be noted that the construct in this study barely passes the weak market test. The solution was not in regular use, but all the users believed that it could be useful in their work. Therefore, one could say that the users were willing to apply the solution.

12.4. Suggestions for future research and development

This section outlines the future implications presented in chapters 10 and 11. The implications are divided into development actions related to the created solution and research work associated with performance measurement.

12.4.1. Development

From the system developers' point of view, the first thing to do would be to address the challenges associated with the use of the created solution, namely the accessibility, trust and management practices. The technological solutions suggested by the end-users are such that they can be constructed by using existing information technology. Automating some parts of the performance measurement process could be performed quite easily. For example, an automatic notification could be sent to the user of the system when performance metric figures reach certain alarm thresholds. However, the challenges that require changes to work practices are more difficult to answer and they will take longer to be solved. Although one could take example from other areas of performance management, accomplishing changes in the field of building operation and maintenance can be especially difficult since, as was noted in the beginning of the study, the maintenance of buildings has been considered to be the "Cinderella" of the building industry. To achieve the required changes, close co-operation is needed between the users of the solution.

The current solution is primarily intended to be used by building operation and maintenance organisations. However, with minor changes the solution could provide valuable information to other users as well. One of the end-user groups could be building occupants. For instance, by providing feed-back information at the building's energy performance, the occupants could learn to use building systems more efficiently. The solution could also provide valuable feedback to building and HVAC system design on the actual building performance. With this information, design practices as well as the accuracy of simulation tools could be improved. The third group who could utilize the solution is equipment manufacturers. As the solution is capable of collecting performance data from various building systems, the data could be transformed into information that is useful for the manufactures and their product development teams.

12.4.2. Research

There is very little research done on continuous building performance measurement. The previous studies in the area have focused on energy performance measures, but as this study showed there are many other performance aspects to be measured. Several questions need to be answered in the future. For example, very little guidance is available regarding how to calculate or report measured building performance. However, before going into this level of detail in performance reporting one should note that there is not even a consensus on what performance metrics should be measured. The list of possible building performance measures is extensive as was illustrated in chapter seven. Therefore, there are still many issues to be examined in both selecting appropriate measures as well as determining methods for calculating and displaying the measures. As there are no current standard in this field, organisations and companies are developing their own solutions for performance measurement. This makes it difficult for the building owners to decide which performance measurement solution they should choose for their building as well as complicates the opportunity to compare buildings. At the moment, very little has been done in terms of evaluating and reporting measured building performance, and therefore it is evident that it takes time to find consensus in this field.

More information is also needed regarding the benefits of continuous building performance measurement. Can solutions similar to the one presented in this study aid in gaining a better overall building performance or will some other performance aspects suffer at the expense of these metrics? For example, if a building operation and maintenance organisation concentrates on these performance metrics, will it lead to a sub-optimal situation where some other performance perspectives will decrease? As mentioned earlier, we have very little knowledge on these issues and therefore more experience in the use of continuous building performance measurement is needed to answer these questions.

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Appendix A: Key building performance indicators

Key building performance indicators (adapted from Lavy et al. 2010) part 1/2

Financial		Physical		Functional		Survey-based	
Indicators	**Units**	**Indicators**	**Units**	**Indicators**	**Units**	**Indicators**	**Units**
Operating costs	$US per (1) unit area, (2) person, (3) employee or (4) product	Building physical condition - quantitative: Building Performance Index (BPI)	Measured as a 100-point scale	Productivity	(1) turnovers per year; (2) absentees per year; (3) survey-based data	Customer/building occupants' satisfaction with products or services	Survey-based data
Occupancy costs	$US per (1) unit area, (2) person, (3) employee or (4) product	Building physical condition - qualitative: general building maintenance in: (1) building physical condition; (2) sanitary, plumbing adn storm water; (3) mechanical services; and (4) lighting and electrical	Measured on a scale of good, fair, poor and unsarisfactory based on condition assessment	Parking	Number of parking spaces per person	Community satisfaction and participation	Survey-based data
Utility costs	$US per unit area	Property and real estate	Area in sq. Ft. And fraction of leased or owned area in %of total real estate	Space utilization	Survey-based data	Learning environment, educational suitability, and appropriateness of facility for its	Survey-based data
Capital costs	$US or $US per employee	Waste	Volume per year or month, $US per year or month, ton per month & $US per month; reused or recycled waste: percentage of total waste generated; disposal cost:$US per volume	Employee or occupant's turnover rate	Ratio (number of employees turned over to the total average number or employees in a given period of time) and number or turnovers per year	Appearance	Survey-based data
Building maintenance cost	$US per unit area	Health and safety	Employees' number of accidents per year, number of lost work hours, number of workers' compensation claims	Mission and vision, and Mission Dependency Index (MDI)	MDI is measured using a 100-point scale		
Grounds-keeping cost	$US per unit area	Indoor environmental quality (IEQ)	Each parameter is measured in its respective units of measurement	Adequacy of space	Survey-based data		
Custodial and janitorial cost	$US per unit area	Accessibility for disabled	Measured on the basis of level of accessibility of the facility for disabled				
Current replacement value (CRV)	$US	Resource consumption - energy, (1) energy use: total facility energy use; or building energy use; (2) net energy consumption; (3) annual energy consumption; (4) total natural gas consumption; (5) building electrical consumption; or (6) building electrical demand, demand intensity, or peak	(1) kWh, Btu or Joules; (2) kWh, Btu or Joules; (3) kWh or KVA, kWh or kVA per unit area per hour, or kWh or KVA per person per hour; (4) kBtu per unit area, kBtu per person, or threms per year; (5) kW or kVA; (6) kWh per sg.ft or kVA per sq.ft., kW or kVA				

Key building performance indicators (adapted from Lavy et al. 2010) part 2/2

Financial		Physical		Functional		Survey-based	
Indicators	Units	Indicators	Units	Indicators	Units	Indicators	Units
Deferred maintenance and deferred maintenance backlog	$US	Resource consumption - water: (1) water consumption; or (2) net water consumption	(1) Total building water use; (2) Total water consumption minus reused, recycled and treated water				
Capital renewal	$US	Resource consumption - materials: (1) material consumption; or (2) net material consumption	(1) Quantity of total material used in the process of operation and /or production; (2) Total material consumption minus waste, reused, and recycled material				
Maintenance efficiency indicators (MEI)	MEI values can be divided into three ranges: low, reasonable, and high, based on the actual investment in maintenance, compared to the actual performance of the building	Security	Describes the condition of security and effectiveness of security measures in the facility or organization				
Facility condition index (FCI)	Percentage of CRV	Site and location	Characterictis of facility's site in terms of sixe, location, safety, sound and quality, accessibility, contours, preservation and development				
Churn rate and churn costs	Expressed as percentage of total average employees in a specific time period or in currency						

Appendix B: Energy performance metrics

Energy performance metrics (adapted from Fowler et al. 2010)

Level 1	Level 2	Level 3	Level 4	Reporting Units
Total Building Energy Use				kBtu/ft2, total & itemized by fuel type
Total Building Energy Cost				cost/ft2, total & itemized by fuel type
	Indoor Energy Use			kBtu/ft2, total & itemized by fuel type
	Indoor Energy Cost			cost/ft2, total & itemized by fuel type
		Lighting Energy Use		kWh/ft2
			Installed Lighting Energy Use	kWh/ft2, kWh/occupant
			Plug-in Lighting Energy Use	kWh/ft2, kWh/occupant
			Facade Lighting Energy Use	kWh/ft2 of facade area
		HVAC Energy Use		Btu/ft2, Btu/occupant, total & itemized by fuel type
			Pump Energy Use	Btu/ft2, Btu/occupant
			Fan Energy Use	Btu/ft2, Btu/occupant
			Exhaust Fan Energy Use	Btu/ft2, Btu/occupant
			Chiller Energy Use	Btu/ft2, Btu/occupant
			Boiler Energy Use	Btu/ft2, Btu/occupant
			Reheat Coil Energy Use	Btu/ft2, Btu/occupant
			Packaged HVAC Energy Use	Btu/ft2, Btu/occupant
			Heat Rejection Energy Use	Btu/ft2, Btu/occupant
			Purchased Chiller Water Energy Use	Btu/ft2, Btu/occupant
			Purchased Steam Energy Use	Btu/ft2, Btu/occupant
			Air Compressor Energy Use	Btu/ft2, Btu/occupant
			Freeze Protection Energy Use	Btu/ft2, Btu/occupant
		DHW Energy Use		Btu/occupant, Btu/gal
		People-mover Energy Use		kWh/mover
			Elevator Energy Use	kWh/mover
			Escalator/Moving Sidewalk Energy Use	kWh/mover
		Refrigeration Energy Use		kWh/ft2
			Refirgeration Compressor Energy Use	kWh/ft2, kWh/occupant
			Refirgeration Condenser Energy Use	kWh/ft2, kWh/occupant
			Refirgeration Evaporator/Case Fan Energy Use	kWh/ft2, kWh/occupant
			Refirgeration Case Lighting Energy Use	kWh/ft2, kWh/occupant
			Refirgeration Defrost Energy Use	kWh/ft2, kWh/occupant
			Refirgeration Anti Sweat/Door Heater Energy Use	kWh/ft2, kWh/occupant
		Cooking Energy Use		kWh/ft2
		Dishwasher Energy Use		kWh/ft2
		Plug Load Energy Use		kWh/ft2, kW/ft2
		Data Center Energy Use		kWh/ft2, kW/ft2
		Other Building Energy Use		kWh/ft2, kW/ft2
			Swimming Pool (hot water) Energy Use	Btu/ft2, Btu/occupant
			Swimming Pool (pump) Energy Use	Btu/ft2, Btu/occupant
			Water Feature Pump Energy Use	Btu/ft2, Btu/occupant
			Water Treatment Energy Use	Btu/ft2, Btu/occupant
			Laundry Energy Use	Btu/ft2, Btu/occupant
		Industrial Process Energy Use		Btu/unit production
		Cogeneration Fuel Use		Btu/ft2
		Cogeneration Electrical Output		kWh/ft2
		Cogeneration Thermal Output		Btu/ft2
			Cogeneration Losses	% loss/total energy
	Outdoor Energy Use			kBtu/ft2, total & itemized by fuel type
	Outdoor Energy Cost			cost/site area
		Parking Lot Lighting Energy Use		kWh/site area, kW/site area
		Walkway Lighting Energy Use		kWh/site area, kW/site area
		Sign Lighting Energy Use		kWh/site area, kW/site area
		Landscape Lighting Energy Use		kWh/site area, kW/site area
		Outdoor Swimming Pool Energy Use		kWh/site area
	Landscape Energy Use			Btu/site area
	Landscape Energy Cost			cost/site area
		Motorized Equipment Energy Use		fuel gal/site area
		Electric Equipment Energy Use		kWh/site area

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