Doctoral thesis

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Real-time supervision of building HVAC system performance

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ABSTRACT

This thesis presents techniques for improving building HVAC system performance in existing buildings generated using simulation-based tools and real data. Therefore, one of the aims has been to research the needs and possibilities to assess and improve building HVAC system performance. In addition, this thesis aims at an advanced utilization of building energy management system (BEMS) and the provision of useful information to building operators using simulation tools.

Buildings are becoming more complex systems with many elements, while BEMS provide many data about the building systems. There are, however, many faults and issues in building performance, but there are legislative and cost-benefit forces induced by energy savings. Therefore, both BEMS and the computer-based tools have to be utilized more efficiently to improve building performance.

The thesis consists of four main parts that can be read separately. The first part explains the term commissioning and the commissioning tool work principal based on literature reviews. The second part presents practical experiences and issues introduced through the work on this study. The third part deals with the computer-based tools application in design and operation. This part is divided into two chapters. The first deals with improvement in the design, and the second deals with the improvement in the control strategies. The last part of the thesis gives several rules for fault diagnosis developed using simulation tools. In addition, this part aims at the practical explanation of the faults in the building HVAC systems.

The practical background for the thesis was obtained though two surveys. The first survey was carried out with the aim to find the commissioning targets in Norwegian building facilities. In that way, an overview of the most typical buildings, HVAC equipment, and their related problems was obtained. An on-site survey was carried out on an example building, which was beneficial for introducing the building maintenance structure and the real hydronic heating system faults.

Abstract

Coupled simulation and optimization programs (EnergyPlus and GenOpt) were utilized for improving the building performances. These tools were used for improving the design and the control strategies in the HVAC systems. Buildings with a hydronic heating system were analyzed for the purpose of improving the design. Since there are issues in using the optimization tool, GenOpt, a few procedures for different practical problems have been suggested. The optimization results show that the choice of the optimization functions influences significantly the design parameters for the hydronic heating system.

Since building construction and equipment characteristics are changing over time, there is a need to find new control strategies which can meet the actual building demand. This problem has been also elaborated on by using EnergyPlus and GenOpt. The control strategies in two different HVAC systems were analyzed, including the hydronic heating system and the ventilation system with the recovery wheel. The developed approach for the strategy optimization includes: involving the optimization variables and the objective function and developing information flow for handling the optimization process.

The real data obtained from BEMS and the additional measurements have been utilized to explain faults in the hydronic heating system. To couple real data and the simple heat balance model, the procedure for the model calibration by use of an optimization algorithm has been developed. Using this model, three operating faults in the hydronic heating system have been elaborated.

Using the simulation tools EnergyPlus and TRNSYS, several fault detection and diagnosis (FDD) rules have been generated. The FDD rules were established in three steps: testing different faults, calculating the performance indices (PI), and classifying the observed PIs. These rules have been established for the air cooling system and the hydronic heating system. The rules can diagnose the control and the component faults. Finally, analyzing the causes and the effects of the tested faults, useful information for the building maintenance has been descriptively explained.

The most important conclusions are related to a practical connection of the real data and simulation-based tools. For a complete understanding of system faults, it is necessary to provide

real-life information. Even though BEMS provides many building data, it was proven that BEMS is not completely utilized. Therefore, the control strategies can always be improved and tuned to the actual building demands using the simulation and optimization tools. It was proven that many different FDD rules for HVAC systems can be generated using the simulation tools. Therefore, these FDD rules can be used as manual instructions for the building operators or as a framework for the automated FDD algorithms.

SAMMENDRAG

Denne avhandlingen presenterer noen fremgangsmåter for forbedring av ytelser for VVS-tekniske anlegg i eksisterende bygninger basert på bruk av simuleringsverktøy og virkelige måledata. Ett av målene har vært å undersøke behov og muligheter for vurdering og forbedring av ytelser for VVS-anlegg i bygninger. I tillegg har denne avhandlingen hatt som mål å fremme bruk av SD-anlegg samt å fremskaffe nyttig informasjon til driftspersonalet.

Bygninger blir stadig mer kompliserte systemer som inneholder flere og flere komponenter mens SD-anlegg håndterer en stadig større mengde data fra bygningsinstallasjoner. På den ene siden registreres det ofte feil og problemer med hensyn til ytelsene til de VVS-tekniske installasjonene. På den andre siden innføres det stadig strengere lovmessige pålegg og kost-nyttekrav motivert i energieffektiviseringen. SD-anlegg og databaserte verktøy bør derfor brukes mer effektivt for forbedring av ytelsene.

Avhandlingen består av fire hoveddeler hvor hver del kan leses separat. Den første delen, som er basert på literaturstudie, forklarer funksjonskontroll som begrep og prinsipper for oppbygging av verktøy for funksjonskontroll. Den andre delen presenterer praktisk erfaring og problemstillinger utviklet og behandlet i løpet av arbeidet med avhandlingen. Den tredje delen handler om anvendelse av databaserte verktøy for forbedring av ytelsen for VVS-tekniske installasjoner. Den tredje delen er delt opp i to kapitler, hvorav et handler om forbedring av systemløsninger og et om forbedring av styringsstrategier. Den siste delen presenterer flere regler for feilsøking og diagnostisering utviklet gjennom bruk av simuleringsverktøy. I tillegg gir denne delen en praktisk forklaring av feilene i de VVS-anleggene som er behandlet i undersøkelsen.

Det praktiske grunnlaget for avhandlingen er etablert gjennom to undersøkelser. Den første var en spørreundersøkelse som hadde til hensikt å kartlegge målsetninger for funksjonskontroll i norske bygninger. Gjennom dette ble det etablert en oversikt over de mest typiske bygninger med tilhørende VVS-anlegg og de mest forekommende problemene. En dypere undersøkelse ble utført på ett casebygg. Denne undersøkelsen viste seg å være nyttig både for kartlegging av betydningen

av organisering av driften av bygningen og for avdekking av de virkelige feilene i det vannbårne oppvarmingssystemet.

En kobling mellom et simulerings- og et optimaliseringsprogram (EnergyPlus og GenOpt) har vært benyttet for forbedring av ytelsene for de VVS-tekniske installasjonene. Disse verktøyene har vært brukt for forbedring av både systemløsningene og styringsstrategiene for VVS-anlegg. Bygninger med vannbåren oppvarmingssystem har vært analysert for å forbedre systemløsningen. På grunn av begrensninger i bruken av optimaliseringsverktøyet GenOpt, har det blitt utviklet egne prosedyrer for håndtering av visse typer problemstillinger hvor denne begrensningen opptrer. Resultatene for optimaliseringen viser at valg av objektfunksjoner påvirker betydelig parametrene i det vannbårne oppvarmingssystemet.

Endringer i egenskapene til både bygningskonstruksjoner og utstyr som skjer på grunn av aldring over tiden, gjør det nødvendig med tilpassning av styringsstrategier slik at det virkelige behovet kan bli dekket. Denne problemstillingen har vært analysert ved bruk av EnergyPlus og GenOpt. Styringsstrategiene for to forskjellige VVS-anlegg, et vannbåret oppvarmingssystem og et ventilasjonsanlegg med varmegjenvinner har blitt behandlet. Den utviklete prosedyren for optimalisering av styringsstrategien består av følgende steg: innføring av optimaliseringsvariabler og objektfunksjon, samt utvikling av informasjonsflyt for behandling av optimaliseringsprosessen.

De virkelige data, både fra SD-anlegg og tilleggsmålinger, har vært benyttet for praktisk forklaring av feilene i oppvarmingssystemet. En prosedyre for modellkalibrering basert på bruk av en optimaliseringsalgoritme som kobler sammen de virkelige data og en enkel varmebalansemodell har blitt foreslått. Tre konkrete driftsfeil i oppvarmingssystemet har blitt belyst gjennom bruk av denne varmebalansemodellen.

Flere regler for feilsøking og diagnostisering har blitt utviklet ved hjelp av simuleringsverktøyene EnergyPlus and TRNSYS. Denne utviklingen har bestått av tre ulike steg: testing av bestemte feil, beregning av ytelsesindikatorer og til slutt klassifisering av de observerte ytelsesindikatorer. Reglene har blitt utviklet for et system av aggregater for luftkjøling og for et vannbåret oppvarmingssystem. Reglene kan diagnostisere både styringsfeil og komponentfeil. Til slutt

presenteres informasjon som er nyttig for drift av VVS-tekniske installasjoner i bygninger basert på en analyse av årsakene for og virkningene av de feil som er behandlet.

De viktigste konklusjonene er knyttet til praktisk kombinasjon av virkelige måleverdier og simuleringsverktøy. Informasjon fra det virkelig liv er helt nødvendig for å få en god forståelse av feil som oppstår i anlegg. Det er også vist at potensialet som ligger i alle de data som er tilgjengelige gjennom SD-anlegg, ikke er fullt utnyttet. Gjennom bruk av simuleringsverktøy kan styringsstrategiene alltid bli bedre tilpasset og innjustert til de virkelige behov i bygningen. Simuleringsverktøy kan også brukes for utvikling av prosedyrer for feilsøking og diagnostisering i VVS-tekniske anlegg. Disse prosedyrene kan brukes enten som en veileder for manuell feilsøking og detektering eller som grunnlag for utvikling av automatiserte algoritmer.

TABLE OF CONTENTS

GLOSSARY OF TERMS

This list gives the most widely used terms and abbreviations in the study.

Terms

Building automation system – BAS

Centralized control and/or monitoring system having several forms. A basic BAS may be a computer-based center for an energy management system (EMS) providing an operator interface terminal and alarm display with optional audible and/or printout. A BAS has one or more operator stations.

Building energy management system - BEMS

A building energy management system consists of one or more self-contained computer based 'outstations' that use software to control energy consuming plant and equipment and that can monitor and report on the plant's performance.

Commissioning - Cx

The process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent. Commissioning begins with planning and includes design, construction, start-up, acceptance, and training, and it should be applied throughout the life of the building.

Fault detection

Fault detection is the determination that the operation of the building is incorrect or unacceptable in some respect.

Fault diagnostic

Fault diagnosis is the identification or localization of the cause of faulty operation.

Maintenance

Maintenance in terms of time and resource allocation documents objectives, establishes evaluation criteria, and commits the maintenance department to basic areas of performance, such as prompt response to mechanical failure and attention to planned functions that protect capital investment and minimize downtime or failure. The maintenance includes people, documents, programs, etc. Actually, maintenance is a more general concept than only operating.

Operation/Operating

The system operation defines the parameters under which the building or systems operator can adjust components of the system to satisfy occupant comfort or process requirements and the strategy for optimum energy use and minimum maintenance. The operating level treats a component or a system.

Operator

The operator is enabled to request and respond to all commands from one location, and he or she uses BEMS to carry out all required actions.

Optimization

Optimization is the minimization or maximization of a function subject to constraints on its variables. The function is called an objective function that is a quantitative measure of the performance of the system under study. The optimization variables can be either constrained or unconstrained.

Performance metric

A performance metric is a standard definition of a measurable quantity that indicates some aspect of performance.

Retrofit

A retrofit is a modification of existing equipment, systems, or buildings to incorporate improved performance, updated operation, or both. The word is derived from "retroactive refit".

Computer simulation or only simulation

1. computer-aided decision process in which proposals are tested in a computer before one or more of the proposals are considered for use.

2. (general) representation of an actual system by analogous characteristics of some device easier to construct, modify, or understand.

3. (physical) the use of a model of a physical system in which computing elements are used to represent some but not all of the subsystems.

Abbreviations

Air handling unit - AHU

Building energy management system – BEMS

Energy service company - ESCo

Fault detection and diagnosis – FDD

Heating, ventilation and air-conditioning – HVAC

Operation and maintenance – O&M

Performance indices - PI

Variable air volume - VAV

LIST OF SYMBOLS AND INDEXES

Since the studies in Chapter 3 and 4 are different from the study in Chapter 5, there are some overlapping in used symbols and indexes. Therefore, the lists of symbols for these chapters are listed separately. In addition, in the text, clear explanations are given for each symbol.

List of symbols in Chapter 3 and 4

A	the insulation surface of all exterior walls, (m^2)
C	the total cost, (€/year)
C_E	the cost of energy, (€/year)
C_I	the cost of insulation, (€/year)
C_R	the radiator cost, (€/year)
c_E	the price of energy per kWh, (€/kWh)
c_p	the annual energy price for kW of installed power equipment, (€/kWyear)
c_I	the insulation price per unit of surface, $(€/m^2)$
c_{RI}	the radiator price per section, (€/section)
DD	the number of degree-days, $(^oC \cdot day)$
e	the coefficient of limitation, (-)
e_b	exploitation limitation, (-)
ES	the energy savings, (%)
e_t	coefficient of temperature limitation, (-)
n	the economic lifetime, (year)
P	the installed power, (W)
PPD	predicted percentage of dissatisfied, (%)
Q	energy consumption, (J) or (kWh)
T	temperature, (^oC)
t_i	the indoor air temperature, (^oC)
t_o	the outdoor design air temperature, (^oC)
U	the mean value of the overall heat transfer coefficient, (W/m^2K)
UA	the overall conductance of a heater, (W/K)

y the coefficient of simultaneous effect of unfavorable conditions, (-)

Indexes in Chapter 3 and 4

1,i   the inlet air before the heat recovery wheel,

2,i   the inlet air after the heat recovery wheel,

1,o   the outlet air before the heat recovery wheel,

2,o   the outlet air after the heat recovery wheel,

b   baseline,

DD   design day,

opt   optimal,

pr   post-retrofit,

rec   recovery.

List of symbols in Chapter 5

C the vector of the model parameters,

C_b the overall conductance of walls, (W/K)

C_r the overall conductance of the radiator, (W/K)

dH_{pump} the first derivative of the pump head over the water flow rate, $(Pa/(m^3/s))$

Δp the pressure difference, (Pa)

E a building performance,

H_{pump} the pump head, (Pa)

$k_{v,i}$ the flow resistances of the ith control valve, (-)

n total number of the time steps, (-)

$(ON/OFF)_i$ the system status of ith coil,

PI performance index, (%)

Q energy consumption, (kWh)

$\dot{Q}_b$ the heat loss of the zone, (W)

Q_r the radiator energy consumption, (kWh)

$\dot{Q}_r$ the heat capacity of the radiators in the zone, (W)

Q_v	the ventilation system energy consumption, (kWh)
$\dot{Q}_v$	the heat capacity of the ventilation system, (W)
$q_{wf,i}$	water flow rate of the ith coil, (kg/s)
T	temperature, (°C)
$val_{pos,i}$	the valve opening of ith valve, (-)
X	the input vector,
Y	the output vector.

Indexes in Chapter 5

fault	system state with a fault,
hr	heating return branch,
hs	heating supply branch,
i	the time step,
in	indoor,
j	the zone index,
k	an element index,
m	model,
max	maximum,
m,run period	model output over run period,
no_fault	system state without faults,
out	outdoor,
P	index for the pump rate performance index,
Q	index for the heat rate performance index,
r	real data,
set	set value,
T	index for the temperature performance index,
TOA	the temperature of the outlet air,
t	hot tap water heating branch,
v	ventilation.

LIST OF FIGURES

LIST OF TABLES

1   INTRODUCTION

1.1 Motive for this thesis

The motives for this thesis can be explained as practical and theoretical (computer-enhanced).

The practical motives are induced by degradation and needs to improve building performances. For example, there is an increasing realization that many buildings do not perform as intended by their designers. The reasons for this include faulty construction, malfunctioning equipment, incorrectly configured control systems, system ageing, and inappropriate operating procedures. When a fault occurs in the system, however, diagnosis of the defect is left to the operator. In addition, the building demand is changing over time. Therefore, it is necessary to identify opportunities for energy improvement and to implement effective system upgrades.

The theoretical or the computer-enhanced motives are induced by available simulation and optimization tools. The application of simulation and optimization tools for solving a variety of energy management problems in HVAC systems or building design problems has been proven in the literature. In addition, engineers and researchers around the world use simulation tools to validate different energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, and alternative energy systems.

Since this thesis aims at utilization of BEMS and providing useful information to operators by using simulation tools, the hypotheses for this work are the following:
  – Both BEMS data, as real data source, and the computer-based tools, as virtual data, are not enough utilized to improve the building performances.
  – Computer-based tools can help in finding new control strategies.
  – Computer-based tools can help in generating FDD rules.
  – The simulation outputs can be transferred into useful information for the building operators.

The motivation for the thesis is explained in the literature review by studying the lifetime commissioning.

1.2 Commissioning as a tool for improving building performance

Buildings are becoming more complex systems with lots of included elements (heating/cooling, hot tap water, ventilation, controls, etc.). In addition, users may have different demands. To make this complex system sustainable, there are many participants during the life of a building, including owners, designers, constructor, managers, operators, and users. A building life-cycle can be described in a few phases: design, construction, operation, and disintegration. Since the building complexity grows, communication and understanding among the building participants and elements can be poor during the building life.

Energy management in buildings is the control of energy use and cost while maintaining indoor environmental conditions to meet comfort and functional needs [1]. BEMS provide much data about building performance. These data can be used by operators and managers. Operators can use performance data for maintenance and improving the building performance. Energy management requires technical knowledge to understand how well, or how poorly, a building and its systems are functioning, to identify opportunities for improvement, and to implement effective upgrades. Well-trained and diligent building operators are important to the financial success of energy management [1]. To utilize BEMS data more successfully for maintenance, it is necessary to provide useful information about the building performance to the operators, actually understanding what really happens in a building.

Commissioning is a systematic process of ensuring that all building facility systems perform interactively in accordance with the design documentation and intent. It implies accepting the different methods, guidance, and procedures. The process eliminates the need for costly capital improvements, and can give short payback time [2, 3]. The hierarchy of building needs including commissioning as a new part in the building system can be organized as in Figure 1.1.
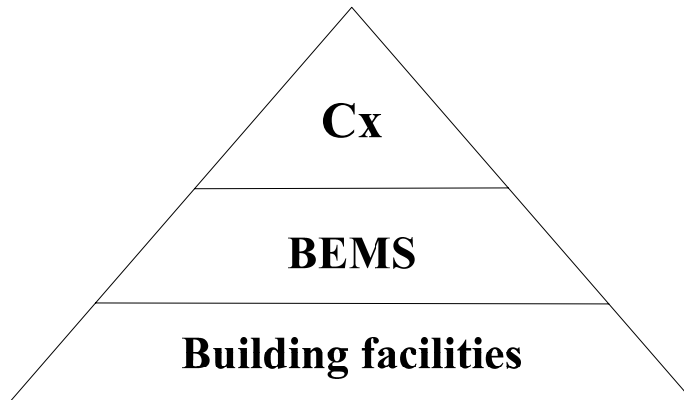
Figure 1.1. The hierarchy of building needs

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

1.3 Why is commissioning necessary?

1.3.1 Faults in building operation

There is an increasing realization that many buildings do not perform as intended by their designers. Reasons include faulty construction, malfunctioning equipment, incorrectly configured control systems, and inappropriate operating procedures [4]. Due to abnormal physical changes, ageing, or inadequate maintenance of HVAC components, HVAC components easily suffer from complete failure (hard fault) or partial failure (soft fault) [5]. Even though building performances are normally supervised by BEMS, when a fault enters the system, the BEMS programs currently available do not adequately assist in finding the underlying cause of the fault. Therefore,

diagnosis of the defect is left to the operator [6]. Both increase in energy consumption and degradation in the indoor thermal comfort, however, follow each fault regardless of the source.

Research on fault detection and isolation in automated processes has been active over several decades. The HVAC process has also been a subject of interest during the last 10 years. Annex 25 [6], organized by International Energy Agency (IEA) and its implementing agreement Energy Conservation in Buildings and Community Systems (ECBCS), was a leading forum in this field in the beginning of 1990s. A number of methodologies and procedures for optimizing real-time performance, automated fault detection, and fault isolation were developed in Annex 25. Many of these diagnostic methods were later demonstrated in real buildings in Annex 34 [7] (also organized by IEA ECBCS), which concentrated on computer-aided fault detection and diagnosis [8].

A short list of some of the faults in three typical systems is given in Table 1.1. The faults are chosen from Annex 25, which obtained these results using a survey among designers, constructors, and operators. The list classifies faults based on systems, related faults, and type of fault (design, maintenance, due to user, etc.).

Table 1.1. List of some typical faults in three typical systems listed in Annex 25 [6]

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

Since building complexity is growing, new faults can always appear. Therefore, in the near future, energy savings will be obtained mainly through optimal control and early fault detection of building HVAC systems. Lowering energy consumption and building operation costs with proper occupant comfort level will be reached together with well-organized maintenance, fast detection and correction of faults, and best use of equipment performances [6].

1.3.2 Legislative force

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

- Energy Performance of Buildings Directive (EPBD) [9] in Europe,
- Leadership in Energy and Environmental Design (LEED) in USA.

The objective of the EPBD is to 'promote the improvement of the energy performance of buildings within the community taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost effectiveness' [10]. EPBD is based on experience in Denmark, among other countries. Concerning owner-occupied households, the idea in the Danish labeling scheme is that all houses shall be labeled before they are sold so that the new owners can see the energy performances of the house that they intend to buy [11]. Since 1997, the Danish energy-saving policy has been using a mandatory energy labeling scheme for buildings. At the beginning of 2006, the EPBD was implemented for all EU countries.

The Norwegian Parliament formally decided in 2004 to implement the EPBD in Norway. New minimum energy requirements for new buildings are proposed for 2007, while certification of buildings and inspection of boilers and air conditioning systems could come into force in 2008 for some building categories [12].

The LEED Green Building Rating System was developed by the United States Green Building Council (USGBC) to further the development of high-performance, sustainable buildings in the United States. LEED provides a framework for assessing a building's performance and for achieving sustainability goals. Commissioning is a requirement to achieve LEED certification for both new and existing commercial buildings. In addition to commissioning being a fundamental requirement, additional credits towards certification can be earned through additional commissioning activities [13].

To decrease energy use in buildings and CO_2 emission, commissioning tools encouraged by legislation are necessary.

1.3.3 Commissioning benefit

Commissioning benefits can be defined as:
- energy benefits,
- non-energy benefits.

Energy benefits can be achieved by properly "tuning up" a building. A proper "tuning up" means that the building performs according to its intent. Previous case studies have found that "tuning up" an existing building's HVAC systems results in an average savings of 5-15% of total energy consumption in full commissioning of existing buildings [14]. Building energy consumption is one of the most important building energy performance indicators. Since an energy performance certificate can influence building value when a building is sold or rented out [10], energy benefits encouraged by the legislation can be turned into pure profit. Therefore, application of different commissioning tools through the building lifetime can both improve building energy performance and save energy.

Some of the most important non-energy commissioning benefits are:
- operation and maintenance budget savings,
- improved thermal comfort, and
- liability reduction.

Operation and maintenance service, equipped with appropriate commissioning tools, results in less labor, fewer failures, and improved thermal comfort. Therefore, a certain savings can be achieved. Improved thermal comfort in a building gives increased productivity and tenant retention value. Finally, improved maintenance service results in building liability reduction. Even though these commissioning non-energy benefits are sometimes difficult to quantify, they seem to be more important nowadays.

1.4 How does a commissioning tool work?

1.4.1 Assessment, fault detection and diagnosis

Regardless of the applied logic in the background of a commissioning tool, the main point of the tools is the assessment of building performances. Building assessment tools can be organized into three categories: benchmarking, energy tracking, and diagnostics. Benchmarking is a macroscopic level of performance assessment, where metrics are used to measure performance relative to others. Buildings are typically benchmarked using coarse data, often from utility bills, and some procedure for normalization for variables such as weather and floor area. Tracking energy performance over time is a logical enhancement of one-time benchmarking. Energy tracking can result in an overall understanding of load shapes. Although the data needed for diagnostics are more extensive than for energy tracking, this jump in complexity is essential to obtain the information needed to aid in correcting problems. Benchmarking and energy tracking are useful in identifying inefficiency at the whole building level and focusing efforts toward large energy end-uses, while diagnostics allow detection of specific problems and help target the causes of these problems [14].

There are two levels or stages of 'diagnostics':
  – fault detection,
  – fault diagnosis.

Fault detection is the determination that the operation of the building is incorrect or unacceptable from the expected behavior. Fault diagnosis is the identification or localization of the cause of faulty operation. Therefore, diagnosis involves determining which of the possible causes of faulty behavior are consistent with the observed behavior [15]. The nature of the fault unambiguously may be possible to identify, but it is often possible to eliminate only some of the possible causes. The process of diagnosis requires that the most important possible causes of faulty operation have been identified in advance and that these different causes give rise to behaviors that can be distinguished with the available instrumentation. The costs of detecting a particular fault include the cost of any additional instrumentation, computer hardware and software, and any human

intervention. Both the costs and the benefits will depend on the particular building and application and must be determined on a case-by-case basis [16]. Fault diagnosis methods can include rule-based diagnosis, recognition of statistical pattern, artificial neural networks, and fuzzy logic [17].

1.4.2 Methods for fault detection and diagnosis

Commissioning tools for building performance assessment can be defined as:
- functional performance testing (FPT),
- fault detection and diagnosis (FDD).

FPT is the process of determining the ability of an HVAC system to deliver heating, ventilating, and air conditioning in accordance with the final design intent [1]. FPT is important during the construction and delivering phase of building, while FDD tools are necessary during operation and maintenance.

FDD tools can be manual and automated. Manual tools imply different guidelines for the building operators. Automated commissioning involves analyzing system performance to detect and diagnose problems (faults) that would affect the operation of the system during normal use [18].

Most FDD tools are based on combinations of predicted building performance and a knowledge-based system. They compare the performance of all or part of the building over a period of time to what is expected, so incorrect operation or unsatisfactory performance can be detected. The expected performances can be assumed, desired, and model-based. The model takes an operating point as input and makes a prediction of the set-point expected to drive the system to that operating point. By configuring the model to represent correct operation, a deviation in the actual operating point of the system from the desired point represents an indication of faulty behavior [18]. Comparison of the expected and deviated performance is fault detection, while diagnosis means fault identification. Therefore, different FDD tools have diversity in the fault classifiers used. A fault classifier is a way faults are diagnosed.

Principles and application of six FDD tools are compared briefly here. A model-based feed-forward control schema for fault detection is described in [19]. An example of monitoring-based commissioning by use of information monitoring and diagnostics system (IMDS) was reported in [20, 21]. FDD tools can use the statistical classifier, as reported in the following methods: principal component analysis (PSA) method for sensors [5], the combination of model-based FDD (MBFDD) method with the support vector machine (SVM) method [22], and the transient analysis of residual patterns [17]. Air handling unit performance assessment rules (APAR) is a fault detection tool based on expert rules [23]. A brief comparison of these tools is given in Table 1.2.

Table 1.2. FDD tools comparison

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

The statistical methods indicate a fault based on an index value of faulty conditions. An index can have a different background depending on the method. For example, FDD applications of the PSA method use the squared sum of the residual, named the Q-statistic or squared prediction error (SPE), as an index of faulty conditions. Consequently, the Q-contribution plot can be used to diagnose the fault. The variable making a large contribution to the Q-statistic or SPE is indicated to be the potential fault source [5]. In the MBFDD method combined with the SVM method, an SVM method is used to design a fault classifier, which is based on statistical learning theory that transforms the signal to a higher-dimensional feature space for optimal classification [22].

Since system availability is more important than reliability in most HVAC systems, an FDD system, which is developed using knowledge about typical or important faults, is necessary [24]. Even though a FDD tool can have a different theoretical background, its most important aim is to give accurate information about the building performance.

1.4.3 Commissioning tools application

A commissioning tool for the design phase improves building performance in the operating phase, while a commissioning tool for the operating phase improves maintenance, so that the building performances are as intended to be. Application of a commissioning tool is related to a tool realization and a tool user. Commissioning tools can be automated or manual. Automated tools are embedded in the HVAC control system. An important means for practical application of any commissioning tool in an existing building is BEMS. Therefore, availability of performance metrics [25] is necessary for any assessment in any FDD method.

A practical barrier to the adoption of commissioning tools is the difficulty of setting up communications between the tool and the control devices. Technologies for carrying out automated commissioning are still in their infancy and very few tools are available for practitioners to use [26].

1.5 Commissioning users

To put commissioning into practice, it is necessary to develop tools according to the intended user. Since building lifetime has several phases with different participants, the commissioning users could be most of these building participants. Therefore, commissioning users can be designers, constructors, operators, building managers, and occupants. For example, designers and constructors can be users of FPT methods to confirm the ability of a system. Since building operators and managers need assistance in extracting useful information from the large volume of data produced by new monitoring technologies [21], they can be users of commissioning tools as well. Finally, market and legislative means can make building occupants and owners the potential commissioning users.

1.6 Problem definition

1.6.1 Problem background

This thesis has been part of a Project Life-Time Commissioning for Energy Efficient Operation of Buildings (LTC Project) at the "Gemini-Center Energy Supply and Air-Conditioning of Buildings" (NTNU and SINTEF). The project is a network, or a "user club", of industrial companies, private and public entities, and R&D organizations. The overall objective of the proposed national project is to contribute to the implementation of life-long commissioning of building HVAC systems so that this becomes a standardized way of building, operating, and maintaining the HVAC systems. This improves energy efficiency, ensures a rational use of energy, and thereby decreases CO_2 emissions.

In 1999, the International Energy Agency's Implementing Agreement on Energy Conservation in Buildings and Community Systems initiated the activity "Annex 40: Commissioning of Building HVAC systems for Improved Energy Performance". The Annex 40 project was finished in 2004 with publication of the final report. In 2005, the Executive Committee for the same Implementing

Agreement decided to launch a new activity: "Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings" [27]. This new annex has three tasks:

  − Subtask A: Initial commissioning of advanced and low energy building systems,

  − Subtask B: Commissioning and optimization of existing buildings,

  − Subtask C: Commissioning cost-benefits and persistence.

The research work on this thesis contributes to the work on Subtask B.

1.6.2 Objectives

Since the fault diagnosis system should be considered as a tool for obtaining information on the process and as an aid to help the operator identify the defects causing the faulty process operation [6], the objective of this thesis is to develop a background for the maintenance manual for building operators. Since buildings can be sustainable only if they are maintained properly, instructions for undertaking corrective action are necessary.

To achieve the above objective, several subtasks are necessary. First, real building on-site and BEMS data have to be organized. Second, calculation engines should be utilized for the performance estimation. Appropriate building and HVAC system models have to be established. Different possible cases have to be tested either by use of simulations or coupled simulation and optimization tools. These simulation tests should give resulting building performances influenced by either faults or retrofit measures. Finally, real-life data encouraged by the simulation tests should help for better utilization of the real BEMS data so that building operators can realize problems. Among the above subtasks, an important task is establishment of a data model for better result presentation.

1.6.3 Contributions from this thesis

This thesis makes contributions in the utilization of simulation and optimization programs for improving control strategies in HVAC systems. In addition, a thesis contribution is the development of useful information that can be used in the building maintenance. The contributions from this thesis are the following:

1. Possible commissioning targets in Norwegian building facilities have been noted by doing a survey. Even though there have been many international works on building commissioning, it was necessary to find the commissioning users.

2. A commissioning plan management has been developed. This plan management includes organization of responsible persons in building, available data from BEMS, and performing on-site surveys in buildings.

3. To present the results, a data model has been proposed. The data model implies the information tracking from building attributes over building performances to the final estimation of the performances.

4. Coupled simulation and optimization programs (EnergyPlus and GenOpt) have been utilized for obtaining better control strategies. Several procedures have been suggested.

5. To couple real data and the model, the procedure for the model calibration by use of an optimization algorithm has been proposed. In addition, the difficulties of the detailed model (EnergyPlus) calibration have been discussed.

6. Several faults in the hydronic heating system have been elaborated so that useful information can be drawn for building maintenance.

7. A method for fault assessment has been suggested. The method consists of a performance indices calculation and their classification. Based on the biases in the performance indices, a few faults can be diagnosed.

8. Using the simulation tools EnergyPlus and TRNSYS, several FDD rules have been generated. These rules have been established for the AHU air cooling system and hydronic heating system. The rules can diagnose the control and the component faults.

1.7 Thesis organization

This thesis constitutes six main chapters. Several parts of the thesis have been presented in seven papers, a list of which is given below. Therefore, the subject matter and the background of these papers have been discussed at the related places in the thesis. All the papers are printed and attached at the end of the thesis.

Chapter 1 gives the literature review for this thesis. This review has been published in Paper VI. The practical experiences, the survey results, and results presentation are discussed in Chapter 2. The survey results of the existing building have been presented in Paper I. Chapter 3 deals with the application of the simulation and optimization in the design. Papers II, III, and IV are related to Chapter 3. Use of coupled simulations and optimization tools in improving the control strategies has been elaborated in Chapter 4. Paper V is related to a part of the study presented in Chapter 4. Chapter 5 deals with the model calibration and fault detection and diagnosis. A few faults have been explained descriptively, while FDD rules have been developed for two HVAC systems. A part of the study in Chapter 5 was presented in Paper VII.

List of papers

Paper I	N. Djuric, F. Frydenlund, V. Novakovic, J. Holst, Preliminary Step in Collecting Data for Commissioning of Existing Buildings (Characterization of buildings, systems and problems), Proceedings of the Clima 2007 WellBeing Indoors, Helsinki, REHVA, 2007.
Paper II	N. Djuric, V. Novakovic, J. Holst, Optimization of energy consumption in building with hydronic heating system by use of computer based tools, The 8th REHVA World Congress, Clima 2005, Lausanne, Swiss, 2005.
Paper III	N. Djuric, V. Novakovic, J. Holst, Optimizing the building envelope and HVAC system for an inpatient room by using simulation and optimization tools, The 5th International Conference on Cold Climate Heating, Ventilation and Air-Conditioning, Moscow, Russia, May 21-24, 2006.

Paper IV	N. Djuric, V. Novakovic, J. Holst, Z. Mitrovic, Optimization of energy consumption in buildings with heating systems considering thermal comfort by use of computer-based tools, Energy and Buildings 39 (2007) 471-477
Paper V	N. Djuric, V. Novakovic, F. Frydenlund, Existing building commissioning using computer based tools, Proceedings of the Clima 2007 WellBeing Indoors, Helsinki, REHVA, 2007.
Paper VI	N. Djuric, V. Novakovic, Review of possibilities and necessities for building lifetime commissioning, Renewable and Sustainable Energy Reviews, 2007, Accepted by the journal
Paper VII	N. Djuric, V. Novakovic, F. Frydenlund, Heating system performance estimation using optimization tool and BEMS data, Energy and Buildings, 2007, Accepted by the journal

2   PRACTICAL EXPERIENCES AND DATA PRESENTATION

2.1 Data collection for commissioning of existing buildings

The objective of the work in Paper I was to make an overview of the most typical buildings, HVAC equipment, and their related problems. The survey was carried out by developing a questionnaire for the building operators and managers.

As the term commissioning has been defined in the introduction as a lifetime process, it was necessary to find the commissioning targets in the Norwegian building facilities. Therefore, such a survey should point to different building characteristics, owner attitudes, and building ability to be done in the commissioning process. Building ability to be done in different commissioning processes means how many data are available and in which ways they are available.

Since a real-life application of the commissioning tools is necessary, the energy efficiency attitude of building owners is important for the commissioning. In addition, maintenance service influences building performances; therefore, the structure of the maintenance service is important to know due to a proper tool definition.

Information about building area and the position of the HVAC system is important for developing the building models. In addition, the BEMS measurements give building performances. Therefore, the relation among both the building net total area, number of systems, and the number of the controllers is beneficial for establishing the commissioning protocols for the building estimation.

2.1.1 Method for data collecting

The questionnaire was developed as a tool for the survey, and it consists of eight groups of questions. It is attached in Appendix I.

The content of the questionnaire

The first group of questions aims to obtain general data about the buildings. The most important questions from this group are about net total area, year of construction, year of the last renovation, and if a renovation is planned in the next two years [28].

The second group of questions should show the most used equipment and type of HVAC system in the buildings. Besides the information about equipment, this group of questions collects the number of controllers, the number of the particular types of HVAC systems, and the age of the oldest HVAC equipment in the building.

The third group of questions deals with the most common problems in the buildings. The suggested problems are noted generally as the following: too warm or too cold, unstable temperature, drafts, and noise. There is no emphasis on when problems occur.

The fourth group of questions treats the building documentation. All the terms in this group of questions were defined based on the Norwegian translation of the commissioning terms [27]. The questionnaire asks for the following documentation: design intention, ordinary operation step, as-built records, and testing, adjusting and balancing (TAB) documentation.

The fifth group of questions aims at energy use and the attitude of the building owners in practicing energy efficiency. A question from this group asks about using Enova energy efficiency tools. Enova SF is a governmental agency established to deal with the implementation of energy efficiency and renewable energy policy in Norway [29]. There are four questions in this group, and they ask about the following: energy bills for the last two years, practicing the energy efficiency measures in the building, practicing some of the authority measures in the energy efficiency, and using the Enova tools.

The sixth group of questions is about the accessibility to a building for making measurements.

The seventh group of questions aims at maintenance in the buildings. There are questions if either the building owners perform their own maintenance service or use a hired company. There is a question about if the operators attend training for HVAC equipment. In addition, there is a question about the responsibility of a hired company for the maintenance.

The last question is if they would use some of the commissioning tools.

2.1.2 The survey results

The following building owners took part in the survey: Forsvarsbygg (the Norwegian Defense Estates Agency), Telenor (Governmental telecommunication company), and Norwegian University of Science and Technology (NTNU) campus. The questionnaire was completely answered by 32 building operators from 15 towns.

The most important conclusions are noted here, while a deeper discussion about each group of the questions is given in Paper I. Since this study deals with the lifetime commissioning in the existing building, it was important to note that the buildings have been extended through the entire lifetime, and there is no any regularity about how it happens.

Another conclusion is that the building owners invest in the buildings throughout the buildings' entire lifetimes. This is shown by establishing the relation in Figure 2.1. Therefore, the building commissioning would be necessary on a continuous basis.
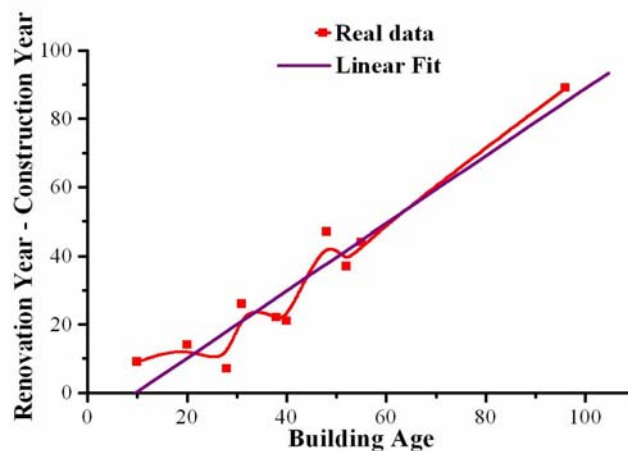
Figure 2.1. The rate of building renovation during the lifetime

Figure 2.1 shows that the building renovation rate is constant during the building lifetime. Actually, a building is renewed after the same number of years.

Retrofit estimation is also part of the commissioning, making knowledge about when and how the building owners practice retrofit measures is important. For example, the HVAC systems might be renovated but not changed completely because some of the components are still kept. In addition, another conclusion is that buildings less than 50 years old have at least one piece of HVAC equipment as old as the building.

The building's ability to be commissioned implies a possibility of using a BEMS system in the building. The survey shows that there are BEMS in 91% of the buildings in the survey. Therefore, in the most of the buildings there is a possibility to estimate the building performances. A few conclusions have been drawn about the number of the systems and controllers. There is a trend that several different types of HVAC systems imply a higher number of the controllers. The buildings with all three types of HVAC systems (ventilation, heating, and cooling) have a higher number of controllers than the others. In addition, a larger total net area of the building implies a higher number of the ventilation systems. The number of the heating and the cooling systems is mostly the same regardless of net total area.

Even though each building has its own maintenance service, 69 % of buildings hire an outside company for maintenance. The hired companies have the responsibilities for all the HVAC

equipment only in 19 % of the cases because they are hired only for particular equipment. This implies that, for some issues in the building, only the employed staff is in charge. Since there are a few levels of maintenance service, a discrepancy between duties can appear. Consequently, some faults or issues can appear in a building, so a commissioning protocol for the maintenance service can be useful.

The collected data have been classified regarding building type, HVAC system, equipment, and problems, and an abbreviated form of Table 1 from Paper I is given in Table 2.1 for multipurpose buildings. The most widely used HVAC systems and equipment are represented in Table 2.1.

Table 2.1. Classification of the systems, equipment, and problems in multipurpose buildings

Type of building	Type of HVAC	Equipment	Problem
Multipurpose	Ventilation	Water heating coil	Draft
			Noise
		Cooling coil	Poor air quality
			High air temperature
	Heating	Radiator	Too warm
			Too cold
			Unstable temperature
	Cooling	Air cooling	Too warm
			Unstable temperature

In Table 2.1, there are the same problems but related to the different systems. The causes of these problems can be different even if the names are the same. In addition, the problems are related to HVAC systems with certain equipment.

2.2 Practical experience in on-site survey

The aim of this on-site survey is to find as many data as possible that can be successfully used in the building performance assessment. In addition, these data should be used for a building model calibration and for establishing rules for fault detection and diagnosis. This data collection includes the following: talking with the building operators and the BEMS supplier technical support, on-site surveys, and both the BEMS and additional measurements. The surveyed building, Material teknisk, is located at the University campus in Trondheim. This building is introduced in Chapter 5.3, where faults have been studied.

The terms "in-building person" and "e-data" have been used in this chapter to explain all the found information in this building.

This on-site survey was inspired by "A Practical Guide For Commissioning Existing Buildings" [28]. Since commissioning situations are not the same in Norway and the USA, this document gives good ideas for the on-site survey used in this study. Some of the points from this document tell that the staff member chosen should have expertise in the BEMS, HVAC equipment, and lighting systems. It is preferable to assign a building operator who knows the building's history and why and how systems are operated and maintained. In addition, a benefit of allowing in-house staff to work on the project is the training they receive. Participating in the project allows them to incorporate many of the troubleshooting and testing methods learned during retro-commissioning into the facility's O&M program [28]. Therefore, contact with the persons who are in charge of a building can be a very important part in this on-site survey.

This chapter presents the practical experience received through the on-site survey. In addition, the contributions of the contact persons are presented. Therefore, it includes brief descriptions of contact persons, the on-site visit, data organization, and measurements.

2.2.1 Necessary contacts for data collection

In-building persons contacted for the purpose of this study included a project leader for energy conservation, a BEMS operator, and a BEMS supplier technical support person. An in-building person is a person who works in a building, a person directly employed as maintenance service, or who gives a service to the building via an external company. In addition to these in-building contact persons, a few additional contacts were necessary to carry out the on-site survey.

At the beginning of the on-site survey, a contact with a project leader for energy conservation was established. Since data from the BEMS are necessary for the building performance assessment, the operator of the BEMS was introduced. Since the project leader for energy conservation explained that the BEMS system is supported by BEMS supplier technical support, contact with this person was made as well. Technical support obtained by a BEMS supplier technical support implies that the technical support person provides the control system programming and help in the system use. These in-building contacts provided the data related to this building.

Besides in-building contacts, it was necessary to establish contacts with persons who can help in making additional measurements. These measurements have also been used for the building performance assessment. These persons are laboratory staff and a person from the instrumentation company, Flow-teknikk [30]. The instrumentation distributor provided valuable and specific help in the use of the measurement equipment.

2.2.2 Building visit

To make the on-site building survey easier, a general building plan was provided. In addition, an HVAC system schematic was provided from the BEMS. These drawings were obtained before the visit. The first building visit was made together with the project leader for energy conservation, and started from the district heating consumer substation and continued to other energy emitters (such as the AHU units and other equipment). During the future visits, it was important to find any connections between building geometry and the HVAC system schematic.

Since the BEMS was installed or extended several years after the building was constructed, it was difficult to make this connection between the building geometry and the HVAC system schematic.

After each visit brief notes were written. They have been useful for the model development and fault diagnosis.

2.2.3 Data structure and data quality

Different data have been necessary to establish a model and to estimate building performances. The data explained in this chapter are e-data that are either available via Internet or could be downloaded from the BEMS database. In addition, the validity of such data has been discussed.

A building as a main source of data is assumed to be the first part in a chain of the information transfers. BEMS and the BEMS supplier technical support are the second part in this transfer. Consequently, the next member in this chain is the third part, and so on.

The general building plan was found on the NTNU's web page [31]. Such a plan includes only the position and the room numbers, not dimensions. In addition, a general map of the surrounding area was downloaded. The HVAC system schematic with the measured points was provided from the BEMS. Since these drawings can be obtained as soft copies, they are also e-data.

The third part in this information transfer was Entro [32], which is an ESCo focused on energy and the environment. This company uses the BEMS database of NTNU and gives consulting services for energy savings to the NTNU campus. The Entro energy database is available on the Internet. This database does not contain as much data as the BEMS database in the building. Since Entro does not have enough tools and skills to utilize all the available data, the BEMS database was not completely utilized in improving the building performances. In addition, due to data transfer from the BEMS database to another database, it is possible that some of the data were lost or changed. For example, a time delay discrepancy of one hour between BEMS and Entro's data was found.

The BEMS supplier technical support person explained that his database is the same as the BEMS database in the building. In addition, the BEMS supplier had been sending reports in the case of the system faults. Therefore, such a database can be useful for the building performance assessment. The BEMS supplier cannot, however, share his data with any ESCo since a building owner is the unique owner of in the data from the building.

For this assessment of building performance, it was necessary to have more data than were available in BEMS. In that case, an economical issue has been met. Actually, every additional connected measurement point into the BEMS increases the total supplier service cost.

Among all these e-data, it was necessary to estimate their validity. Even though the data available on the Internet are easy to access, they are not completely valid due to many stages in the data transfer. In addition, these data sometimes can be poor due to the lack of an energy assessment tool, but ESCo's data can still be useful for a preliminary analysis. The BEMS data, measured on a building, are highly valid, while extending them can be expensive.

2.2.4 Measurement

Both BEMS and additional measurements have been used for the purpose of the building performance assessment. The number of measurement points was determined by a model approach. For example, in this case the heat balance equations could not be established by use of the BEMS data. Therefore, additional measurements were necessary. The additional measurements were useful for the BEMS data validation.

Before the BEMS data were logged, the BEMS's abilities were explored. This was done together with the BEMS supplier technical support and the BEMS operator. Since they did not know all the BEMS's abilities, only a few data logs were taken. Finally, the BEMS data had been logged for a certain period. Since the operator and the technical support were usually busy, a list for the data logging was prepared. The list contains names of the logged points. The used list for the work on Paper VII is given in Appendix II.

The additional measurements were done at the same time as the BEMS data were logged so that the measurements could be compared. The additional measurements and the measuring equipment were the following:

- temperature loggers for measuring the indoor air temperature and the outdoor air temperature;

- a thermo-couple for measuring the temperature difference between the supply and return pipe for the hot tap water;

- an ultra-sound flow-meter for measuring the water flow in the supply pipe for the hot tap water.

Before the temperature loggers were programmed, an appropriate program was installed on the computer. The temperature logger programming consisted of setting the start time and the number and frequency of readings. Since these loggers were placed in different rooms, a list of rooms and logger settings was made. The list is given in Appendix III. The thermo-couple was prepared by the technician before the measurement. The ultra-sound flow-meter was also tested in advance. The possible ranges of the measured performances were necessary to know before starting the measurements. These ranges were found by analyzing the system and talking with the operator. For example, in the case of measuring the flow of the hot tap water, the maximum flow rate was assumed to be lower than the consumption of the cold water. After talking with the operator, it was determined that the hot tap water system is designed as all the taps in the building are in use. Therefore, in this case the flow rate of the hot tap water could be expected to be in the range of the cold water consumption or even higher.

2.3 Data presentation

The aim is to find a method to practically express data necessary to improve the building performance. Actually, this method should enable building operators and managers to share and exchange building information. A data model has been suggested for that purpose. Since the building performances have been assessed in most of the commissioning tools, the data model should support performance tracking. Therefore, the background and examples for the

performance tracking by using the data model are presented here. Advantages and disadvantage of such an approach are also noted.

2.3.1 Data model background

A data model is an abstract model that describes how data is represented and used, while a model of energy efficiency analysis and simulation information is a process model. A data model represents the information and structure of an object and its underlying components. A process model represents the information and structure of a workflow and its underlying processes. No technology or innovation can currently map through both an object model and process model [33]. Since the aim is a practical information expression, a data model has been suggested to present necessary data for the performance assessment. In addition, EXPRESS-G has been suggested for that purpose. EXPRESS-G is a formal graphical notation for the display of data specifications defined in the EXPRESS language [34], which is the data modeling language of the STandard for the Exchange of Product Model Data (STEP) and standardized as ISO 10303-11. EXPRESS-G supports simple data types, named data types, relationships, and cardinality. It also supports the notation for one or more schemas [34], and has been used for the Industry Foundation Classes (IFC) definition [35].

The aim of the tools in subtask B of Annex 47 is to create a framework for monitoring, analyzing, and improving a building throughout its lifecycle based on a set of performance metrics. These tools assist in building operation with the information needed to operate the buildings more efficiently and to provide the information required to detect and diagnose faults that degrade energy performance. Therefore, data objects in this data model are building performances, while the relationships should connect these performances.

An object in the data model is defined by attributes. Any change in the attributes gives a change in an object behavior. Behavior is the ability of an object to respond to internal or external stimuli. To explain this, an example of building object behavior (BOB) is used. The BOB notation describes object behavior as a set of pairs of causes (stimuli) and corresponding results (reactions). In this sense, BOB notation clauses have a dichotomy similar to that of if–then

clauses in computer programming [36]. Finally, the building performances can be easily explained by using this logic of stimuli and effects. Actually, by tracking possible changes in the attributes, a possible change in a behavior can be found.

2.3.2 Data model for the building performances

For the purpose of the practical presentation of the performance improvement methods, a building performance is involved to be a data object. Actually, a building performance is a behavior. A building performance can be defined by few attributes. Consequently, a change in the attributes gives a change in the building performance. The number of attributes depends on the model, control, or assessment approach. For example, if a simulation model is used for a building assessment, several parameters define the model. These parameters are attributes. A control of an HVAC system can include different sensors and control equipment. The final performances of such an HVAC are influenced by these sensors and equipments. Therefore, in this case the sensor measurements and the equipment properties are the attributes of the final performances.

An example how the indoor air temperature can be expressed using EXPRESS-G is shown in Figure 2.2. In this model, five necessary attributes define the indoor temperature. The indoor temperature is a performance, or a behavior.
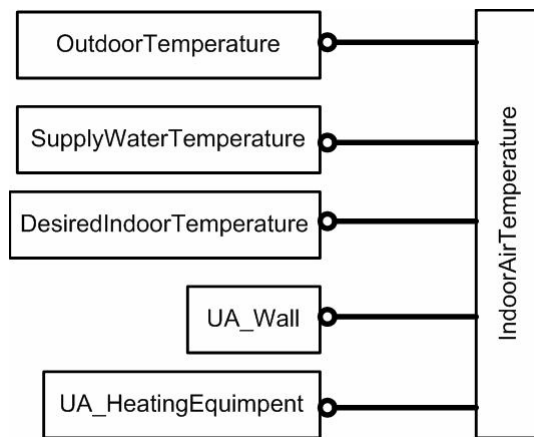
Figure 2.2. A data model for the indoor air temperature

Any change in the attributes in Figure 2.2 gives a change in the indoor air temperature. In addition, the model in Figure 2.2 requires all the five attributes. Without an attribute, it is not possible to state that this is the indoor air temperature.

To diagnose faults in a heating system, the indoor air temperature and the energy consumption can be used for the performance assessment. This means that these two are the system behaviors. An example of the EXPRESS-G schema for the fault diagnosis in a heating system is shown in Figure 2.3. Indoor air temperature and energy consumption, both a real and a baseline value, have to be defined before by using necessary attributes. Therefore, in Figure 2.3, the numbers before the object names are the page number, and the object number in the page. Since the objects have to be defined before, to-page references are used to define a fault in Figure 2.3 [34]. The rounded boxes are used to present to-page references, while the rectangular boxes are used for the objects.
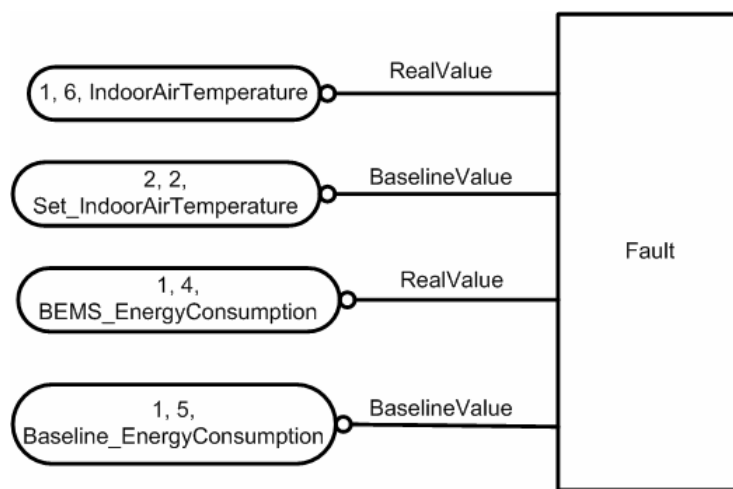
Figure 2.3. A data model for the fault diagnosis

In Figure 2.3, the word above the connection lines is the relation. The schema in Figure 2.3 implies that four objects are necessary to elaborate a fault. For example, without a baseline value, it is not possible to discuss any fault. Such a schema is only an example.

Finally, a guideline for building operators should consist of the necessary objects for the building performance assessment. By using the logic explained above, a guideline should be developed as a data model. Such a data model should include all the information used in a certain approach. In

that way, the operators would have an inspection list with items to be checked to elaborate a fault or make an improvement.

Even though there is a lot of work in fault detection and diagnosis, there is not as much work in a standardization of data in this area. Therefore, the data model has been proposed to make easier data exchange among operators. Simple data exchange is an advantage of the data model. In addition, the data model permits information classification. Since information classification is important to allow generic access to information, this is another advantage of the data model. A disadvantage of the data model is that the assessment approach is not presented.

2.4 Closing remarks regarding the practical experiences in data collection and data presentation

The most important remarks regarding the real environment contacts are the following:
- Since the buildings have been modified during their entire lifetimes, it can be difficult to make the connection between the building geometry, the HVAC system schema, and the BEMS measurements.
- Before or during the on-site survey, it is important to establish the contacts with in-building personnel. Their knowledge is useful for the final system assessment.
- Due to the building data transfer, the original data can be changed or lost. Consequently, the performance assessment can be incorrect. Therefore, for a proper assessment, BEMS data, the on-site surveys, and additional measurements are beneficial.
- If a system model can be established using the BEMS data, then the additional measurements are not necessary. The additional measurements, however, can always be performed for the BEMS data validation.
- A data model can be used for developing the operator guidelines. The data model for that purpose has to include the necessary information for the fault diagnosis and the building improvement. Objects in such a data model are the building performances.
- A disadvantage of the data model is that the assessment approach is not presented.

3 SIMULATION AND OPTIMIZATION APPLICATION IN THE DESIGN

This part of the study presents the possibility for the application of computer-based tools to building design improvement. Papers II, III and IV elaborate the use of EnergyPlus[1] [37] and GenOpt[1] [38] in the building design of a hydronic heating system. The aim is to develop methods for the optimization of design parameters. Since there are issues with using the optimization tool, these methods give instructions on how to couple and rerun these tools for practical problems.

Before the important cases for this part of the study are explained, a review of the literature necessary to use the computer-based tools is presented. In addition, the advantages and disadvantages of EnergyPlus and GenOpt are detailed. Since the approaches in the studied examples rely on the facts from this review, it is important to elaborate on them briefly. This review is also valid for the next chapters dealing with EnergyPlus and GenOpt.

There have been many optimization tools for buildings and HVAC systems in both the design and the operation. The application of simulation and optimization tools to solve a variety of energy management problems in HVAC system or building design problems is shown in the works of Wright [39], Fong [40], and Lu [41]. The example of insulation optimization in order to minimize the Life-Cycle Cost is shown in [42]. A genetic algorithm coupled with computational fluid dynamics was used in the work of Lee [43] to develop an optimal design tool for a hybrid air-conditioning system with natural ventilation.

The design of a building is a multi-parametric problem with few objectives or constraints. Usually, the objectives and constraints do not have the same physical meaning. Since building design and operation have many different and conflicting objectives, the use of multi-objective optimization can be useful to solve such problems. Therefore, the term multi-objective optimization is introduced here as necessary for this study. Multi-objective optimization is the search for acceptable solutions to problems that incorporate multiple performance criteria. An

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[1] Copyright by Lawrence Berkeley National Laboratories, Berkeley, CA, USA

example of fuzzy logic controllers optimized by use of a multi-objective genetic algorithm for a building subjected to an earthquake was explained in [44]. The multi-objective genetic algorithm search method was used to identify the optimal pay-off characteristics between the energy cost of a building and occupant thermal discomfort in the work of Wright et al. [39].

Beta testing of EnergyPlus began in late 1999 and the first release was scheduled for early 2001 [45]. The previous sentence can be found in the article of Crawley et al. [45] from 2001. This means that EnergyPlus was realized for wide use in 2001. EnergyPlus is an all-new program, albeit one based on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus comprises completely new, modular, structured code written in Fortran90. It has three basic components – a simulation manager, a heat and mass balance module, and a building systems simulation module. The simulation manager controls the entire simulation process. The heat balance calculations are based on IBLAST – research version of BLAST with integrated HVAC systems and building load simulations. Finally, the integrated simulation has been the underlining concept for EnergyPlus [45]. The EnergyPlus building simulation software has been tested using the IEA HVAC BESTEST E100-E200 series test. These results show that EnergyPlus results generally agree to within 1% of the analytical results except for the mean zone humidity ratio which agreed to within 3% as shown in [46].

GenOpt is a generic optimization program for minimization of a cost function that is evaluated by an external simulation program, such as SPARK, EnergyPlus, DOE-2, TRNSYS, etc. GenOpt can be coupled to any simulation program that reads its input from text files and writes its output to text files by simply modifying a configuration file [38, 47]. This program has been developed to reduce the labor time in finding the independent variables that yield better performances for building systems [38]. For example, GenOpt can be used to find the values of user-selected design parameters that minimize a so-called objective function, such as annual energy use, peak electrical demand or predicted percentage of dissatisfied people (PPD value), leading to the best operation of a given system [47]. The above noted features of EnergyPlus and GenOpt and the free availability of these programs have been the reasons why these programs have been chosen as the tools for this work.

Even though EnergyPlus and GenOpt have been used here, they have several drawbacks. Today's building energy simulation programs are built on non-smooth models, and their solvers frequently fail to obtain a numerical solution if the solver tolerances are too tight. Numerical experiments with EnergyPlus and analysis of its source code revealed that it does not seem possible to prove that EnergyPlus computes an approximate solution that converges to a function that is smooth in the building design parameters as the solver tolerances are tightened. In fact, since there can be several solvers that control subsystems of the simulation model, it is not possible to analyze how the approximation errors of the different solvers propagate from one model to another, and from one time step to the next [48]. In addition, in the work of Wetter and Wright [49] the possibilities of using EnergyPlus and GenOpt were elaborated, and one of the conclusion has been that the required smoothness of the objective function influences the solution.

3.1 A school building description

The results and analysis in Paper II and Paper IV are related to a school building located in Belgrade. Therefore, the building and the input data are only briefly explained here.

The building consists of 134 rooms. The building envelope is a light construction with wooden exterior walls, while the windows and outside doors consist of three-layer glass with air filling. The partition walls are of light concrete, while the interior doors are wooden. The heating is supplied by a hydronic system using radiators as the heat emitters. The school building is modeled by 21 zones, with nine zones having radiators installed. The building facade is shown in Figure 3.1 and the general plan is shown in Figure 3.2. The results and analysis for this further work deal the indoor air temperature and thermal comfort in Class Zone 2 that is shown as hatched in Figure 3.2.
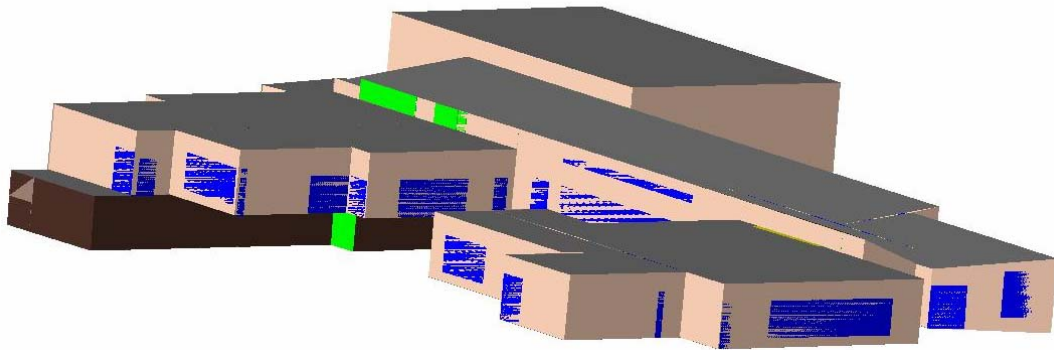
Figure 3.1. School building facade
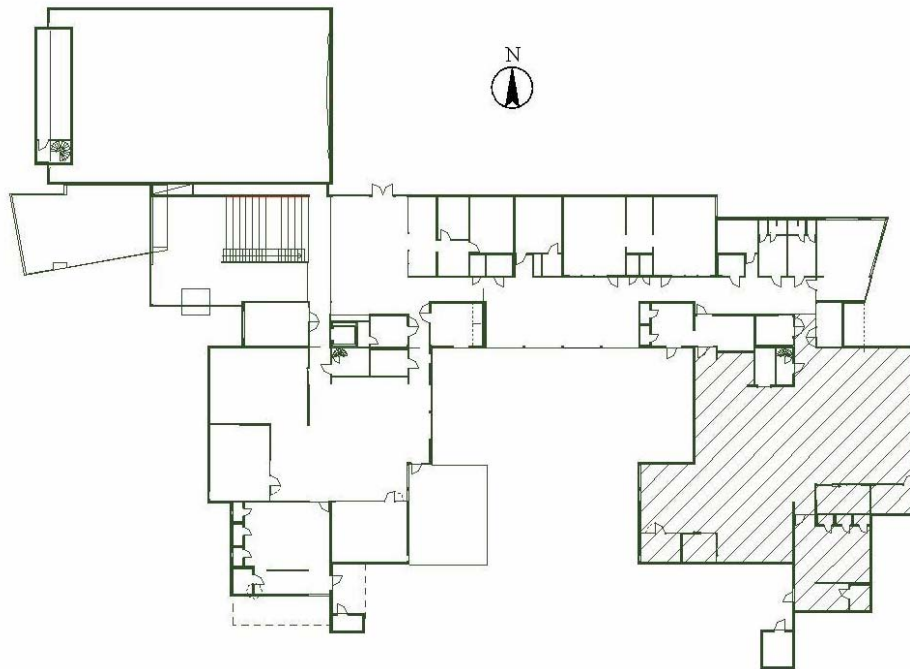
Figure 3.2. The general plan of the school building

Weather data for Belgrade for the year 1995 are provided by ASHRAE and are used in the examples with the above school building [50]. These data imply that the minimal temperature in wintertime is -11.5°C and the maximal temperature in summertime is 33.4°C.

3.2 Objective functions

The objectives are either to decrease the total cost or the energy consumption, while the thermal comfort requirement is satisfied. Even though these objectives have quite simple functions, the way to handle them and their problem variables is an issue. Therefore, the aim of this chapter is to show how to handle these issues in the optimization problems to get valuable results for the improvement of building performance. Explanation of the functions includes the necessary parameters to get these functions. The introduced functions are the following: the total cost, the energy cost, the insulation cost, the radiator cost, and the PPD value. The total annual cost has been estimated by the simplified annuity method. Therefore, while the final results are not highly valid, the methods are recommendable for the practical use.

Total cost is the sum of the investment cost and the operational cost on an annual basis. The investment cost covers both the insulation cost and the radiator cost. The operational cost is the energy cost. Therefore, the total cost can be expressed as:

$$C = C_E + C_I + C_R \tag{3.1}$$

where:

- C (€/year) is the total cost,
- C_E (€/year) is the cost of energy,
- C_I (€/year) is the cost of insulation, and
- C_R (€/year) is the radiator cost.

Since all the included costs are estimated on an annual basis, the same weight is given to all terms in Equation 3.1.

The optimization time of an EnergyPlus model in GenOpt can be significantly reduced if a given EnergyPlus model is a daily instead of a seasonal or an annual simulation. For example, the optimization times for the problems in these papers run from about 30 minutes to three hours for daily simulations on a 3.2 GHz Pentium 4 with 1 GB of RAM. The optimization for the same

building model run over the entire heating season can take the entire day on the same PC. Therefore, all the optimizations in this study are performed for the daily EnergyPlus model. Since Equation 3.1 deals with the annual energy cost, the annual energy consumption should be used. Therefore, the energy cost for the heating season is calculated by using the degree-day method. The total energy cost consists of two parts: the energy consumption itself and the cost for the installed power. Finally, the energy cost is calculated as:

$$C_E = \frac{Q_{DD}}{3600 \cdot 1000} \cdot \frac{DD \cdot y \cdot e}{t_i - t_o} \cdot c_E + P \cdot c_P \tag{3.2}$$

where:

- Q_{DD} (J) is energy consumption during the design day,
- c_E (€/kWh) is the price of energy per kWh,
- DD (°C·day) is the number of degree-days,
- e (-) is the coefficient of limitation, which consists of both the coefficient of temperature limitation e_t and the exploitation limitation e_b [51],
- y (-) is the coefficient of the simultaneous effects of unfavorable conditions [51],
- t_i (°C) is the indoor air temperature,
- t_o (°C) is the outdoor design air temperature,
- P (W) is the installed power of heating equipment,
- c_p (€/kWyear) is the annual energy price for kW of installed power equipment.

The insulation cost can be calculated as:

$$C_I = 1.4 \frac{A_I \cdot c_I}{n} \tag{3.3}$$

where:

- A_I (m^2) is the insulation surface of all exterior walls,
- c_I (€/m^2) is the insulation price per unit of surface,

    – n (year) is the economic lifetime.

The additional expense for installation is estimated at 40% of insulation cost.

The radiator cost is:

$$C_R = \frac{c_{R1}}{A_1} \cdot \frac{UA}{U} \cdot \frac{1}{n} \tag{3.4}$$

where:

    – c_{R1} (€/section) is the radiator price per section,

    – UA (W/K) is the radiator characteristic in EnergyPlus,

    – U (W/m²K) is the mean value of the overall heat transfer coefficient for radiators,

    – n (year) is the economic lifetime.

Since the *UA* value is a necessary parameter for defining the radiator in EnergyPlus, the *UA* value is the optimization variable in GenOpt. The *U* value is fixed, so only the radiator size is optimized.

The economic lifetime has been suggested to be 10 years. At a low real return rate, it can be assumed that the investment annuity is obtained simply dividing by 10. Since this study aims at analysis of the computer-based tools rather than an economic sensitivity analysis, the interest rate and the inflation are not taken into consideration in this analysis. However, it has been found that with the rate of interest, rate of inflation and tax deductions from the 80s, the real rate of return was nearly always low, sometimes even negative. In addition, any economic analysis should be interpreted with a good deal of healthy skepticism. The literature suggests that heating system economics primarily depend on fuel, and to a lesser extent, on the system type [52], while economic analysis of a heating system in a detached house in Finland has proven that a lower interest rate permits higher investments, decreasing energy use and the life cycle cost [53]. Even though the economic parameters could influence the total cost, they are not considered in this

study because the energy cost and the investment cost make the most important part of the total annual cost.

The predicted percentage of dissatisfaction (*PPD*) [54, 55] has been used in the Papers to represent thermal discomfort. The *PPD* is calculated as:

$$PPD = 100 - 95 \cdot \exp\left(-0.03353 PMV^4 - 0.2179 PMV^2\right), \qquad (3.5)$$

where the predicted mean vote (*PMV*) is the Fanger thermal sensation index. The *PPD* value is one of the outputs from EnergyPlus, so there is no need for additional calculation of this function. This output can be directly used in the optimization and data post-processing.

Equations 3.1 to 3.5 have been used in the following optimization cases. Even though the equations are the same, there are certain differences in the cases. For example, in the following cases the number of included terms in Equation 3.1 is different, either all three terms are included or only the energy consumption is treated. In addition, the way in which Equations 3.1 and 3.5 have been treated is different. Therefore, an important contribution of this chapter is how to handle these objectives through the coupled use of EnergyPlus and GenOpt. In Paper III, different values for the energy price were used from the values used in Paper II and IV. Conclusions in this and later chapters are related to the values of the parameters used in Equations 3.1 to 3.4, so they are not general for all such systems. However, since the procedures for handling these functions are a major contribution of this study, the main point of later chapters is on explanation of these procedures.

3.3 Application to the estimation of design parameter influence

The aim of Paper II was the analysis and optimization of parameters that influence both energy consumption and thermal comfort in a building with a hydronic heating system. The objective function takes into account both energy consumption and the investment cost. The influence of the following parameters was analyzed: the insulation thickness of the building envelope and the supply-water temperature.

The influence of the insulation thickness on the radiator heat rate and the indoor air temperature during the design day is shown for Class Zone 2 (Figure 3.2), which is oriented south-west. The set-point value of the indoor air temperature (T_z) is 20^oC during the occupancy period from 7 a.m. to 7 p.m., while outside this period the desired value is 15^oC. The supply-water temperature is 60^oC and the radiators are in use the entire day. The radiator surface areas are the same for the different values of insulation thickness, and they are calculated based on analysis of the heat losses. The indoor air temperature in the zone during the design day, for different insulation thicknesses, is shown in Figure 3.3, while the radiator heat rate (Q) is shown in Figure 3.4.
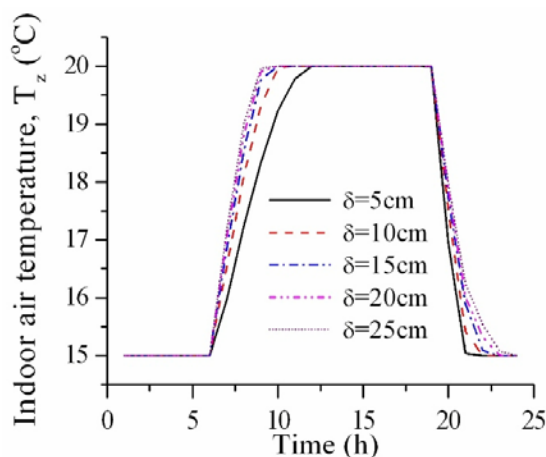
Figure 3.3. Influence of insulation thicknesses on indoor air temperature

Figure 3.3 shows that the desired value of the indoor air temperature can be achieved faster with larger insulation thickness (20 - 25 cm) of the building envelope.
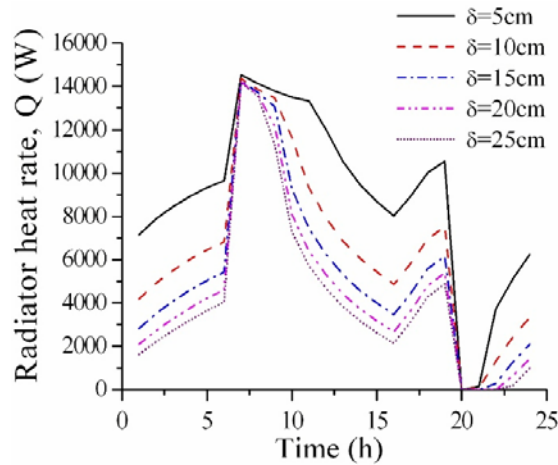
Figure 3.4. Influence of insulation thicknesses on radiator heat rate

Figure 3.4 shows that the radiator heat rate decreases when the insulation thickness increases. The maximum radiator heat rate occurs when the set indoor air temperature increases. If the set-point indoor air temperature is increased from 15°C to 20°C at 7 a.m., then the radiator heat rate is the highest at 7 a.m. This occurs due to the heating system response to the change in the set-point indoor air temperature. The rise is almost the same for different insulation thicknesses because the radiator surface area and the supply-water temperature are the same for different insulation thicknesses. When the indoor air temperature is almost constant, the radiator heat rate decreases when the insulation thickness increases.

The supply-water temperature has influence on both the energy consumption and the time necessary to reach the set-point indoor air temperature. The time necessary to reach the set-point indoor air temperature diminishes when the supply-water temperature increases. The influence of the supply-water temperature on the indoor air temperature during the design day for an insulation thickness of 10 cm and the same radiator surface area as in the above analysis, is shown in Figure 3.5.
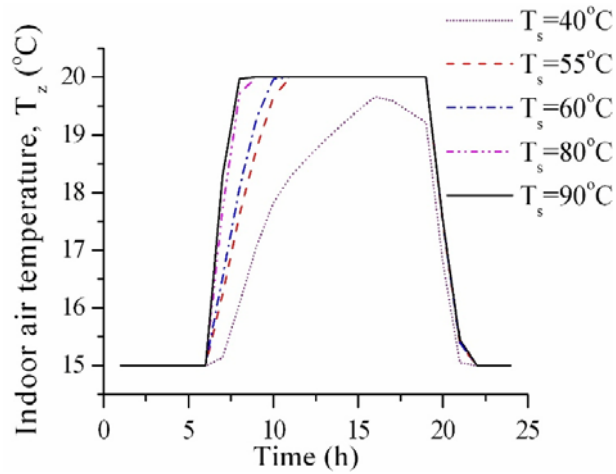
Figure 3.5. Influence of supply-water temperature on indoor air temperature

Figure 3.5 shows that the set-point indoor air temperature is reached after one hour for a supply-water temperature of 90°C, while the set-point value is not reached at all for a supply-water temperature of 40°C. The set-point indoor air temperature in the zone is maintained during the entire occupancy period for the highest supply-water temperature.

In this case, the optimization variable is only the insulation thickness. Therefore, the objective function deals only with the energy and insulation cost in Equation 3.1. Since the one-parametric optimization is used, the relationships between the total cost and the insulation thickness can be established easily. The relationships between these costs and the insulation thickness of the building envelope are shown in Figure 3.6.
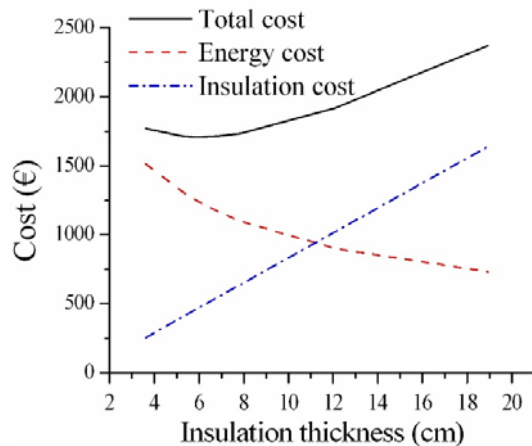
Figure 3.6. Relationship between cost and insulation thickness

For the used price values, it is possible to find the insulation thickness that gives a minimum total cost in Figure 3.6.

3.4 Application to patient room design

The case presented in Paper III had the objective of giving instruction in the design of a patient room in St. Olavs Hospital in Trondheim. The room is modeled as a basic shoebox. The number of degree-days is 4000^oC·day, and the outdoor design temperature is -14^oC. The design indoor air temperature in the patient room is 24^oC. The results show how different objective functions influence the design parameters.

The problem has two objectives: minimal total cost and minimal *PPD* (the best possible thermal comfort). The optimization variables, or the design parameters, are: the insulation thickness, the radiator area, and the supply-water temperature. Since the objective functions can be unsmooth if all the design parameters are optimized at the same time, the optimizations have been rerun for different supply-water temperatures (50^oC-90^oC with steps of 10K). This implies that the insulation thickness and the radiator area have been optimized directly in GenOpt, while the manual rerun has been done for the supply-water temperature. Figure 3.7 shows the information flow of this optimization approach.
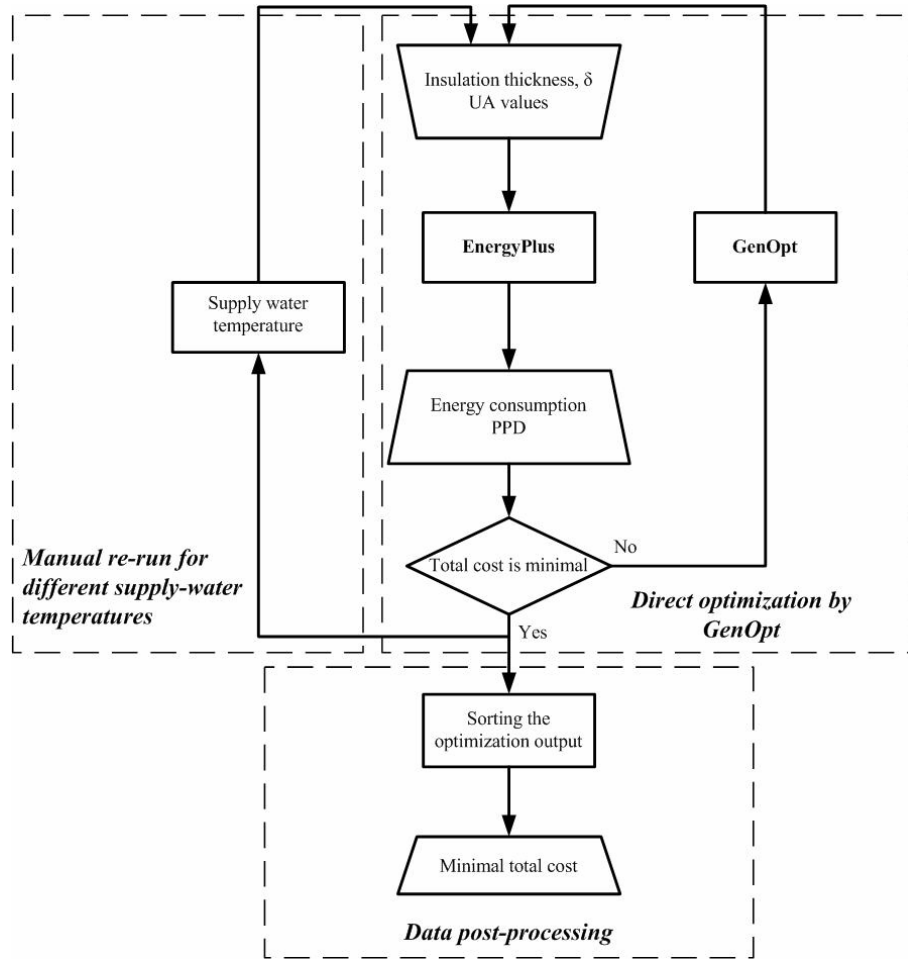
Figure 3.7. Information flow of the optimization approach for the design of a patient room

In Figure 3.7, the total cost is noted as the objective function since that function is minimized in GenOpt. However, the same optimization approach is implemented for both objective functions. In the case when the objective function is *PPD*, then the *PPD* value is minimized. This means that in the decision diamond for the direct optimization in GenOpt, *PPD* should be written. The results of these two optimizations with conflicting objective functions are elaborated later on.

The optimization results with the *PPD* as the objective function are shown in Figure 3.8. By using the optimization approach in Figure 3.7, the minimal *PPD* value is found for each supply-water temperature value by post-processing the optimization output. Finally, the influence of the supply-water temperature on thermal comfort and the total cost can be established, as shown in Figure 3.8. Since the objective function in this first optimization is *PPD*, it is shown in the upper part of Figure 3.8.
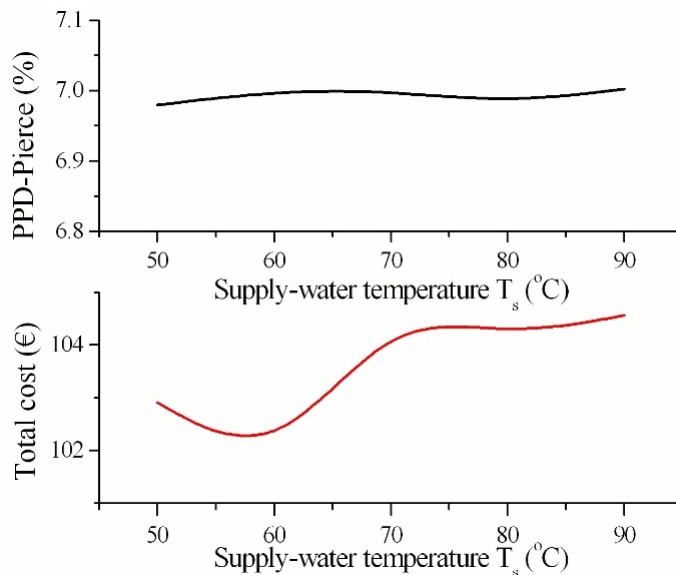
Figure 3.8. Thermal comfort and total cost vs. supply-water temperature with *PPD* as the objective function

Figure 3.8 shows that thermal comfort is almost the same for any combination of the design parameters, while total cost is different for the different supply-water temperatures. The total cost is not the same because the high supply-water temperatures give a high total cost due to high installed power.

The optimization results with the total cost as the objective function are shown in Figure 3.9. In this case, the total cost includes all three terms of Equation 3.1. This optimization leads the optimization variables to the lowest total cost. This means that thermal comfort might not be satisfied for some of the parameters. Since the aim is to satisfy the thermal comfort requirement, the optimization results are post-processed in the area where *PPD*<7.5%. This area with very low *PPD* is chosen because this is a patient room. In Figure 3.9, the total cost is shown in the upper part since the total cost is the objective function for this case.
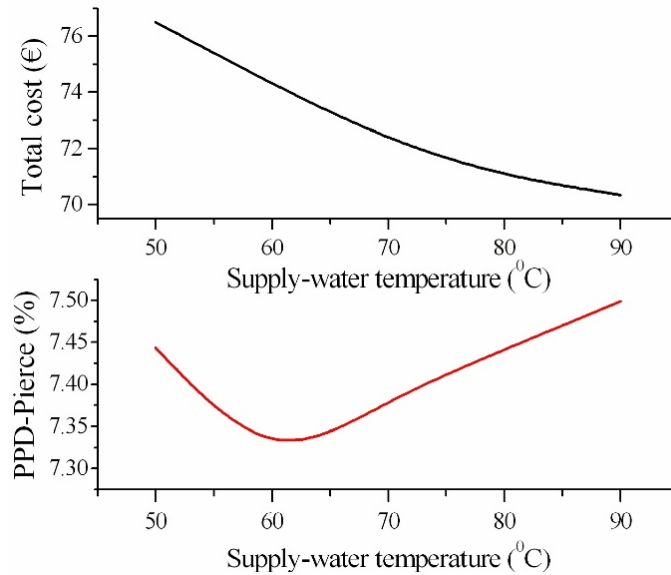
Figure 3.9. Total cost and thermal comfort vs. supply-water temperature with total cost as the objective function

Figure 3.9 shows that the total price is the lowest for the highest supply-water temperature for the given prices, because the radiator surface is the smallest. The lowest supply-water temperature needs the largest radiator and the thickest insulation. However, in this second case the *PPD* value is not as low as when *PPD* is the objective function. By comparing Figures 3.8 and 3.9, the difference in total cost can be noted, depending on what the objective function is. In addition, if thermal comfort is changed by 0.5%, the total cost is changed by 25 €/year. The above two cases show how the choice of objective function can influence the design parameters. For example, if *PPD* is the objective function, all the supply-water temperatures are acceptable, while if the total cost is the objective function, the higher values of the supply-water temperature are preferable.

Therefore, it can be meaningful for a practical use to test different optimization approaches with different objectives so that the most suitable solution for a certain practical problem can be found.

An important issue in searching for optimal values of the design parameters is the economic lifetime, which is a parameter in Equation 3.3. The influence of the economic lifetime on insulation thickness has been analyzed with the EnergyPlus model for heat loss. The objective function for this problem includes the energy cost and the insulation cost, or the first two terms of Equation 3.1. This optimization problem has insulation thickness as the optimization variable.

Since this optimization problem is a one-parametric problem, the Golden Section [38] method has been used as the optimization algorithm. The economic lifetime is the same within each optimization run, but is changed manually for each successive optimization run. The information flow for this problem is shown in Figure 3.10.
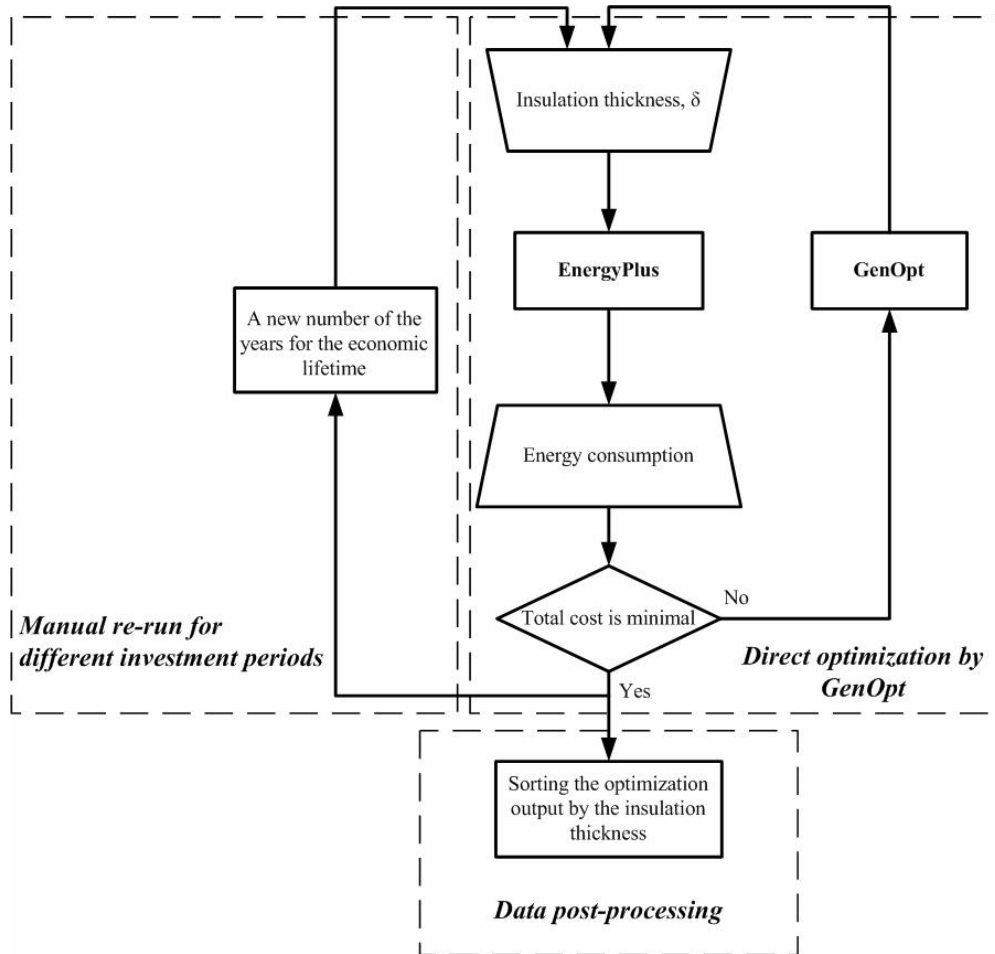
Figure 3.10. Information flow for estimation of the influence of economic lifetime

By using the approach shown in Figure 3.10, the influence of the economic lifetime on the relationship between the total cost and the insulation thickness is shown in Figure 3.11. The optimization output for each economic lifetime has been sorted by increasing values of insulation thickness. Three economic lifetimes have been examined: 5, 10 and 15 years.
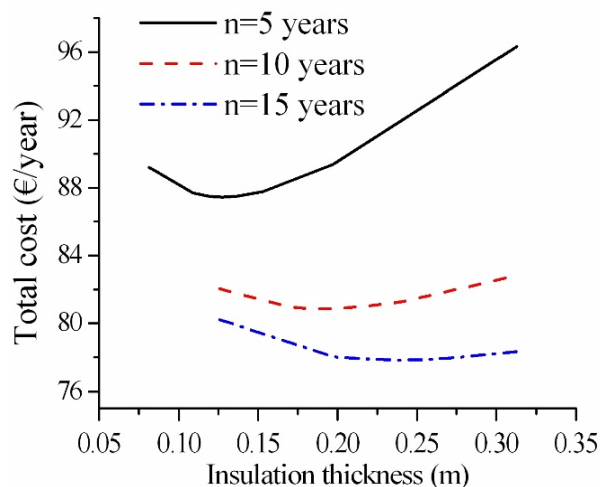
Figure 3.11. Relationship between total cost and insulation thickness influenced by the economic lifetime

Figure 3.11 shows that the highest annual total cost is induced by the shortest economic lifetime, five years. Therefore, in the case with the shortest economic lifetime, the optimal insulation thickness has the lowest value. When the economic lifetime is longer, the optimal insulation thickness is thicker. In addition, if the economic lifetime is longer, 10 or 15 years, then the relationships in Figure 3.11 have wider minimum than for five years. This gives the possibility of more opportunities for the insulation solution than with a short economic lifetime. All the conclusions in Paper III are valid only for the prices and parameters used in that case, and could be different for different parameter settings. However, the approach for coupling the simulation and optimization, rerunning and post-processing the data can be used for many different examples with different problem settings.

3.5 Application for solving conflicting objectives in the building design

Paper IV shows how to analyze the problem of two conflicting objectives by using a one-objective optimization algorithm and the practical use of a mathematical optimization coupled with the simulation software. These two conflicting objectives are: total cost and thermal comfort. Building energy analysis has been done for the school building introduced in Chapter 3.1. The

optimization variables in the study are: the insulation thickness of the building envelope, the supply-water temperature and the heat exchange area of the radiators.

The objective functions for the study in Paper IV are introduced by Equations 3.1 and 3.5, while the relevant parameter values are given in Paper IV. Since the optimization of many variables can be difficult in GenOpt, as explained in the introduction to this chapter, the approach for the optimization in Paper IV is explained here. The supply-water temperature is the parameter defined as schedule-type in EnergyPlus. The option schedule-type in EnergyPlus is used for defining parameters that change hour by hour (e.g., supply-water temperature, set-point indoor air temperature, zone occupancy, etc.). In this approach, the optimization of the supply-water temperature has been performed by the manual rerun of the direct optimization in GenOpt. The direct optimization in GenOpt has total cost as the objective function, and the optimization variables are: the insulation thickness of the building envelope and the heat exchange area of the radiators. Each manual rerun of the direct optimization has been performed the different values of the supply-water temperature, covering the range from 35°C to 90°C with steps of 5°C. The minimum of the total cost is determined for each value of the supply-water temperature regarding thermal comfort. Actually, post-processing of the results has been done by analyzing the total cost in the range where PPD<10%. This approach is similar to the approach given by the information flow in Figure 3.7, except that for this approach it is necessary to add an additional diamond for the data post-processing. That diamond asks if *PPD*<10%. Finally, the data post-processing gives two relationships:

- − The relationship between total cost and the supply-water temperature;
- − The relationship between *PPD* and the supply-water temperature.

The first relationship is shown in Figure 3.12, while the second one that treats thermal comfort is shown in Figure 3.13. The total cost in Figure 3.12 is the annual total cost, and is defined by Equations 3.1 to 3.4.
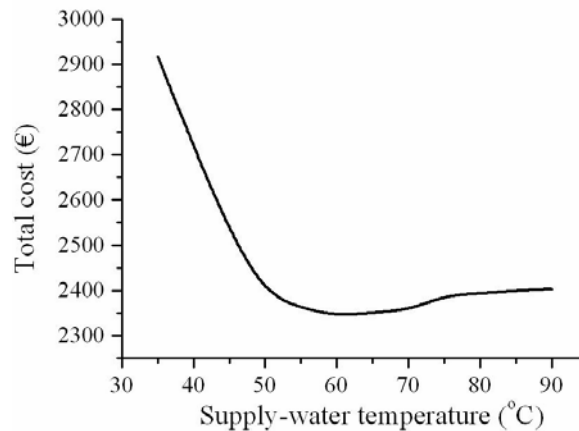
Figure 3.12. Relationship between total cost and supply-water temperature

Figure 3.12 shows that the total cost is strongly influenced by the lower supply-water temperature. Actually, the lower the supply-water temperature, the higher the total cost. After a value of 60°C, the total cost does not have a large increase. These conclusions regarding total cost and the supply-water temperature are valid only for the data used in Paper IV.
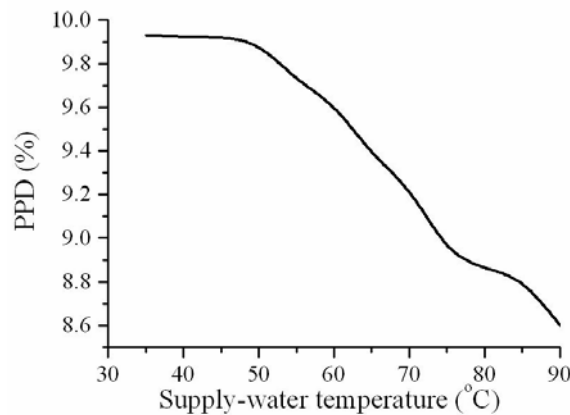
Figure 3.13. Relationship between *PPD* and supply-water temperature

Finally, Figure 3.13 shows that the thermal comfort requirement is satisfied in the whole range of supply-water temperatures. Therefore, the objective regarding satisfied thermal comfort is fulfilled by filtering the optimization output during data post-processing.

3.6 Closing remarks regarding the use of simulation and optimization tools in the design

Based on the experiences in the cases explained above, the most important remarks regarding the use of simulation and optimization tools are the following:

- Since a lot of time is spent in creating the input for a simulation model, it is desirable to utilize all the features of a simulation model by using the optimization tool. In that way, it can be possible to determine the parameter values that lead to optimal system performance. Actually, an optimization tool provides a good opportunity to play with the simulation model.
- Optimization outputs can give an overview of results obtained by the different combinations of optimization variables. This is useful in choosing the solution to a given problem. The optimization process gives the direction in which the considered parameters have to be chosen considering the objectives and constraints.
- The optimization problem approach that suits a certain problem should be developed. Actually, that approach should establish an information flow among data. Since it is not always possible to perform only a direct optimization, it is necessary to establish an alternative approach for handling the problem. The established approach should take into consideration the problem objectives, constraints, and the limits of the program.
- Using multiple reruns of the simulation model with the optimization tool, it is possible to better understand the building and HVAC system behavior. Depending on the problem objective, the optimization approach should be tailored in such a way that the final user of the simulation/optimization results gets the best understanding of the building system.
- Conclusions in this chapter are related to the objective functions and parameters used. Since these objective functions are not always relevant, the conclusions are not general for all such systems. However, the suggested optimization approaches and the noted issues are relevant for the used tools.

4   SIMULATION AND OPTIMIZATION APPLICATION TO BUILDING CONTROL STRATEGY IMPROVMENT

This part of the study presents the advantages of computer-based tools in the improvement of existing building performance. It is often necessary to make an analysis of the cost-effectiveness of any HVAC system retrofit. In addition, no system modification should be undertaken without carefully study of the economic and technical feasibility of any proposed retrofits. Since computer-based tools provide the ability to carefully examine any proposed improvement measure with very little effort, it is useful to develop the building and HVAC system model until improvements in the building performance are achieved. This part of the study presents how to find better strategies for two different systems. Even though the simulation and optimization tools are the same as for the cases in Chapter 3, the approaches are different. The first case is a study of improvement to the building control strategy for a hydronic heating system. The second case deals with the control strategy for a ventilation system using the heat recovery wheel.

There have been many examples of optimization tools for the improvement of building control strategies in literature. Since the existing building energy management control strategies are mostly heuristic, there is a need to systematically examine and improve them, as mentioned in [56]. For example, Lu et al. [41] used a modified genetic optimization algorithm to find the optimal set points of the controllable variables in an HVAC system with cooling coils. In order to obtain effective energy management for an existing HVAC system, an evolutionary programming algorithm was coupled with the simulation tool to provide the optimal combination of the chilled water and supply-air temperatures in [40]. Building control strategies can include strategies for different building elements. Each proposed strategy should be compared with an alternative until an improvement is found. A comparison of ten different control strategies developed for a glazing system was presented in [57], while the time based building operation schedule was treated as an integral part of the optimization problem in [58].

This study gives a suggestion for how to utilize EnergyPlus and GenOpt to improve performance in existing buildings.

4.1 Control strategy optimization

Before these two cases with strategy optimization are presented, a general approach to optimization is explained. This approach includes: involving the optimization variables and the objective function, and developing information flow for handling the optimization process so that the desired aim can be achieved. The desired aim can be to achieve the desired system performance.

Since each model input influences the model output, any model input can be involved as an optimization variable. EnergyPlus needs a large number of parameters as inputs. Therefore, any optimization problem using the EnergyPlus model should try to choose the most important inputs as the optimization variables. Therefore, the optimization variables have to be involved according to a certain optimization problem. For example, the building envelope insulation, an EnergyPlus input, influences the energy consumption, so that input can be an optimization variable.

In a performance-based simulation such as EnergyPlus, each output presents a certain building performance. Therefore, any EnergyPlus output can be used as an optimization objective. In addition, several EnergyPlus outputs can be combined in one objective function. Since there are many EnergyPlus outputs, the point of defining an objective function depends only on a particular practical problem. Therefore, any user can create the objective function according to a particular analysis.

Examining different control strategies together with building properties can require a large number of variables. Even though the optimization tools are powerful, they cannot handle a large number of variables. In addition, understanding the optimization output can be difficult. Therefore, a variable classification can help to simplify the direct optimization problem. In the following examples, the variables are classified so that some of them are optimized directly by GenOpt, while the others are used for a manual rerun. Finally, the outputs from several optimizations are post-processed. Therefore, it is important to develop an approach to data handling that can give practically useable and valuable results in a simple way.

4.2 Possibilities for new control strategies in a hydronic heating system

Possible new control strategies have been tested on a school building located in Belgrade. ASHRAE weather data for Belgrade are used [50]. This building has already been introduced in Chapter 3.1. Different control strategies for the hydronic heating system in this building have been examined for the winter design day, which is used as an example to find an appropriate procedure for this type of optimization problem. If the desired thermal comfort could be achieved for the winter design day with a certain control strategy and building construction, then that strategy can be used as an upper limit to find strategies for other days in the heating season. Therefore, the use of the winter design day in the study does not influence the conclusions drawn about the problem. In addition, for other locations with similar weather data, the conclusions from this work can be used. However, the same procedure can also be repeated with different weather data for the purpose of finding a better control strategy.

The background for this idea comes from the fact that building construction and equipment characteristics change over time. Therefore, a control strategy should be adjusted to the actual building demand. By examining different control strategies, the optimal control strategy can be found for certain building construction and equipment characteristics. The optimal control strategy for a certain building construction and its heating equipment properties can be found for at a minimal total cost, as long as the thermal comfort requirement is satisfied. Therefore, review of the optimization outputs provides the possibility of choosing the most suitable solution for actual building demand according to the building properties.

Problem variables
A control strategy in EnergyPlus for the heating system of the school building consists of the set-point supply-water temperature, the set-point value of the indoor air temperature and the system status. The system status shows whether a system is shut down or not. These control parameters can be set up in different ways so that heat consumption is decreased, while thermal comfort is satisfied during the occupancy period. Therefore, the optimization problem deals with the following variables: the insulation thickness of the building envelope, the radiator size (the UA value of the radiator), the supply-water temperature, the set-point value of indoor air temperature,

and the system status. The three last variables are defined by a schedule, implying different values for each hour of a day.

Since this problem has many variables, they are separated into two groups. Such a variable classification gives a framework for the optimization approach in this case. The first group consists of insulation thickness and the radiator sizes. The second group consists of the control variables, such as the supply-water temperature, the set-point indoor air temperature and the system status. The first group of variables is optimized directly by GenOpt, while the second group is fixed for each optimization run. All these variables are listed in Table 4.1.

Table 4.1. The problem variables in the heating system

Variable Name	Lower bound	Upper bound	Optimization approach
Insulation thickness – δ (m)	0.05	0.3	Directly by GenOpt
UA1 – (W/K)	400	800	Directly by GenOpt
UA2 – (W/K)	60	120	Directly by GenOpt
UA3 – (W/K)	50	110	Directly by GenOpt
UA4 – (W/K)	80	160	Directly by GenOpt
UA5 – (W/K)	20	50	Directly by GenOpt
UA6 – (W/K)	80	180	Directly by GenOpt
UA7 – (W/K)	140	280	Directly by GenOpt
UA8 – (W/K)	380	760	Directly by GenOpt
UA9 – (W/K)	350	700	Directly by GenOpt
Set-point indoor air temperature – T_{in} (°C)	15	20	Fixed for each optimization run
Supply-water temperature – T_s (°C)	50	90	Fixed for each optimization run
System status – (On/Off)	0	1	Fixed for each optimization run

The control strategy could be optimized directly by GenOpt, but this is not done here since the EnergyPlus output data analysis would be difficult. It would be difficult to connect each strategy with its corresponding output.

The suggested control strategies are shown in Figure 4.1. The idea for the suggested control strategies is based on the school working hours.
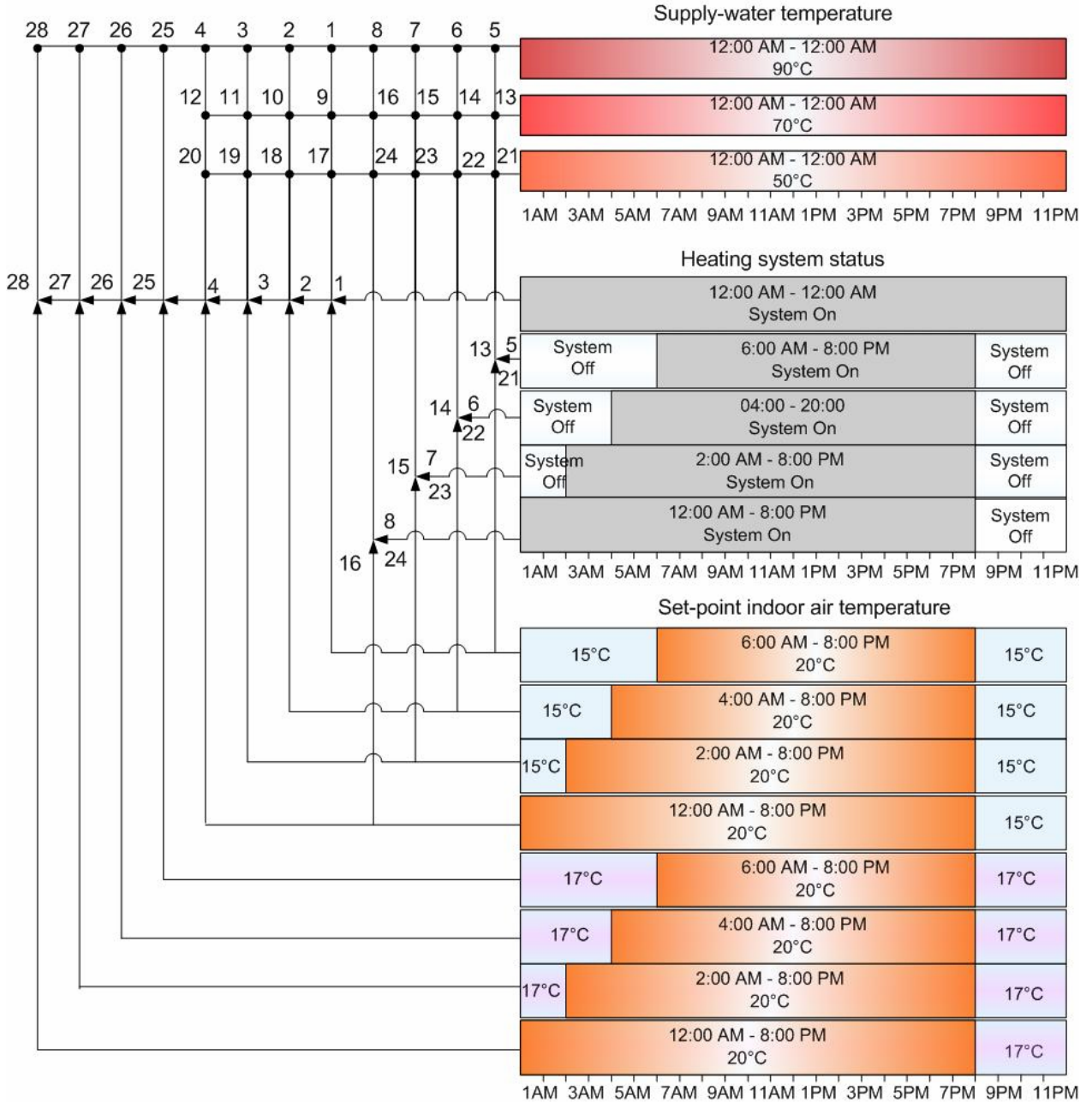

Figure 4.1. Control strategies for the heating system

There are 28 different control strategies in Figure 4.1. The black bullets show that a particular strategy has been completed. The arrows in Figure 4.1 help to follow which variables are used. For example, Strategy 1 implies a set-point indoor air temperature of 20°C from 6 a.m. – 8 p.m.

55

and 15°C for the remaining hours (the system is in use continuously) and the supply-water temperature is 90°C. Strategy 21 implies the same set-point indoor air temperature as in Strategy 1 while the system is on 6 a.m. – 8 p.m., and the supply-water temperature is 50°C. Strategies 1 to 8 and 25 to 28 use a supply-water temperature of 90°C. The total cost and the thermal discomfort for all these 28 strategies have been examined. Since the school working hours are from 7 a.m. to 8 p.m., thermal comfort has to be satisfied during this period. During the unoccupied period some of the control variables can be changed so that energy is saved. Therefore, examination of the above strategies is necessary to find the appropriate strategy for different building properties so that energy can be saved while thermal comfort is satisfied.

The problem constraints

The problem constraints are the values of the desired thermal comfort level. The problem constraint is derived from satisfactory thermal comfort at 7 a.m. The thermal comfort is evaluated by use of the *PPD* [1, 54], which is one of the outputs from EnergyPlus. Therefore, it is easy to handle such a parameter in further optimization. For the suggested strategies in Figure 4.1, the maximal *PPD* value during the occupancy period can be expected at 7 a.m. because that is the first hour of the occupancy period and the desired thermal comfort level may not yet have been achieved. Therefore, in this study the *PPD* value at 7 a.m. is observed. The mean value of the thermal comfort for the entire design day does not give a proper estimate of thermal comfort over the occupancy period. Since the optimization and simulation tools do not provide the ability to calculate either the mean or maximal value of thermal comfort over a certain period, the value of thermal comfort at 7 a.m. is assumed to be suitable for the purpose of this case.

This constraint was applied during the post-processing data phase, while the optimization in GenOpt was run unconstrained.

Objective function

The objective function for this example is defined by Equations 3.1 to 3.4 in Chapter 3.2. This objective function was used for design purposes in Chapter 3, while here it is used for strategy optimization.

Before the information flow for this optimization problem is involved, an approach that extracts a maximal value from the EnergyPlus output is explained. In Equation 3.2, Chapter 3.2, the installed power of heating equipment, P (W), has to be used for calculation of the energy cost. Sometimes it is difficult to know the value of the installed power of heating equipment. Instead, the maximal heating power over a certain period of time can be used for that purpose. GenOpt provides the ability to optimize a unique value of a certain variable output from a performance-based simulation such as EnergyPlus. This unique EnergyPlus value can be either the value of a variable at a certain time step, or an integral or mean value for the particular period (design day, heating season, etc.). The integral or mean value of a variable is influenced by the nature of the variable (for example if the value of temperature is optimized, then the mean value for the given period is used, while for energy consumption it is the total consumption for the same period) [59]. Since this simulation tool does not provide the ability to calculate the maximal value of the heating equipment rate over a certain period [59], a procedure for how to deal with this is suggested. This procedure gives a simple instruction on how to find the maximal value of the heat rate over a daily simulation. The maximum heat rate occurs at a moment when there is a change in the system, either due to a change in the set-point indoor air temperature or in the system status. This occurs due to the heating system response to a change in the set-point indoor air temperature. Therefore, the value of the radiator heat rate at the moment when there is a change in the control strategy is used to calculate the energy consumption cost in the objective function.

The optimization approach for the control strategies consists of a direct optimization by GenOpt, a manual rerun, and data post-processing. In the direct optimization, the total cost is defined as the objective function, while the insulation thickness and the *UA* values are the optimization variables. In addition, the thermal discomfort (*PPD* value) is calculated simultaneously during the optimization process. Afterwards, these *PPD* values are used as constraints during the post-process analysis. This direct optimization problem has been manually rerun for each of the 28 control strategies as shown in Figure 4.2. Finally, data post-processing sorts the optimization output by the *PPD*, so that relationships between the total cost and the thermal discomfort have been established. After the optimization output is sorted by *PPD*, it is easy to choose for a certain control strategy the minimal total cost in the area where *PPD*<10%. The information flow of the explained optimization approach is shown in Figure 4.2.
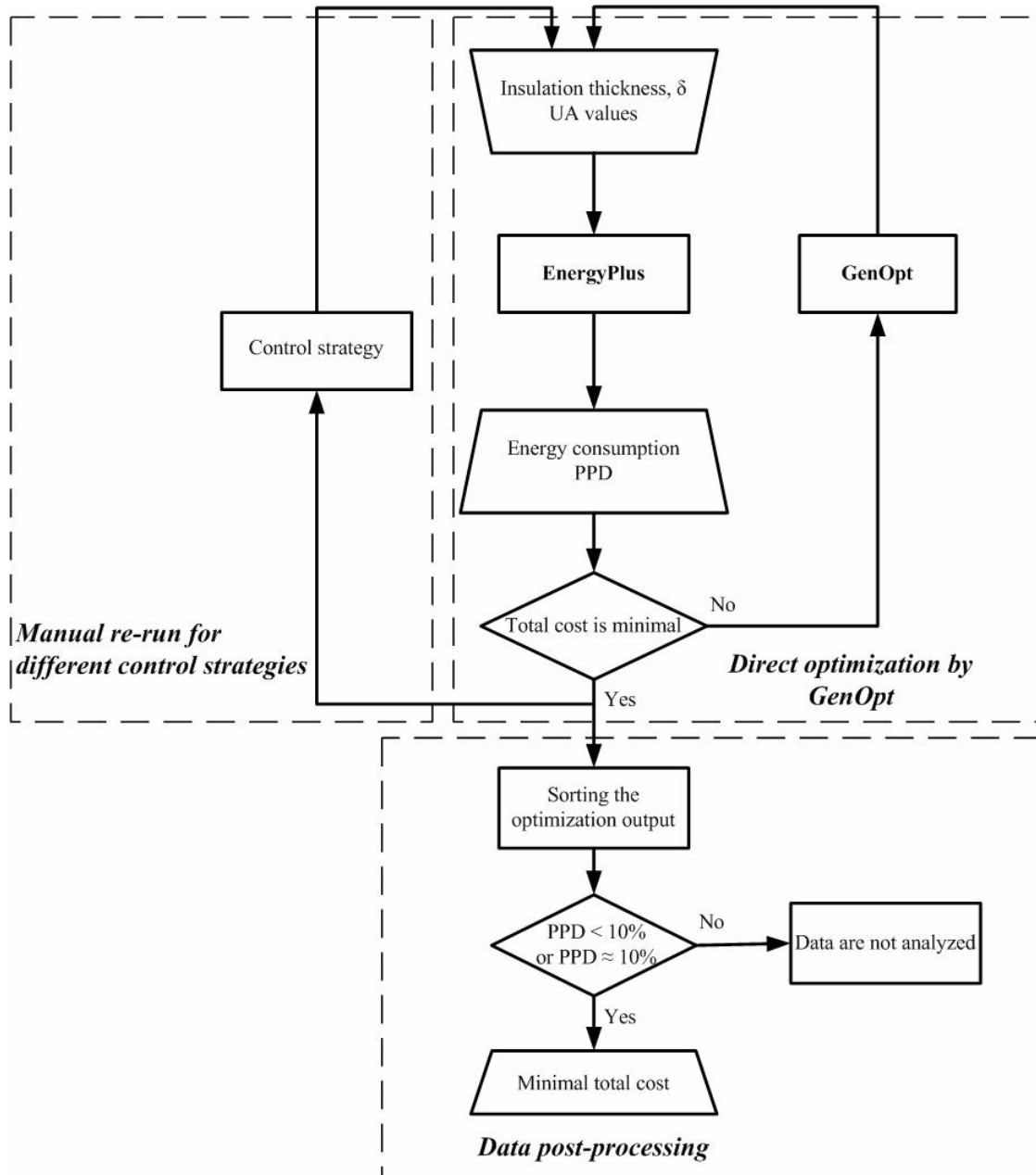
Figure 4.2. Information flow for strategy optimization in the heating system

The applied optimization method for the direct optimization by GenOpt (Figure 4.2) is the generalized pattern search (GPS) implementation of the Hook-Jeeves search algorithm. This optimization algorithm is available in the GenOpt library, and is recommended in order to reduce the risk of failing at a point that is non-optimal [38].

The relationships between the total cost and the thermal discomfort are established by post-processing the optimization outputs as explained above. The problem constraints deal with the values of *PPD* at 7 a.m., so these values are used for the relationship to total cost. These relationships, total cost vs. thermal discomfort, are valid for the different combinations of insulation thickness and radiator size regarding the different control strategies. Therefore, each point in the following figures represents a different combination of insulation thickness and radiator size for a particular control strategy. Figures 4.3 to 4.9 show the post-processed optimization outputs for all the suggested strategies. Since the scales are different in each of the figures, there are horizontal and vertical reference lines at € 3500 of the total cost and 10% of *PPD*, respectively. It can be easily noted in the figures that all the points left of the 10% of *PPD* line are acceptable.
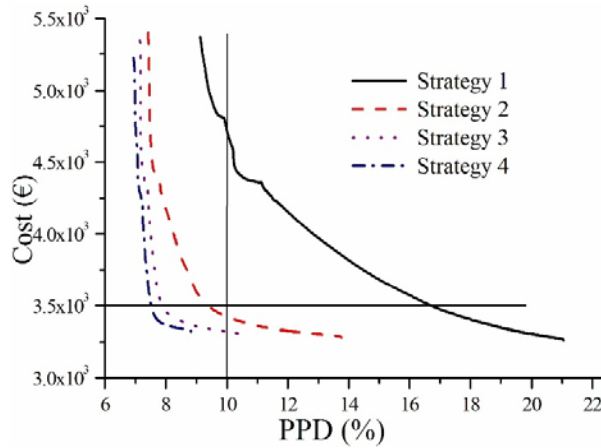
Figure 4.3 Total cost vs. PPD for Strategies 1 to 4
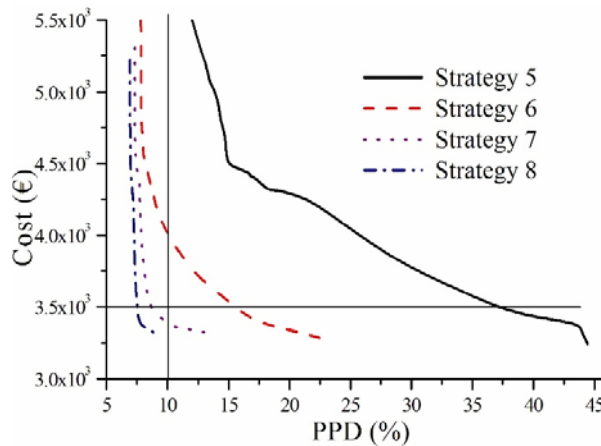
Figure 4.4 Total cost vs. PPD for Strategies 5 to 8

59
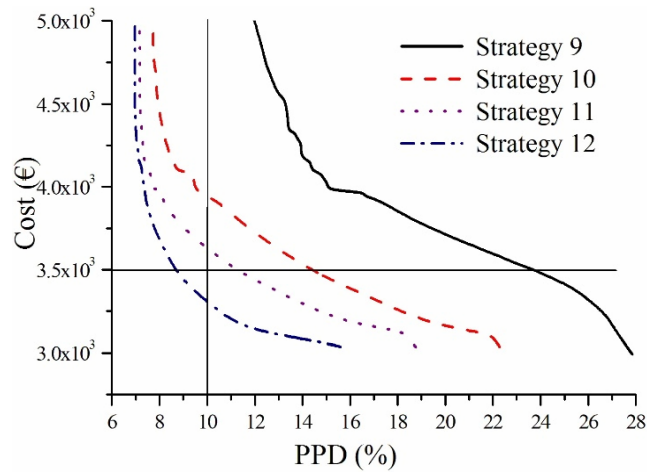
Figure 4.5 Total cost vs. PPD for Strategies 9 to 12
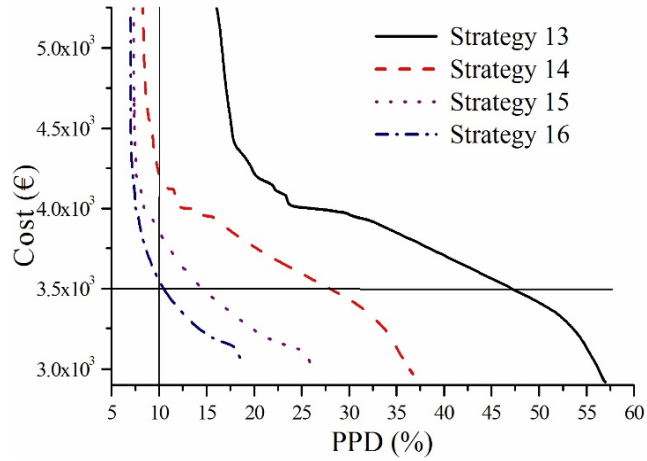
Figure 4.6 Total cost vs. PPD for Strategies 13 to 16
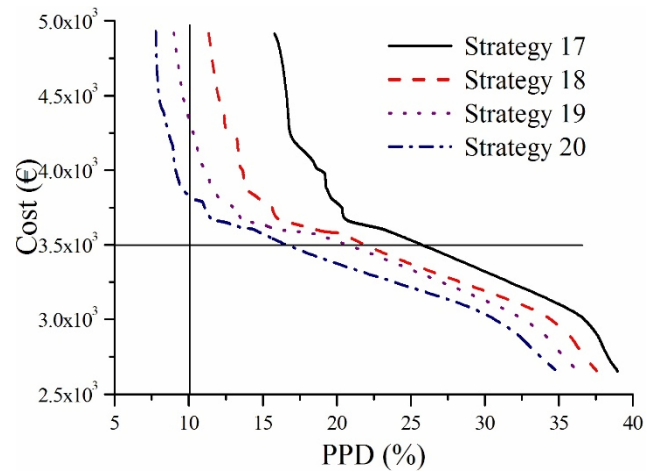
Figure 4.7 Total cost vs. PPD for Strategies 17 to 20
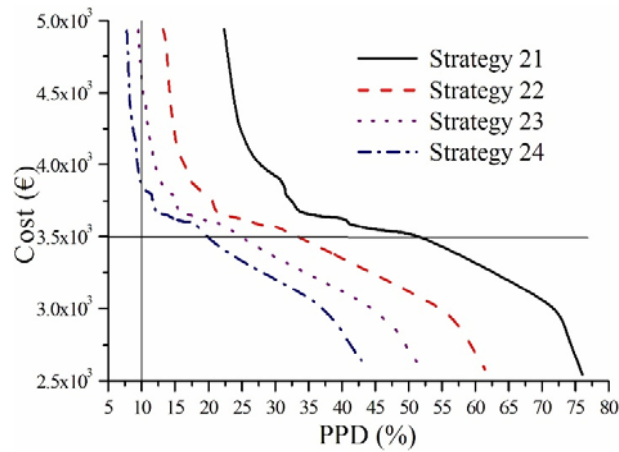
Figure 4.8 Total cost vs. PPD for Strategies 21 to 24
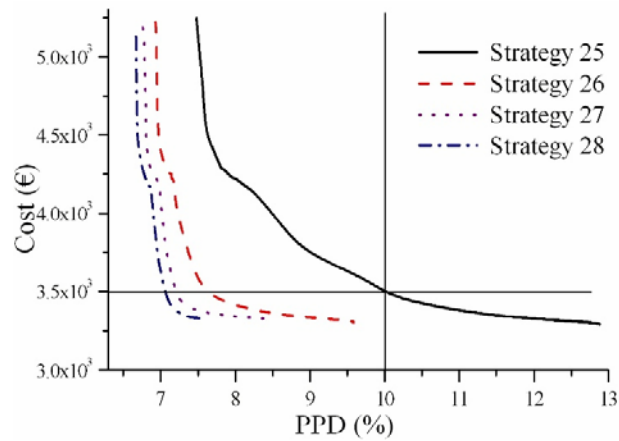
Figure 4.9 Total cost vs. PPD for Strategies 25 to 28

In the case of the short night setback periods (Strategies 3 and 4 in Figure 4.3) the desired thermal comfort is achieved at 7 a.m. for all values of the total cost. The total cost is higher if the period with the night setback period is long, since the maximum radiator heat rate is higher in the transient period. If during the entire non-working period the system is shut down and the night setback is implied, then the desired thermal comfort cannot be achieved at 7 a.m., no matter what combination of insulation thickness and radiator size is used (Figure 4.4). Therefore, long night setbacks together with system shut down measures are not recommendable, even when the supply-water temperature is 90°C.

The optimization results for a supply-water temperature of 70°C and 50°C with radiators in use during the night setback period are shown in Figure 4.5 and 4.7, respectively. Since the heating

system is in use the entire day for all the strategies in Figures 4.5 and 4.7, there are more combinations of parameters that provide a possibility of achieving the desired thermal comfort at 7 a.m. than when the heating system is shut down during the night setback period. Since the *PPD* is higher than 10% for Strategies 13, 21 and 22 at 7 a.m., these strategies cannot be implemented for any combination of insulation thickness and radiator size, as shown in Figures 4.6 and 4.8. These low supply-water temperatures can be used for the shorter night setback and system shut down periods and a few combinations of insulation thickness and radiator size. For example, by using Strategies 15, 16 and 24, the desired thermal comfort is achieved at 7 a.m. for the particular combinations of the optimization variables. Therefore, these low supply-water temperatures and long system shut down periods cannot be implemented for the purpose of energy saving.

If the night setback temperature is 17$^\mathrm{o}$C and the supply-water temperature is 90$^\mathrm{o}$C, then desired thermal comfort levels can be achieved at 7 a.m. for almost all combinations of parameters, as shown in Figure 4.9. Actually, Strategies 25 to 28 can give the desired thermal comfort at 7 a.m. for almost all combinations of insulation thickness and radiator size.

The optimal control strategy for a certain building construction and its heating equipment properties can be found by choosing the minimal total cost, as long as the *PPD* value is lower than 10% in the above Figures 4.3 to 4.9. Actually, in this way the optimal combination of building construction, heating equipment, and the related control strategy can be established. It was not possible to find the minimal total cost in the areas where the *PPD* < 10% for Strategies 5, 9, 13, 17, 18, 21, and 22. Therefore, these strategies cannot be implemented practically, even though they give a certain energy savings. Even though these seven strategies cannot achieve a *PPD* value of 10% at 7a.m., the minimum of the total cost has been found for the *PPD* value nearest to 10%. Finally, for each of the strategies the total cost per year, the energy cost per year and the achieved *PPD* at 7 a.m. are compared in Figure 4.10.
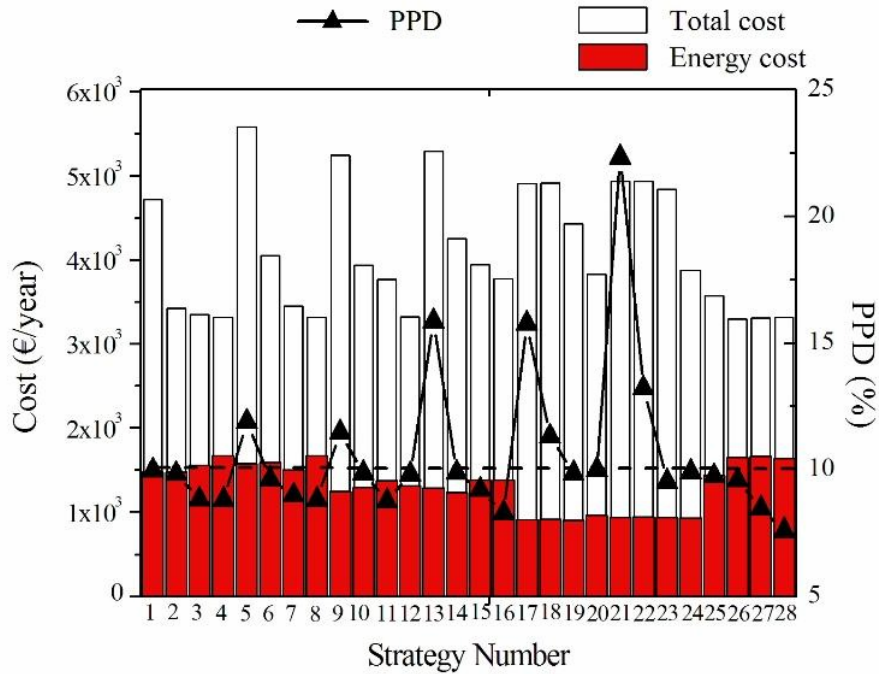
Figure 4.10. Comparison of the strategies for the heating system

Figure 4.10 shows that for control Strategies 5, 9 and 13, the desired thermal comfort at 7 a.m. cannot be achieved, even though the total cost is quite high compared to the other strategies. This occurs due to the high energy cost induced by the high equipment installed power, and the investment costs are increased due to thicker insulation and the heating equipment necessary for such long night setback periods. Strategies 17 to 24 have the lowest energy cost, while the total cost is increased due to large heating equipment and thick insulation. Even though Strategy 21 requires the largest equipment and the thickest insulation, it cannot achieve the desired thermal comfort level by 7 a.m. Actually, for a supply-water temperature of $50^{\circ}C$, long night setback periods are not a good solution for the control strategy.

To prove the benefit of the suggested strategies in the heating system, the energy savings for each strategy has been found as:

$$ES = 100 \cdot \left(Q_b - Q_{opt}\right)/Q_b \qquad (4.1)$$

where:

- − *ES* (%) is the energy savings,
- − Q_b (kWh) is the total baseline energy consumption,
- − Q_{opt} (kWh) is the total optimal energy consumption.

Total energy consumption has been found for the entire heating period. The baseline energy consumption, Q_b, has been defined as the heating energy necessary when there is neither a night setback nor a system shut down. Since each strategy requires different building construction and heating equipment size, this baseline energy consumption is different for each strategy. The achieved energy savings are given in Table 4.2. The energy savings have also been calculated for the control strategies that cannot achieve the desired thermal comfort at 7 a.m. Therefore, comments are given in Table 4.2. For example, using Strategy 5 it is possible to save 15.07% of energy, while thermal comfort is not satisfied. Therefore, the comments are useful for choosing the strategy that can best achieve the desired thermal comfort level.

Table 4.2. The energy saving achieved by the suggested strategies in the heating system

Strategy number	Baseline energy consumption (kWh)	Optimal energy consumption (kWh)	Energy savings (%)	Comments
1	15857	13573	14.40	TC[2] is satisfied
2	21940	19800	9.76	TC is satisfied
3	24576	22932	6.69	TC is satisfied
4	28443	26857	5.57	TC is satisfied
5	14474	12292	15.07	TC is not satisfied
6	20025	17908	10.57	TC is satisfied
7	21940	20419	6.93	TC is satisfied
8	28443	26605	6.46	TC is satisfied
9	14474	12232	15.49	TC is not satisfied
10	19250	17207	10.61	TC is satisfied
11	21939	20395	7.04	TC is satisfied
12	23085	21632	6.30	TC is satisfied
13	14474	12158	16.00	TC is not satisfied
14	16212	14414	11.09	TC is satisfied
15	20912	19386	7.29	TC is satisfied
16	21939	20705	5.62	TC is satisfied
17	14459	11860	17.98	TC is not satisfied
18	14459	12451	13.89	TC is not satisfied
19	14862	13531	8.96	TC is satisfied
20	17328	16052	7.37	TC is satisfied
21	14459	11694	19.12	TC is not satisfied
22	14459	12464	13.80	TC is not satisfied
23	14459	13049	9.75	TC is satisfied
24	16428	15085	8.18	TC is satisfied
25	20025	18184	9.19	TC is satisfied
26	28443	26481	6.90	TC is satisfied
27	28443	27067	4.84	TC is satisfied
28	27318	26306	3.70	TC is satisfied

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[2] Thermal comfort - TC

4.3 Possibilities for improving the performance of a ventilation system

Paper V deals with a ventilation system with a heat recovery wheel and several related operational parameters. The idea for this work first appeared after the results of the survey of Norwegian building facilities (see Chapter 2.1.2) showed a problem with excessively warm air and poor air quality in the buildings. In addition, it has been found that heat recovery efficiency is usually studied separately from the buildings themselves. Considering the significant influence of the heat recovery wheel on energy consumption, it is necessary to consider it together with the building and HVAC equipment as mentioned in [60]. Since the aim of Paper V is to develop a control strategy for the supply-water temperature, a few retrofit measures are suggested. The presentation of the study in Paper V includes: the building and the ventilation system description, the optimization problem approach, and the effect on energy consumption of these retrofit measures.

The building has a ventilation system with a heat recovery wheel and a water-heating coil. Weather data for Trondheim are used in this example. The base of the building and the building facades are shown in Paper V. For calculation purposes, the building has been zoned so that the exterior zones extend six meters inside of the exterior surface as recommended in [4]. Such a way of zoning implies two exterior zones, both of which are ventilated and share a common ventilation system. The only internal loads are assumed to be loads from the occupants. The occupant density is 0.1 persons/m^2 [61]. This implies 32 persons in the larger zone and 22 persons in the smaller zone.

The building and the ventilation system models are developed in EnergyPlus, while GenOpt is used as the optimization tool.

A simple configuration of the ventilation system has been chosen to establishing a basic overview of this type of system. A sketch of the system is shown in Figure 4.11. The air flow through the system is 3.3 m^3/s (11,880 m^3/h) with the larger zone consuming 2 m^3/s and the smaller consuming 1.3 m^3/s. The amount of air is chosen according to ASHRAE recommendations for hourly air exchange in office buildings [1].
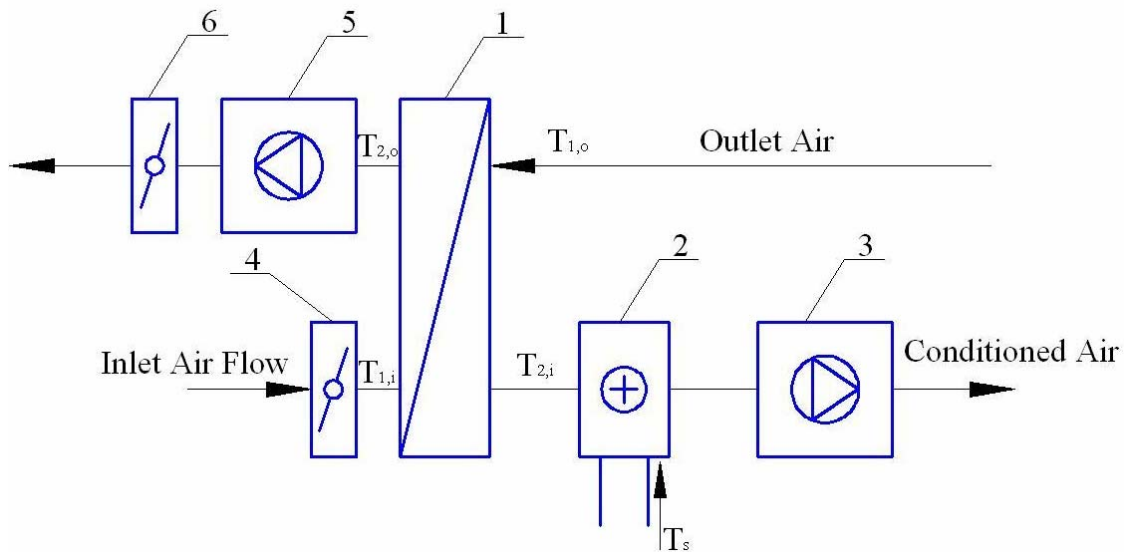
Figure 4.11. Ventilation system with the heat recovery wheel

In Figure 4.11, the ventilation system consists of the following components: (1) the heat recovery wheel, (2) the water-heating coil, (3) the supply fan, (4) a damper, (5) the exhaust fan, and (6) another damper. In addition to these components, the important temperatures are also noted in Figure 4.11. T_s is the supply-water temperature of the heating coil, $T_{1,i}$, $T_{2,i}$ are the inlet air temperatures before and after the heat recovery wheel, and $T_{1,o}$, $T_{2,o}$ are the outlet air temperatures before and after the heat recovery wheel.

The problem definition

The conditioned air temperature (in this case, the indoor air temperature) is controlled by the supply-water temperature of the heating coil. In addition, the indoor air temperature is influenced by the performance of the heating coil. The supply-water temperature is controlled by two sensors and the outdoor temperature compensation curve, the upper solid black curve in Figure 4.14. These two sensors are the outdoor air temperature sensor and the supply-water temperature sensor. The heating coil does not operate when the outdoor air temperature is above 5°C.

Even though the heating coil size is fixed, the UA value of the heating coil can change over time due to fouling. A poorly tuned compensation curve can result in a high supply-water temperature

for the heating coil. In addition, there is the problem of selecting at which outdoor air temperature to shut down the heating coil so that the set-point indoor air temperature is not biased. Since the heat recovery wheel is chosen for the design conditions, the performances of the heat recovery wheel may differ from the design conditions due to the above faults. For example, if the heating coil capacity is low for a certain outdoor air temperature, then the heat recovery wheel cannot provide enough energy, even if it is in use all the time. On the other hand, if the heating coil capacity is high for a certain outdoor air temperature, then the achieved indoor air temperature can be high due to both types of equipment being unnecessarily in use. Therefore, it can be useful to study the influence of these parameters, the supply-water temperature and the UA value, on the achieved indoor air temperature. A new outdoor temperature compensation curve for the supply-water temperature can be found.

Finally, this optimization problem deals with the supply-water temperature and the heating coil UA value in order to find the mutual influence between the performance of the heat recovery wheel and the heating coil. In this way, a better energy management control strategy for the ventilation system can be found. In this case, a better control strategy means a strategy that answers the actual building demand, so that there is no bias in the achieved performance. In this example, the relationships are found by establishing an optimization problem and post-processing the optimization results.

The optimization approach

The direct optimization problem is defined in GenOpt so that the objective is the maximum heat recovery rate of the wheel, Q_{rec}. Therefore, the optimization problem is defined as:

$$\max Q_{rec}, \tag{4.2}$$

$$\text{and the variables are} \begin{bmatrix} UA \\ T_S \end{bmatrix}. \tag{4.3}$$

where:
- Q_{rec} (W) is the heat recovery rate of the heat recovery wheel,
- UA (W/K) is the heating coil characteristic in EnergyPlus,

    − T_s (°C) is the supply-water temperature of the heating coil.

The water flow rate through the heating coil is not considered in this optimization problem because the defined value of the maximum flow rate in EnergyPlus is only a limit for the simulation. The water flow is calculated at each time step so that the load requested of the coil is met at a flow rate that is less than the defined flow rate. This implies that changing the maximum flow rate will not change any results. The entire optimization process is performed for a volumetric air flow of 3.3 m³/s. Since the analyzed ventilation system is exposed to different weather conditions, the above optimization problem was rerun for different values of the outdoor temperature. The range of outdoor temperatures is from -15°C to 0°C, with a step of 5°C. The problem variables are listed in Table 4.3.

Table 4.3. The problem variables in the ventilation system

Variable Name	Lower bound	Upper bound	Optimization approach
UA – (W/K)	2	8000	Directly by GenOpt
Supply-water temperature – T_s (°C)	30	90	Directly by GenOpt
Outdoor temperature – T_{out} (°C)	-15	0	Fixed for each optimization run

The optimization approach for this example consists of the direct optimization by GenOpt, the manual rerun, and data post-processing. The information flow for this optimization approach is shown in Figure 4.12.

The applied optimization method in the direct optimization by GenOpt (Figure 4.12) is the hybrid generalized pattern search algorithm using a particle swarm optimization (PSO) algorithm. This optimization algorithm is available in the GenOpt library. This algorithm consists of the PSO with a constriction coefficient algorithm and the Hook-Jeeves algorithm. The PSO algorithm is a stochastic population-based algorithm, while the Hook-Jeeves algorithm is a direct search algorithm. First, this hybrid algorithm performs the PSO for the continuous variables and then switches to the Hook-Jeeves generalized pattern search algorithm to refine the continuous

variables. Since the PSO algorithm is a global optimization algorithm, the hybrid algorithm is, compared to the Hook-Jeeves algorithm, less likely to be attracted by a local minimum that is not global. Thus, the hybrid algorithm combines the global features of the PSO algorithm with the provable convergence properties of the GPS algorithm [38].
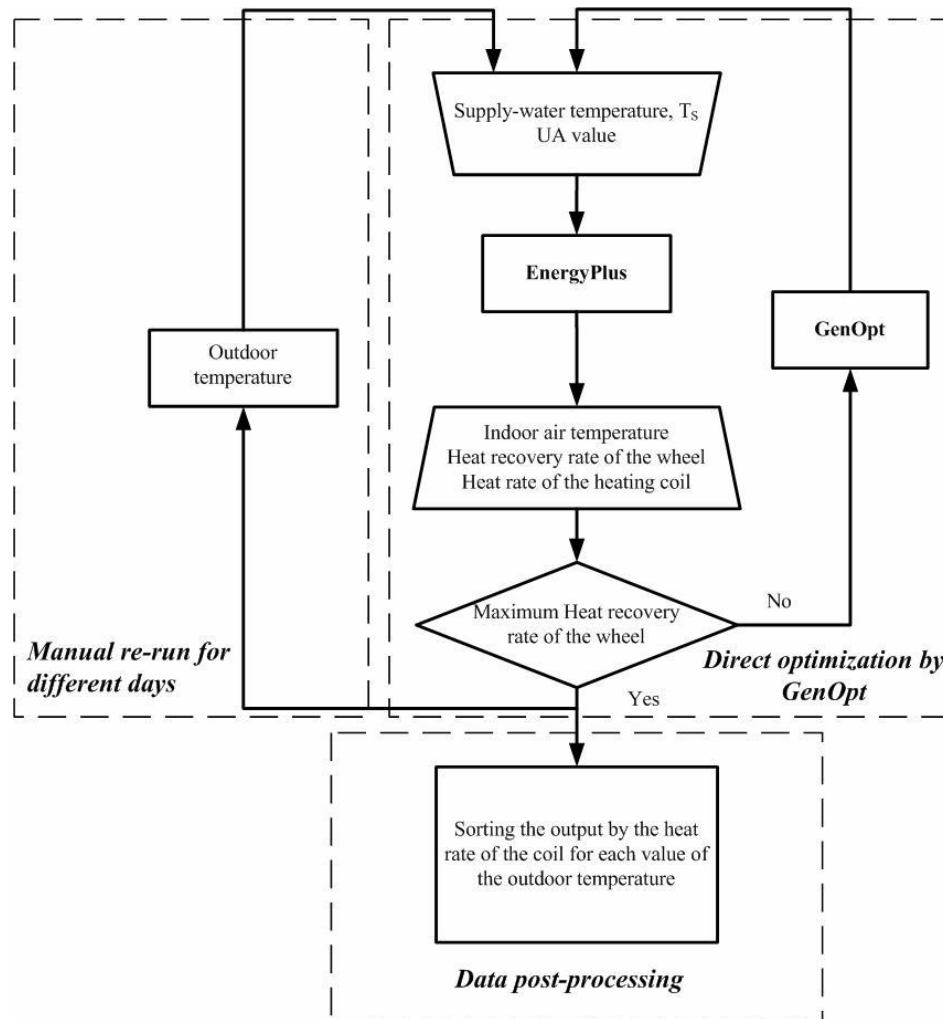
Figure 4.12. Information flow for strategy optimization in the ventilation system

The information flow in Figure 4.12 implies that the direct optimization, where the maximum heat recovery rate of the wheel is the objective, has been rerun manually for different outdoor temperatures. In addition, the achieved indoor air temperature and the heat rate of the heating coil have been calculated simultaneously with the objective function. Therefore, these outputs from the direct optimizations can be used for data post-processing. In data post-processing, the heat

recovery rate of the wheel and the indoor air temperature have been sorted by the heating coil rate. Finally, the following two relationships can be established for each outdoor air temperature:

1. Heat recovery rate of the wheel vs. heat rate of the heating coil, and

2. Indoor air temperature vs. heat rate of the heating coil.

The above relationships are established for the different values of the outdoor air temperature, T_{out}, and in this case they are: -15°C, -10°C, -5°C, and 0°C. The results are shown in Figure 4.13.
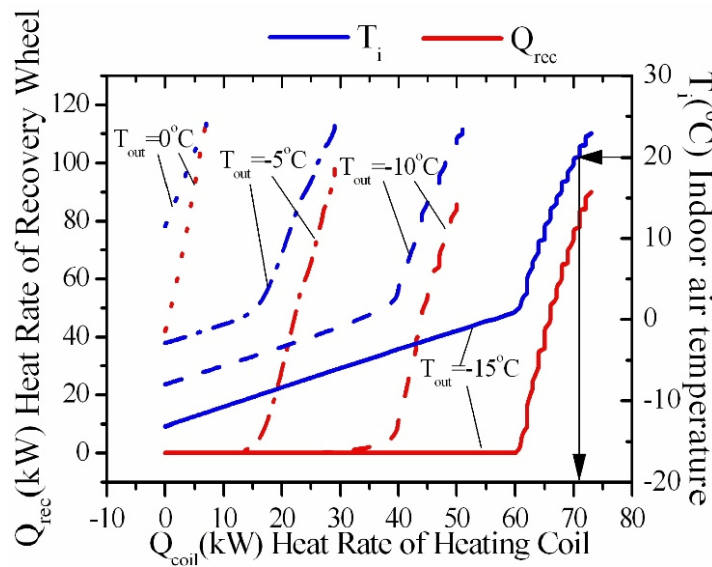
Figure 4.13. The indoor air temperature defines the necessary heating coil rate, while the heating coil rate shows how much of the heat recovery wheel rate is used

Figure 4.13 shows that the relationships between the heat recovery rate and the heating coil rate are different depending on the heat rate of the recovery wheel. For example, for T_{out}=-15°C, even though the heat recovery wheel is in use, its recovery rate is negligible until the heat rate of the heating coil is 60 kW. Even though the heat recovery wheel is in use, it cannot recover energy due to low heating coil capacity. Low heating coil capacity can appear due to fouling. In addition, the slope of the indoor air temperature line is different depending on the heat rate of the recovery wheel. If the heat recovery wheel gives a significant amount of energy, then this slope is steeper. Figure 4.13 shows that regardless of the heating coil performance, the set-point indoor air temperature can be achieved for the higher outdoor air temperatures. This means that the heating

71

coil cannot be fouled under the low outdoor air temperatures, while its performance does not influence the achieved indoor air temperature at 0^oC with the recovery wheel in use.

The results in Figure 4.13 can be used to find the appropriate outdoor temperature compensation curve for a certain pairing of outdoor air temperature and heating coil rate so that the set-point indoor air temperature can be achieved. For example, to achieve 20^oC for the indoor air temperature, if the outdoor air temperature is -15^oC, the heating coil capacity should be higher then 70kW. By using the optimization outputs (Figure 6 in Paper V) it is possible to find the suitable supply-water temperature that gives this heating coil capacity. Consequently, by using the results in Figure 4.13, suitable capacities can be found for each outdoor air temperature that give an indoor air temperature of 20^oC.

The results in Figure 4.13 show that it is possible to shut down the coil when the outdoor air temperature is higher than 0^oC. This means that when the outdoor air temperature is higher than 0^oC, only the heat recovery wheel can be used in this ventilation system. Based on the optimization results, it is possible to obtain the new outdoor temperature compensation curve. Both the new and the current outdoor temperature compensation curves are given in Figure 4.14.
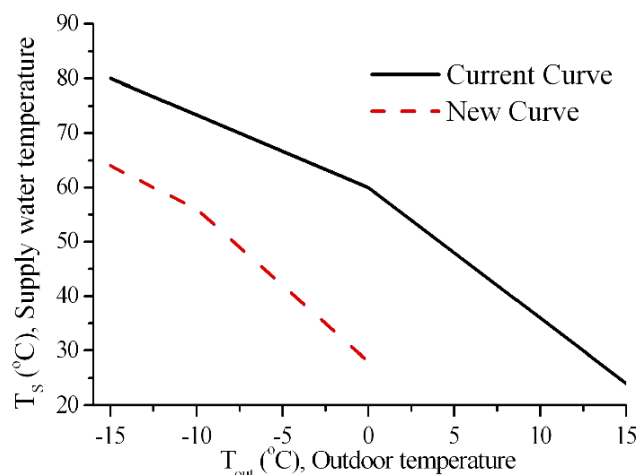
Figure 4.14. Current and new outdoor temperature compensation curves

As Figure 4.14 shows, the supply-water temperature can be lower than the current values, so this new compensation curve can be used as a retrofit measure for this ventilation system.

The retrofit measures

The following retrofit measures have been tested on the ventilation system with the heat recovery wheel:

- Case 1: the current supply-water temperature (the supply-water temperature drawn by the solid black curve in Figure 4.14);

- Case 2: the new supply-water temperature (the supply-water temperature is the red-dashed curve in Figure 4.14) is applied and the coil is shut down when $T_{out}=0^{o}C$;

- Case 3: the current supply-water temperature with the coil shut down when $T_{out}=0^{o}C$;

- Case 4: the new supply-water temperature with the coil shut down when $T_{out}=0^{o}C$, and the entire system shut down within four hours after 8 p.m.;

- Case 5: the current supply-water temperature with the coil shut down when $T_{out}=0^{o}C$, and the entire system shut down within five hours after 8 p.m.

The obtained energy savings can be determined based on [62] by using an equation that compares the difference between the continuous end-use baseline and the continuous post-retrofit energy use measurement. In this study the energy savings are calculated as:

$$ES = 100 \cdot \left(Q_b - Q_{pr} \right)/Q_b \tag{4.4}$$

where:

– ES (%) is the energy savings,

– Q_b (kWh) is the total baseline energy consumption,

– Q_{pr} (kWh) is the total post-retrofit energy consumption.

The energy savings are calculated in the same way for both heating and electric energy. Case 1 has been used as a baseline for the retrofit estimation. The baseline energy use is calculated for the outdoor air temperature range from $-15^{o}C$ to $5^{o}C$. This outdoor air temperature range implies 190 days from the weather data for Trondheim. In this study, the post-retrofit consumption represents possible energy consumption if the retrofit measures were implemented.

The resulting energy savings for the above retrofit measures are given in Table 4.4. Table 4.4 gives the energy savings for both heating and electrical energy. The energy consumption in Table 4.4 is the total energy consumption when the outdoor air temperature ranges from -15$^{\mathrm{o}}$C to 5$^{\mathrm{o}}$C. The heating energy, Q_{coil}, is the energy consumed by the heating coil, while the power consumption, Q_{el}, is the energy for the fans, pump, and the motor for the heat recovery wheel.

Table 4.4. The energy savings implied by each measure in the ventilation system

Case	Q_{coil}(MWh)	Q_{el}(MWh)	Heating Energy Saving (%)	Electric Energy Saving (%)
1	55.6	26.2	0	0
2	44.7	26.2	19.6	0
3	47.0	26.0	15.5	0
4	38.2	21.7	31.0	17.1
5	38.2	20.5	31.0	21.8

The highest energy savings are achieved when the coil is shut down. The energy consumption of the coil is slightly lower by using the new supply-water temperature curve. The reason is that the same amount of the energy is necessary to achieve the set-point indoor air temperature regardless of the level of the supply-water temperature.

The largest part of total power consumption is due to the fans. Therefore, there is no big difference in the power consumption between the first three cases. When the entire system is shut down, there is also a significant energy savings in power consumption. The energy savings are 19.6% when the new curve is applied for the supply-water temperature. In addition, it is possible to save 15.5% of the energy by using the current curve for the supply temperature, but while shutting down the coil when the outdoor air temperature is higher than 0$^{\mathrm{o}}$C. The highest heating energy savings are 31% when the entire system is shut down during four or five hours of the non-working period. A shut down period of four or five hours has been suggested to achieve the desired thermal comfort during the working hours. In the case of a longer system shut down, the desired thermal comfort cannot be achieved. Indoor air quality (IAQ) has not been discussed here, because EnergyPlus cannot provide any indices of IAQ as outputs. Therefore, the last two measures should be accepted only with reservation.

4.4 Closing remarks regarding use of the simulation and optimization tools in the existing building performance improvement

Based on the experiences in the examples explained above, the most important remarks about using the simulation and optimization tools to improve the building performance are the following:

- Since the building and HVAC characteristics change over time due to ageing and fouling, it is necessary to systematically improve the control strategies, so that the HVAC system meets the real building demand. The use of optimization tools provides a possibility to play with the simulation model. Therefore, the simulation tool coupled with the optimization tool can help to examine different possible strategies so that the optimal strategy can be found.
- Sometimes a certain practical problem has many variables. Therefore, it can be desirable to classify the variables and simplify the direct optimization problem so that the optimization outputs are easier to handle. The framework for the variable classification has to be in accordance with how the variables are optimized, either directly by the optimization program or by manual rerun.
- After the variables are classified, an approach for a certain optimization problem should be established using an information flow. The approach should include the description of the direct optimization, the optimization rerun, and the data post-processing.
- Each proposed new control strategy should be compared with an alternative until an improvement is found.
- Faults in equipment caused by fouling or poor operation settings can be easily involved by using the optimization tool, because a huge range of the values can be tested with little effort.
- The conclusions in the above examples are not general for all such systems. The solution is always determined by the objective and important variables. Therefore, the above examples of strategy optimization give the instructions on how to deal with such problems. In addition, the above examples aim to overcome several of the issues with using EnergyPlus and GenOpt for strategy optimization.

5 MODEL CALIBRATION, AND FAULT DETECTION AND DIAGNOSIS

This chapter presents the utilization of computer-based tools for improving the building HVAC systems maintenance. For that purpose, it is necessary to either develop a system model or use already existing performance simulation tools. To make valuable conclusions about the system, any system model output should be adjusted to the real data. Actually, any used model for the fault detection should be calibrated first. Therefore, at the beginning of this chapter, a possibility for the calibration of an EnergyPlus model against the BEMS data using GenOpt is tested. A few problems in such a calibration have been noted. Therefore, in Paper VII, a simple heat balance model is used to elaborate a few faults in the hydronic heating system. Regardless of the model calibration problems with GenOpt, several faults have been tested in EnergyPlus for the purpose of establishing the cause-effect rules for the fault detection and diagnosis. The rules have been generated using simulations. EnergyPlus cannot model the control loop or a hydraulic system, while the simulation program TRNSYS has such an ability. Therefore, an HVAC system with AHUs has been modeled in TRNSYS and tested on a few faults to generate the rules for their diagnosis.

In this chapter, two different buildings and HVAC systems have been studied. Therefore, these two facilities are briefly presented before the related faults are elaborated.

Before the main part of this chapter is elaborated, a brief literature review of this subject is presented.

There has been much interest in the development of FDD techniques that are suitable for use in building control systems. In addition, there are many different diagnosis techniques and listed faults for different HVAC systems [6]. For example, a practical algorithm for diagnosing control loop problems in an AHU was provided in [18]. Deviations in the indoor air temperature and energy consumption caused by different faults were explained practically, using an easy-to-use tool for FDD in [63]. A method for the AHU sensor fault detection based on the principal

component analysis (PCA) was elaborated in the work of Wang and Xiao [5]. Two types of faults, an open window and a defective radiator valve, were studied using the model-based FDD in [64]. An on-line diagnostic test, which diagnoses distinct and abrupt faults in an AHU, was directly programmed in the building automation system in the work of Pakanen and Sundquist [8].

Despite the many works in the building maintenance area, there still is a need to efficiently utilize FDD techniques and algorithms for the practical explanation of deviations in building performances. Therefore, this chapter aims at the practical explanations of a few operating faults in the hydronic heating system and at generating the diagnosis rules for several faults in two HVAC systems.

5.1 Model calibration

The calibration process compares the results of the simulation with measured data and tunes the simulation until its results closely match the measured data. There are eight steps in the calibrated simulation method [65], and one of them is comparing the model output to the measured data. This step is elaborated here, and a method based on optimization programming is suggested for that purpose. The method is presented in Paper VII as well.

Before an objective function for the model calibration is involved, a general model of a system can be defined as:

$$Y_m = C \cdot X_m, \qquad\qquad (5.1)$$

where:
- Y_m is the vector of the model output,
- X_m is the vector of the model input,
- C is the vector of the model parameters.

Then the objective function for the calibration of the model given in Equation 5.1 could be defined as:

$$\min \sum_{k=1} \left(\frac{Y_{r,k} - Y_{m,k}}{Y_{r,k}} \right)^2 , \qquad (5.2)$$

such that:

- k is an output element index,

- $Y_{m,k}$ is a model output,

- $Y_{r,k}$ is a corresponding measured data (or the real data in this text).

In Equation 5.2, the optimization variables are the model parameters. The objective function 5.2 requires that the vectors, Y_m and Y_r, are the same size.

A simple graphical interpretation of this model calibration approach is shown in Figure 5.1.
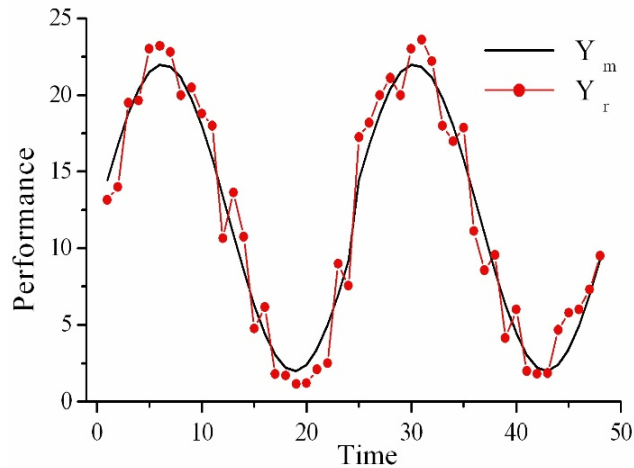

Figure 5.1. An optimization problem for the model calibration

Figure 5.1 does not show a certain performance, yet it is an example of how the optimization has to decrease the differences among the model outputs, Y_m (black, solid line), and the real data, Y_r (red bullets). Therefore, the objective function for the model calibration has to be the minimum of

the difference among the model outputs and the real data. Actually, in each time step, the model output should be as close as possible to the real data of the same time step. Therefore, an optimization program has to have the ability to adjust each value in the model outputs, Y_m, to the real data, Y_r. The real data, in the case of the fault detection, can be data from both the BEMS and additional measurement. Chapters 2.2.3 and 2.2.4 give the explanation of the data used.

The study in Paper VII uses the same approach, described above, for the calibration of the model on an hourly basis. In that study, sequential quadratic programming (SQP) [66] was used as the optimization algorithm. In this algorithm, it is possible to pass from point to point of the two vectors and to fit the model to the real data. Since MATLAB was used to model the building and the heating system, the MATLAB optimization toolbox was used to solve this optimization problem. The information flow of this optimization problem is shown in Figure 5 of Paper VII.

5.1.1 The calibration problem of an EnergyPlus model using GenOpt

A model that is calibrated should correspond to the real data in each time step. In addition, a model performance has to be the same as the real system performance. Therefore, the optimization algorithm that adjusts the model in each step is acceptable for the model calibration. The approach with the SQP algorithm in the MATLAB optimization toolbox is acceptable for this purpose. Since the performance-based simulation, EnergyPlus, coupled with GenOpt was used in most of this work, it is necessary to test their ability to calibrate an EnergyPlus model. Two issues in this calibration are reported.

In Chapter 4.2, under the objective function, it was emphasized that GenOpt uses a unique value of an output over a run period in the objective function. This means that GenOpt algorithms cannot handle an output vector in the optimization problem. Therefore, an objective function for the model calibration in GenOpt can be defined as:

$$\min\left(\frac{Y_r - Y_{m,run\ period}}{Y_r}\right)^2, \tag{5.3}$$

such that:

- – $Y_{m,run\ period}$ is an EnergyPlus output for a run period,

- – Y_r is a real value for the same period as a corresponding EnergyPlus output.

The objective function defined by Equation 5.3 means that only one output value is optimized. Since GenOpt does not handle an output vector, it does not adjust the model output at each time step. Equation 5.3 is equivalent to Equation 5.2 only if GenOpt runs through a group of simulations, but such a possibility is not currently available. In addition, using optimization with EnergyPlus requires much effort on pre-processing input files and post-processing results. Therefore, the current GenOpt algorithm library cannot be used for the EnergyPlus model calibration against real performance data.

Besides the above issue in the model calibration by GenOpt, an additional issue was found. This second issue is related to the EnergyPlus model for the radiators. The majority of this work deals with the heating system. The radiators are modeled by using Baseboard Heater:Water:Convective units [67] that are intended to model thermostatically controlled baseboard heater. The model for this unit does not perform in the same way as the real radiator in that the model does not control return water temperature but rather controls the water flow rate to add the required amount of heat to the zone to meet the thermostat set-point [68]. Since in the real case, as explained in Paper VII, the radiators are controlled by the supply-water temperature, it is not possible to use this model to be calibrated against the available real data for the heating system. For a successful model calibration, it is necessary that the system model performs in the same way as the real system.

Regardless of the above issues, GenOpt is a good solution for adjusting the parameters in the design. For example, the U value of the windows can be adjusted to be the same as in a producer catalog. The input data for a window in EnergyPlus are quite detailed, and usually it is difficult to know all parameters exactly. Such parameters are usually assumed. To adjust the resulting window U value with the producer value, the objective function in GenOpt can be defined as in Equation 5.3, while the optimization variables can be the parameters that are the most uncertain.

In a similar way, any design requirement can be adjusted to the desired value by using the objective function in Equation 5.3, while uncertain parameters are the optimization variables.

5.2 Case study building for the hydronic heating system

The case building, Material teknisk, located at the University campus in Trondheim, consists of two connected buildings that are offices and laboratories. They have a common district heating consumer substation. Therefore, they will be treated as one aggregate building in this study. The building has three floors and a basement, and the total area is 13,700 m^2. The building facades are shown in Figures 5.2 and 5.3. The building base with the north orientation is shown in Figure 5.4.

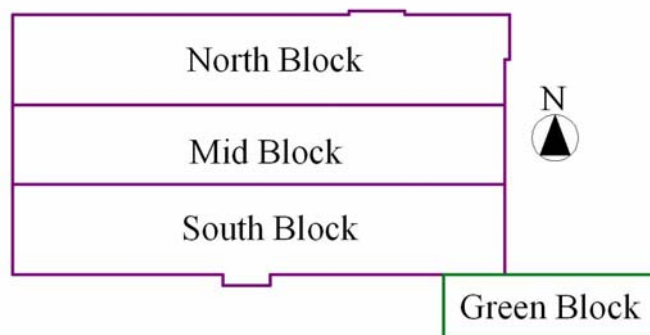| Figure 5.2. The south facade | Figure 5.3. The west facade |

Figure 5.4. Sketch of the general building plan

Heat is supplied by district heating, indirectly connected to a heating network through the heat exchangers. There are two types of heating system in the building: hydronic heating with the radiators and the fan coils. The hydronic heating system is centrally controlled by BEMS, while the fan coils are locally controlled. Since the building is divided into four zones, there are four main branches in the substation. The hydronic heating system description and the schematic figure were presented in Paper VII (see Figure 2).

The structure of the maintenance service was explained in Chapter 2.2.1 through the necessary contacts in the building.

5.3 The model approach of a simple heat balance model for the heating system

In Paper VII the heat balance model was used to model the heating system and the building. The heat balance equations include the zone heat balance and the heat balance for the consumer substation. The ventilation systems are controlled locally, and they are all the simple fan coil units. Since only the heat balance model is defined, only the total capacity of the ventilation is counted discretely as an additional term for each zone. The model is hourly based. Even though the model is steady-state, the building response is obtained by changing the temperature values. Such a simple model approach has been used because it is suitable for the optimization. Since this model has been calibrated against the real data, there is a necessity to simplifying the model and hence save simulation time, particularly in the optimization process as shown in the work of K.F. Fong et al. [40].

As the building is divided into four zones, four heat balance equations have to be established. The heat losses of the zones are described by C_b, the overall conductance of the walls, which is a multiplication of the heat conductance and the wall area. The heat capacity of the radiators is calculated by use of overall conductance of a radiator, C_r, and the mean temperature of the heating water is based on [51]. A similar approach for defining the heat energy balance in such a system was applied in the work of Bojic and Trifunovic [69, 70]. Therefore, the heat balance for one zone can be written as

$$\dot{Q}_{bj,i} = \dot{Q}_{rj,i} + \dot{Q}_{vj,i}, \tag{5.4}$$

such that:

- $\dot{Q}_{bj,i}$ is the heat loss of the zone j,

- $\dot{Q}_{rj,i}$ is the heat capacity of the radiators in the zone j,

- $\dot{Q}_{vj,i}$ is the heat capacity of the ventilation system in zone j.

Consequently, Equation 5.4 can be written as

$$C_{bj} \times \left(T_{inj,i} - T_{out,i}\right) = C_{rj} \times \left(\frac{T_{hs,i} + T_{hrj,i}}{2} - T_{inj,i}\right) + \dot{Q}_{vj,i}, \tag{5.5}$$

where:

- j is the zone index,

- i is the time step.

In Equation 5.5, the heat balance equations are established for each of the four zones in Figure 5.4. C_{bj}, C_{rj} and $\dot{Q}_{vj,i}$ are the model parameters. Since there are four zones with two parameters each, C_{bj}, C_{rj}, which are time-independent, there are 8 time-independent parameters. In addition, there is a model parameter for the heat capacity of the ventilation system, $\dot{Q}_{vj,i}$, which is different in each time step. Since there are four zones with the ventilation system and n time steps, there are *4n* model parameters for the heat capacity of the ventilation system. Thus, *4n+8* parameters are necessary to define the model.

After Equation 5.5 is solved, the hourly energy consumption of the radiators and ventilation system in each zone can be calculated as

$$Q_{rj,i} = \frac{3600}{1000} \times C_{rj} \times \left(\frac{T_{hs,i} + T_{hrj,i}}{2} - T_{inj,i} \right), \tag{5.6}$$

$$Q_{vj,i} = \frac{3600}{1000} \times \dot{Q}_{vj,i}. \tag{5.7}$$

The total hourly energy consumption of the building is

$$Q_i = \sum_{j=1}^{4} Q_{rj,i} + \sum_{j=1}^{4} Q_{vj,i} + Q_{t,i}, \tag{5.8}$$

where $Q_{t,i}$ is the energy consumption for the hot tap water that is additionally measured.

The model input vector consists of the outdoor air and the supply-water temperature. By solving Equation 5.5, the indoor air temperatures and the return-water temperatures in each time step are obtained. Since there are four zones and n time steps, the output from Equation 5.5 gives $8n$ elements. In addition, by solving Equation 5.8, the total energy consumption in each time step is obtained, so this output gives n elements. Finally, the model output vector contains $9n$ elements, which are the total energy consumption, the indoor air temperatures in each block, and the return-water temperatures from each block in each time step. The total energy consumption and the return-water temperatures from each block were logged by the BEMS, while the indoor air temperatures in each block were measured. Therefore, the measured data corresponds to each element of the model output vector. The $9n$ elements of the output vector are calibrated against the measured data using Equation 5.2. The output vector must have more elements than the model has parameters. In this case, this means that $9n>4n+8$.

5.3.1 Comments on the simple model approach calibration and the model possibilities

These comments include the optimization bounds, model advantages, disadvantages, and possibilities. Equation 5.2 gives only a general objective function for the model calibration. After the model is involved, it is possible to define the lower and upper bounds of the optimization variables.

The upper and lower bounds for the overall conductance of the radiator, C_r, in each block, are defined based on the on-site survey. The upper and lower bounds for the overall conductance of the walls, C_b, are assumed based on the window size and U value. Considering the lack of information concerning the use of the ventilation systems, the lower and upper bounds for the ventilation capacities are chosen arbitrarily.

The approach in this case is that the simple heat balance model is calibrated against available data, measured both by BEMS and additionally. Since the real data are measured in two ways, there is data overlapping. Therefore, the advantage of this approach is that the model is simple and useable to estimate the changes both in the achieved indoor air temperature and energy consumption. A disadvantage of this approach is the incapability to predict the building performances. The model would be completely capable to predict when the model parameters are time-independent. Since there is data overlapping, it is possible to analyze faults and their related effects on energy consumption and the indoor air temperature.

The above developed approach opens a possibility to optimize the supply-water temperature. New supply-water temperature values can be found by minimizing the differences between the achieved and set-point indoor air temperature. Such an optimization problem can be defined in a similar way as Equation 5.2, except that, instead of the measured values, the set-point values have to be used. In the same way, any other model parameter can be optimized until a certain performance achieves the set-point value. In that case, a model input has to be an optimization variable, while a targeted performance is compared with the set-point value in the objective function.

5.3.2 Faults in the heating system detected using the simple heat balance model

The following faults were noted in the studied building: disconnected sensor for the outdoor air temperature, the outdoor air temperature sensor measures an incorrect temperature, a fault in the time scheduling program, and a water flow imbalance problem in the district heating consumer substation. The idea in the fault explanations was to connect the fault causes and effects on the indoor air temperature and the energy consumption. All the faults were explained in detail in Paper VII, while three faults are explained here briefly. These three faults were diagnosed based on the developed heat balance model.

Disconnected outdoor air temperature sensor
The supply-water temperature is controlled by a valve, while the valve stroke is controlled by two temperature sensors, the outdoor air temperature, and the supply-water temperature sensor. Therefore, this control can only be as accurate as the sensor measurements. In addition, in the case when the outdoor air temperature sensor is disconnected, this control strategy is defined by the outdoor air temperature of 0°C. The supply-water temperature then has a value close to an appropriate value at 0°C, defined by the outdoor temperature compensation curve (the red line in Figure 5.5).

A fault in which the outdoor air temperature sensor is disconnected results in the outdoor temperature compensation curve not being fulfilled as shown in Figure 5.5. The values in Figure 5.5 are normalized by the outdoor air temperature. The effects of such a fault are influenced by the BEMS strategy in the case when this sensor is disconnected.
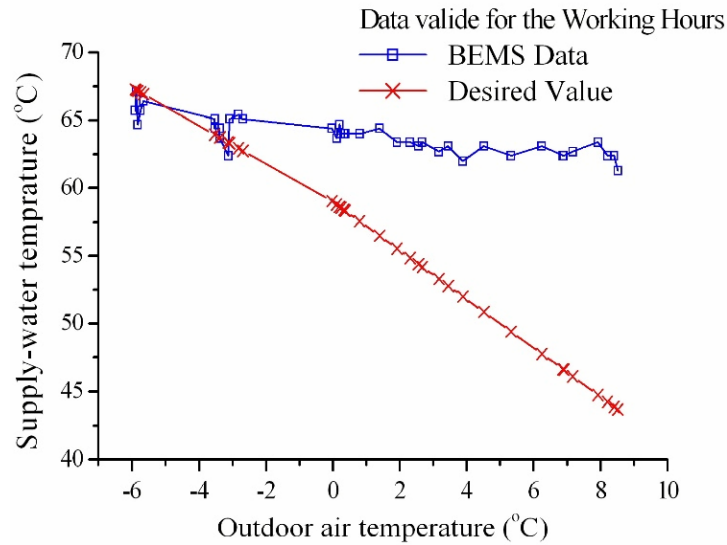
Figure 5.5. Effects on the supply-water temperature when the outdoor air temperature sensor is disconnected during working hours

Figure 5.5 shows the effect on the supply-water temperature when the outdoor air temperature sensor is disconnected during the working hours; the supply-water temperature is almost constant (the blue line) regardless of the changes in the outdoor air temperature. In Figure 5.5, the faulty values of the supply-water temperature are higher than the corresponding values for the supply-water temperature at T_{out}=0°C because there is also a fault in the control valve. For a different BEMS strategy in the case when this sensor is disconnected, this offset of the desired supply-water temperature is different.

When the outdoor air temperature sensor is disconnected, the indoor air temperature is different from the set-point value, and the energy consumption is almost constant outside of the transient period regardless of the outdoor air temperature changes. Actually, depending on the BEMS strategy, the effects of the disconnected sensor are different. In this case, if T_{out}>0°C, then both the energy consumption and the indoor air temperature are increased, while, if T_{out}<0°C, both the energy consumption and the indoor air temperature are decreased.

Fault in the outdoor air temperature sensor measurement

Since this control is as accurate as the sensor measurements, the accuracy of the outdoor sensor measurement influences the achieved indoor air temperature and the energy consumption. Therefore, when the outdoor air temperature sensor measures a fault, the indoor air temperature is not achieved even though the supply-water temperature appears to be achieved. The effects of such fault are determined by the bias in the measurement. The different measurements in Figure 5.6 show a positive bias in this observed BEMS's sensor measurement compared to the accurate measurement. In addition to the additional measurement, the measurements of the Meteorological Institute [71] are shown in Figure 5.6. The red line in Figure 5.6 is treated as the correct measurement of the outdoor air temperature in this analysis of the faults.
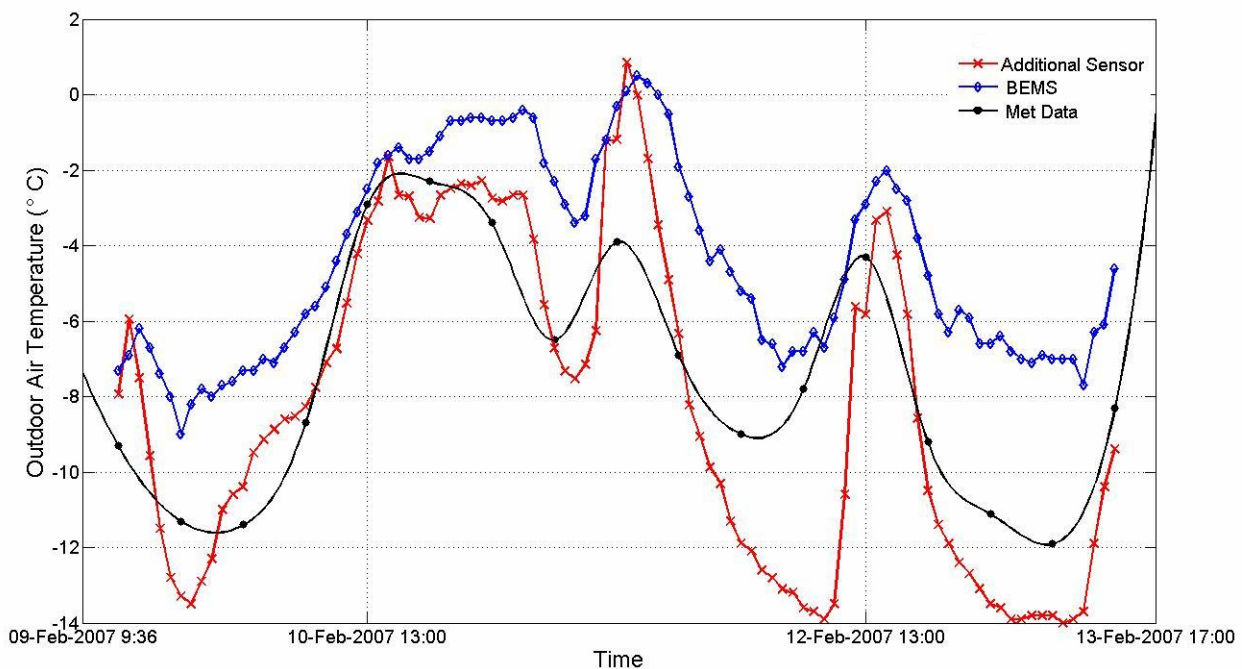

Figure 5.6. Different measurements of the outdoor air temperature

The higher temperatures measured by the outdoor air temperature sensor (blue line in Figure 5.6) decreases both the indoor air temperature and the energy consumption. Such a fault can be noted by measuring the indoor air temperature. If the indoor air temperature is lower than the set-point value, even though the supply-water temperature achieves the set-point value, then the outdoor sensor measures a faulty temperature with a positive bias. The cause of such a fault can be either a poor position of the sensor or defected sensor by any reason.

Fault in time schedule

Before this fault is explained, two different time schedules are briefly introduced. These are the desired schedule and the actual schedule. The desired schedule is set by the project leader for energy conservation in the building, while the actual schedule is set up by the BEMS supplier technical support. The roles of these persons were explained in Chapter 2.2.1.

The desired time schedule for the supply-water temperature should be:

- from 5 a.m. to 4 p.m., the red curve in Figure 5.5 is used,
- from 4 p.m. to 5 a.m., the red curve in Figure 5.5 decreased by 10°C is used,
- from 4 p.m. on Friday to 1 a.m. on Monday, the red curve in Figure 5.5 decreased by 10°C is used.

The actual time schedule for the supply-water temperature is the following:

- from 5 a.m. to 5 p.m., the red curve in Figure 5.5 is used,
- from 6 a.m. on Saturday to 6 p.m. on Sunday, the red curve in Figure 5.5 is used,
- outside of the above periods, the supply-water temperature is decreased by 10°C.

The desired and the actual schedule, explained above, are shown schematically in Figure 5.7. This Figure is only illustrative, showing only the difference in settings; either the high supply-water temperature is in use or the low temperature is in use. The red fields present the periods with the high supply-water temperature, while the white fields presents the periods with a supply-water temperature decreased by 10°C. Due to shortage of space, Thursday is not presented in Figure 5.7, but the schedule for Thursday is the same as for the Wednesday in both schedules.
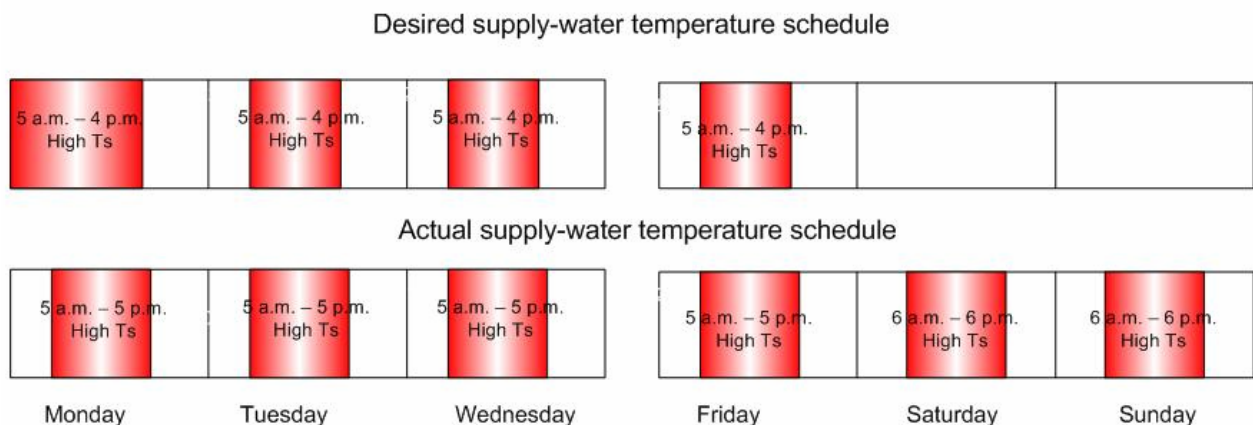
Figure 5.7. Desired and actual schedule for the supply-water temperature

Since the time schedule is directly set up by the BEMS supplier technical support, the actual time schedule is really in use. Such a fault in the time schedule prevents an energy efficiency measure, although such a fault can be easily detected by checking the hourly energy consumption.

Since the actual schedule is used during the weekends, the energy consumption is higher than it should be with the desired operation schedule. The desired operation schedule aims to be an energy efficiency measure. Since the actual schedule is in use, there is no effect of the energy efficiency measure. This difference in the time schedule can easily be noted by checking the hourly energy consumption. If there is no response in the hourly energy consumption at the moment the supply-water temperature is changed, it means that the desired time program is not in use. In addition to these different settings in the time schedule, it is possible that an error appears in the time schedule program, too. The appropriate figures with the cause and effect of this fault are shown in Paper VII.

5.4 The fault effect assessment and performance indices

Even though the difficulties in the EnergyPlus model calibration have been elaborated, it can be useful to test several faults for the purpose of establishing the cause-effect rules for the fault detection and diagnosis. Since the performance simulation software EnergyPlus and TRNSYS have a big output, they are a good opportunity to test many different cases. In addition, a long

time is necessary to develop a model in these programs, so it can be useful to completely utilize the available possibilities. Therefore, by involving faults the effects on the building performances can be obtained. Finally, the cause-effect rules can be established by connecting the faults and their related effects. Such rules can be used practically for building maintenance.

To estimate the effects of the faults, the performance indices, PI, are involved. PI can help to detect a fault. These performance indices measure a bias in a building performance in the case when a fault appears. A performance index is defined as the percent difference between a faulty performance and a correct performance. Therefore, the baseline for the performance indices calculation is defined to be a correct performance, or a system state without faults. To diagnose a fault, cause-effect rules have been established based on the performance indices values and the indices combination, which gives a certain fault. If a PI value is above the positive threshold, or under the negative threshold, then such a PI is labeled. A combination of these PI labels gives a rule for fault diagnosis.

Usually, BEMS can measure and log several performances of an HVAC system. The performance simulation software gives as the output many building performances. Therefore, the performance indices obtained by use of the simulation software should aim at giving the cause-effect rules for FDD for the building performances available in BEMS. These obtained rules should help a BEMS operator so that it becomes easy to detect and diagnose a fault.

Finally, a general form of a performance index can be written as

$$PI_Q = \frac{E_{fault} - E_{no\_fault}}{E_{no\_fault}} \times 100 , \qquad (5.9)$$

where E_{fault} is a building performance when there is a fault in the system, and E_{no_fault} is a building performance when there is no fault in the system. Equation 5.9 can be used to calculate different performance indices, such as for energy consumption or pump power. If there is the set-point value of a performance index, then such an index is defined as

$$PI_E = \frac{E_{fault} - E_{set}}{E_{set}} \times 100 \, , \qquad\qquad (5.10)$$

where E_{set} is the set-point value of a performance E. The performance index defined by Equation 5.10 can be used for a performance such as the indoor air temperature.

Below, two different examples of HVAC systems are presented. These systems have different performance indices that are important for assessment. Therefore, any particularity in the performance calculation is clarified for each example.

After the performance indices have been calculated, rules for fault diagnosis can be developed. Before the rules are developed, three terms are necessary. These terms are:

  – When a PI_Q>10%, then that index is called a positive index and is labeled P.
  – When a PI_Q<-10%, then that index is called a negative index and is labeled N.
  – When there is no fault, the index gets the label NF.

The threshold of ±10% has been suggested for the purpose of the two examples presented in this work. For example, in a diagnostic agent for building operation (DABO), which is a software tool running in the central building operator station, this threshold for the fault detection is ±8%. DABO uses expert knowledge to identify faults through the use of a hybrid knowledge-based system composed of an Expert System and a Case-Based Reasoning module [72]. Haves and Khalsa [73] suggested a threshold for fault detection of 15%, in the case that the baseline model is deemed to be a correct operation. In the case when the model is based on faulty operation, then the threshold could be set to about 7% [73]. Regardless of the threshold value, the most important issue for the performance indices labeling is their positive or negative bias.

The logical rules for the fault diagnosis have been developed based on how many and which performance indices have N, P or NF as labels. For example, if all the observed PIs have the labels NF, then there is no fault in the system, or a fault cannot be detected by using these indices.

5.5 Testing possible faults in hydronic heating system

The possibility of assessing faults in the heating control system and components using EnergyPlus is elaborated in this chapter. In addition, a FDD strategy for the component faults has been proposed.

An EnergyPlus model was developed for the building introduced in Chapter 5.2. The model includes the building construction, heating system, and the internal loads. The desired schedule for the heating system, explained in Chapter 5.3.2, was implemented on this model. Due to an EnergyPlus model requirement, it is necessary to define the set-point indoor air temperature. Therefore, the set-point indoor air temperature is $22^{o}C$ from 5 a.m. to 4 p.m., while outside of this period is $19^{o}C$. In addition, during the weekends when the supply-water temperature is decreased by $10^{o}C$, the set-point indoor air temperature is $19^{o}C$. This simulation model was run for six winter days, when the outdoor temperature ranged from $-14^{o}C$ to $1^{o}C$.

A problem to get the effects of the faults by using EnergyPlus in the control system has been noted. It is possible, however, to involve the component faults and get their effects. Therefore, these component faults are introduced first. Afterwards, the performance indices are presented, so that the FDD rules can be established.

5.5.1 Problem of the fault assessment in the control system by using EnergyPlus

The faults such as a faulty measurement of the outdoor sensor or a disconnected sensor are faults in the heating control system. As shown in Chapter 5.3.2, such faults can influence system performance. To establish the FDD rules it is necessary to test these faults and find their related effects. Therefore, the following faults in the control system were tested in EnergyPlus: a faulty measurement of the outdoor sensor, a disconnected sensor, and a poorly tuned compensation curve. The aim of these tests was to examine the possibility of an EnergyPlus model to respond to such faults. The effects on the achieved indoor air temperature and the total heat rate are shown in Figures 5.8 and 5.9, respectively. Due to issues in this EnergyPlus model, it is difficult to see

the difference in the achieved indoor air temperatures and particularly in the heat rate in these two figures.
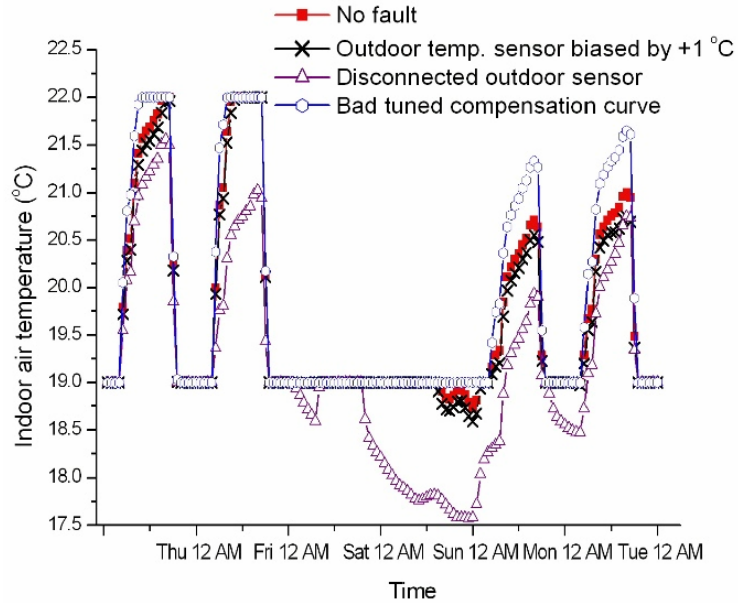

Figure 5.8. Effects on the indoor air temperature caused by faults in the control system
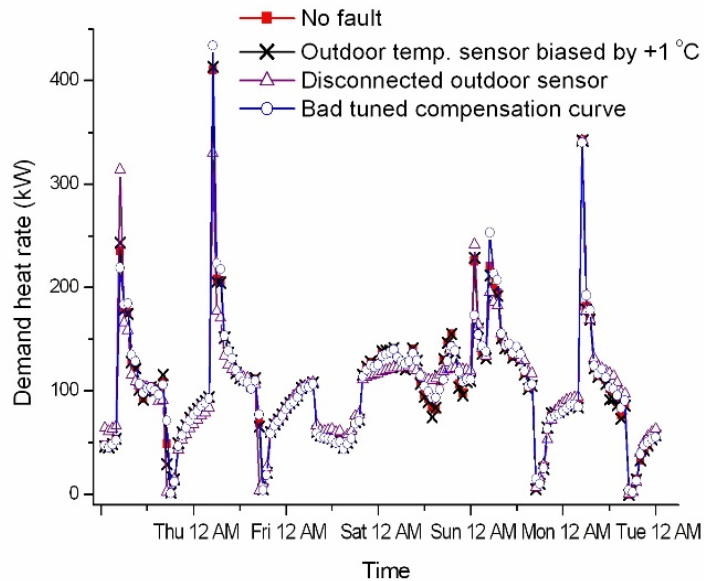

Figure 5.9. Effects on the total heat rate caused by faults in the control system

The EnergyPlus output does not give any significant difference in the total heat rate when there are faults, as shown in Figure 5.8. Even though there is a difference in the achieved indoor air

94

temperature (Figure 5.8), the performance indices of the indoor air temperature would not have a significant value to diagnose these faults. The reason for such results is the EnergyPlus model for radiators. As explained in Chapter 5.1.1, the radiator model is intended to be thermostatically controlled baseboard heater. Actually, this model controls the water flow rate to add the required amount of heat to the zone to meet the thermostat set-point. Therefore, the heat rate is similar for these faults in the control system. Since it is not possible to get the significant values of the performance indices to diagnose the faults in the control, this EnergyPlus model is not suitable for establishing the diagnostic rules for these faults. This issue is related to this heating system. It might not be a problem for another HVAC system modeled in EnergyPlus.

Even though this EnergyPlus model is not suitable for diagnosing the faults in the control, it has been tested on a few component faults. The effects of the component faults on the achieved indoor air temperature are shown in Figure 5.10. The following component faults were tested: open window, fouled radiator, poor wall insulation, and high electric equipment power. A practical explanation of these faults is given below.
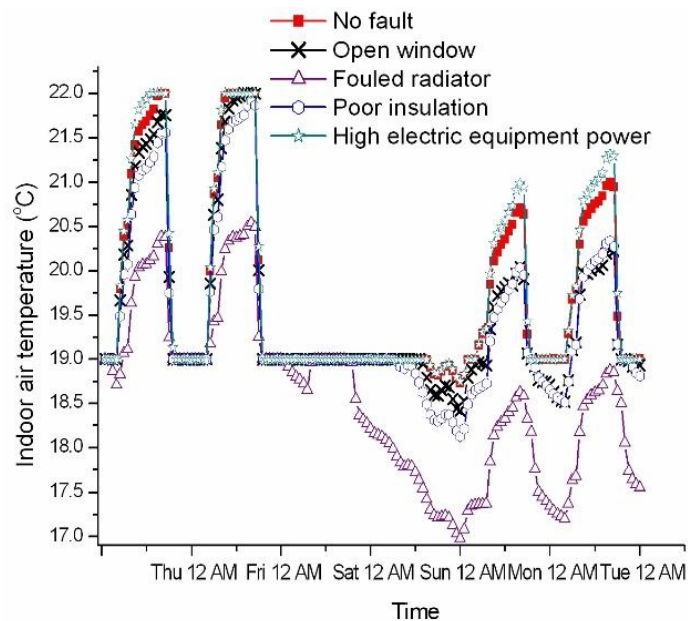

Figure 5.10. Effects on the indoor air temperature caused by the component faults

The deviation in the achieved indoor air temperature is more significant for the component faults than for the faults in the control, as shown in Figure 5.10. Therefore, this EnergyPlus model is suitable for establishing the rules for diagnosing the component faults.

Based on the above results, the developed EnergyPlus model for the case building was used for establishing the FDD rules for the component faults.

5.5.2 Component faults in the heating system

Due to ageing, fouling, changing in the building use, or improper building use, component faults can appear. These faults affect the building performances. The following four faults have been tested in EnergyPlus on the case building.

Open window

This fault is caused by the building occupants. Building occupants can randomly open windows, which they then might forget to close. The effect of this fault can be increasing the energy consumption. The increase in energy consumption appears when the heating system is able to achieve the set-point indoor air temperature.

This fault was involved in the EnergyPlus model by increasing the amount of infiltrated air.

Fouled radiator

This fault can appear due to the system ageing and use of poor quality water in the hydronic system. Due to this fault, the efficiency of the radiator is decreased, and, consequently, the heat released by the radiator is decreased.

This fault was involved by decreasing the *UA* value of the radiator in the EnergyPlus model.

Poor wall insulation

The heating system capacity and the control strategy should be suitable for a certain building construction, so that the desired indoor condition can be achieved, but the heating system can be changed sometimes without checking the real building demand. Due to ageing, the performance of the building's insulation can decline.

The fault caused by poor wall insulation is involved by simply decreasing the insulation of the building envelope.

High electrical equipment load

The building occupant habits and needs change over time. For example, the heating system could have been designed for indoor conditions with lower internal loads than used today. Since the electrical equipment in the offices can increase over time, it can be useful to test such fault.

To find the effects of such fault, the level of the electrical load was increased by 50%.

5.5.3 Diagnosing the component faults in the heating system

To assess the faults in the heating system, the performance indices, PI, for the heating rate and the achieved indoor air temperature were calculated using Equations 5.9 and 5.10, respectively. Figures 5.11 to 5.14 show the performance indices for the involved component faults.
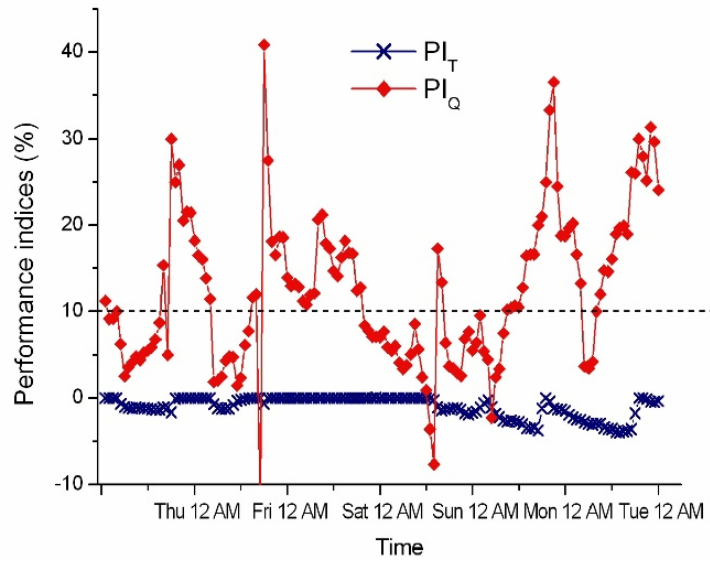
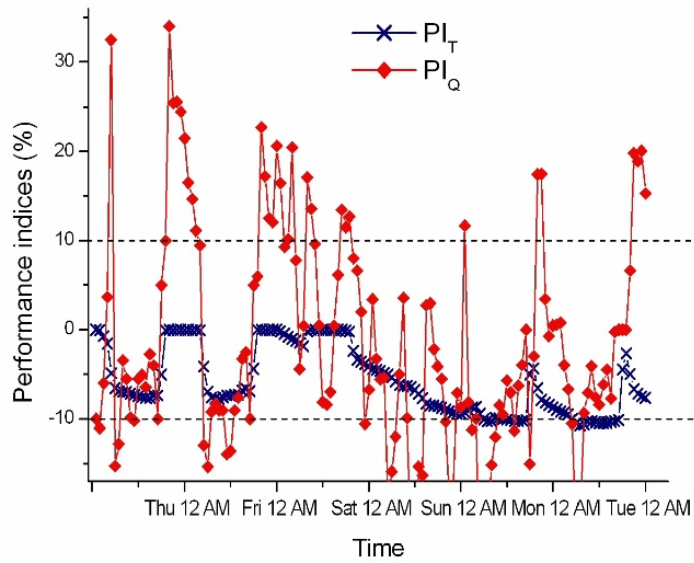Figure 5.11. PIs for fault due to open window

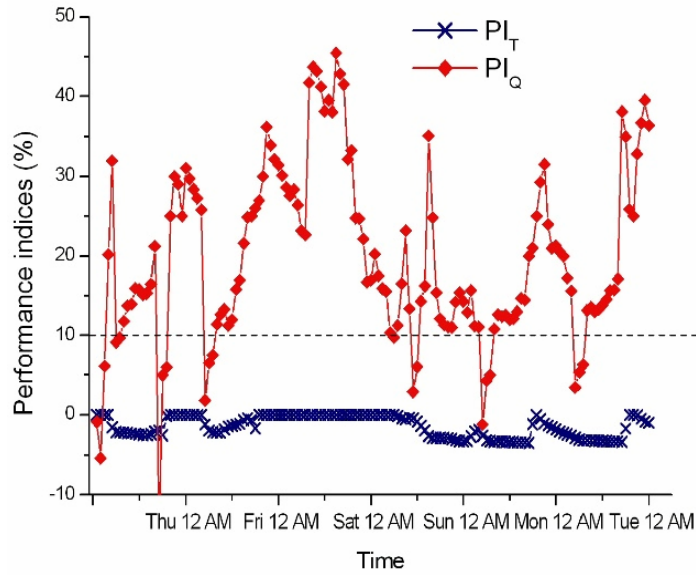Figure 5.12. PIs for fault due to fouled radiator
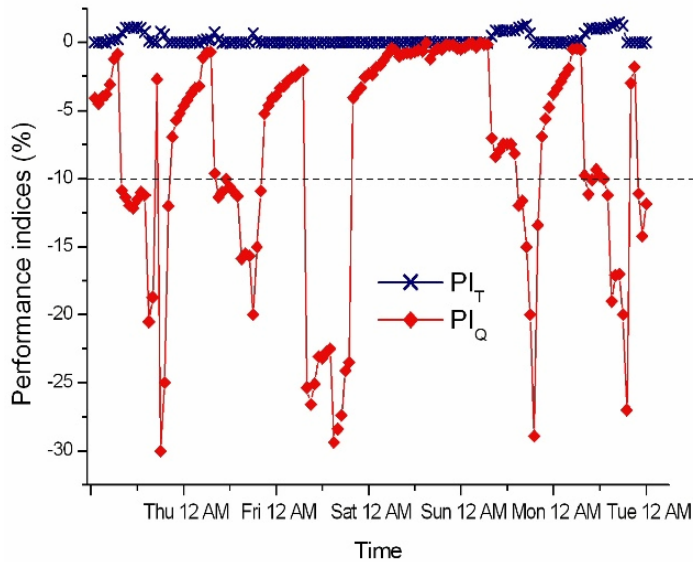
Figure 5.13. PIs for poor insulation

Figure 5.14. PIs for the fault due to high electrical equipment load

In the Figures 5.11 to 5.14, the horizontal lines at ±10% of the performance indices show the thresholds where it can be considered that there might be a fault in the system. If a PI often has a value higher than 10%, then such a PI is labeled as P. In contrast, if a PI often has a value lower than -10%, then such a PI is labeled as N. For the faults in Figures 5.11, 5.13 and 5.14, it is easy to classify PI, while for the fault in Figure 5.12, this is not the case. Therefore, it was necessary to compare the total energy consumptions to estimate the bias of PI_Q of such a fault. Table 5.1 gives

the total energy consumptions for both the case without faults and the cases with the faults. The total energy consumption in Table 5.1 is the consumption for six winter days.

Table 5.1. Total heating energy consumption for the component faults

Fault	Energy consumption (kWh)
No fault	14820
Open window	16195
Fouled radiator	14050
Poor insulation	17345
High electrical equipment load	13920

The results in Table 5.1 can help to give the label to the PI_Q. For example, for the fault caused by open window, the PI_Q gets the label P, based on Figure 5.11. Since the energy consumption in the case of open window is higher than in the case without fault, the results from Figure 5.11 are proven. Actually, there is a positive bias in the energy consumption in the case of open window. In the case of the fouled radiator, the energy consumption is lower than in the case without faults. Therefore, the PI_Q gets the label N for this fault.

Based on positive or negative biases in the performance indices, a logic diagram for the component faults diagnosis can be established, as shown in Figure 5.15. The top part of Figure 5.15 is the PI classifier, or the fault detection part. If there is a deviation in a performance, then it might appear a fault. The lower part of Figure 5.15 gives the rules for the fault diagnosis.
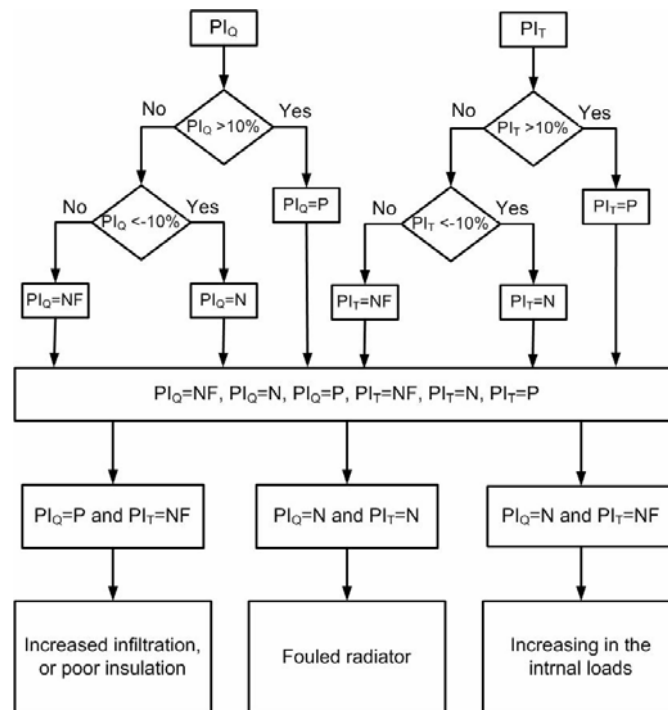
Figure 5.15. Logic diagram for the component faults in the heating system

As shown in Figure 5.15, component faults can be diagnosed by using the following rules:

– Change in the building construction or envelope: If there is a positive bias in the heating rate while there is no fault in the achieved indoor air temperature.

– Fouled radiator: If there is a negative biases in both the heating rate and the achieved indoor air temperature.

– High internal loads: If there is a negative bias in the energy consumption while there is no fault in the achieved indoor air temperature.

FDD rules can be developed by testing different faults first. Afterwards, the performance indices have to be calculated by comparing with the case without faults. Finally, FDD rules can be developed by classifying the PIs.

The above FDD rules can be used only for the component faults in the heating system. These rules cannot be used for multiple faults. For multiple faults, new rules have to be developed using similar methods, testing faults, and classifying the corresponding PIs.

5.6 FDD strategy for five faults in AHU system for air cooling

Possible faults in the AHU system for air cooling have been tested to establish a FDD strategy. This AHU system provides cool air for a part of the building. Therefore, the building and the observed part of the building are presented first. Since the AHU system model was developed and tested in TRNSYS, the TRNSYS possibilities are presented as well. Afterwards, the AHU system and the model concept are briefly introduced.

The model for AHU was developed for the second zone of the International Commercial Center (ICC) building, shown in Figure 5.16. The ICC is located in Hong Kong, and currently it is under construction. The total building area is 440,000 m^2, where a commercial center, offices, and hotel are located. The building has a total of 118 floors, or a height of 490 m. Figure 5.16 shows the general content of the building. For the purpose of energy analysis, the building has been divided into six zones. The zoning concept is shown in Figure 5.17. The second zone consists of offices, is located from the sixth to 42nd floors, and includes 50 AHUs.
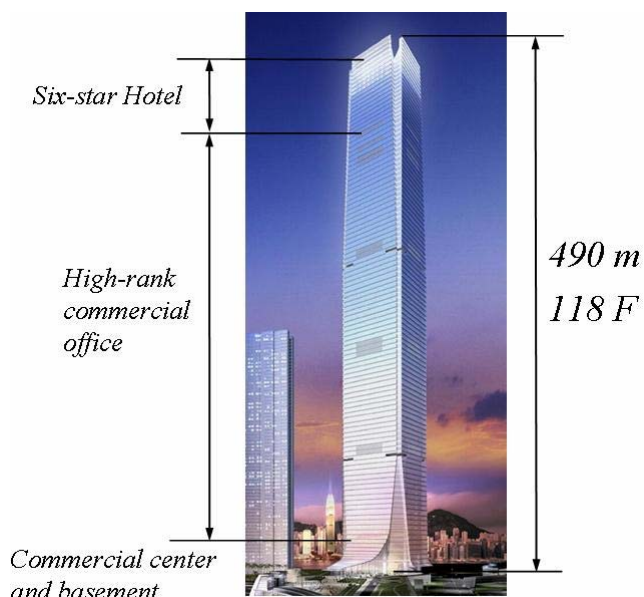

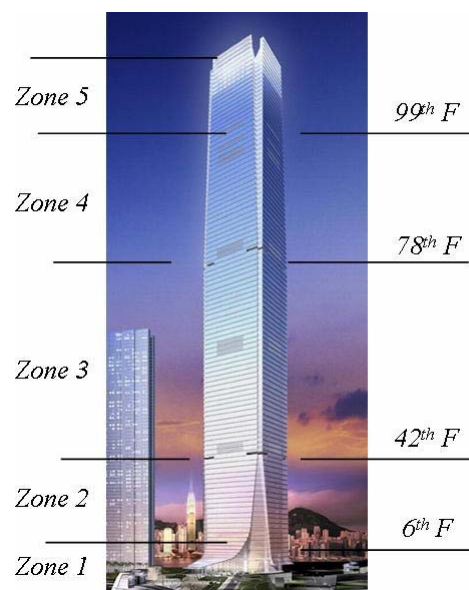Figure 5.16. International Commercial Center

Figure 5.17. Zones in ICC

Figures 5.16 and 5.17 were obtained from the building architectural model. Since the building is in the construction phase, it is not possible to get real photos. In the figures, the letter "F" means floor.

The AHU system model was developed in TRNSYS, a complete and extendible simulation environment for the transient simulation of systems, including multi-zone buildings. It is used by engineers and researchers around the world to validate new energy concepts from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, and alternative energy systems (wind, solar, photovoltaic, hydrogen systems) [74].

5.6.1. AHU system and the model description

The concept of the AHU system and the modeling approach are briefly explained in this section. The modeling aim was to model the hydronic system (water side) of the AHU system. Therefore, the TRNSYS flow balance model component was used. The hydronic system for AHUs is a reverse-return system. The AHUs are connected by pipes, while the control valve controls the water flow through each AHU. In this case, the dynamic balance valve (DBV) at the return side of the cooling coil was not included in the system. Therefore, each parallel branch is the same, with an AHU and a control valve.

In a reverse-return approach, the first coil supplied is the last returned and vice versa. The schematic diagram of these AHUs connected in the reverse-return system is shown in Figure 5.18. In such a system, differential pressure across each coil remains fairly constant. The circulation water pump has a variable speed drive (VSD) controlled by a differential pressure sensor located across the riser taps at the most remote AHU.
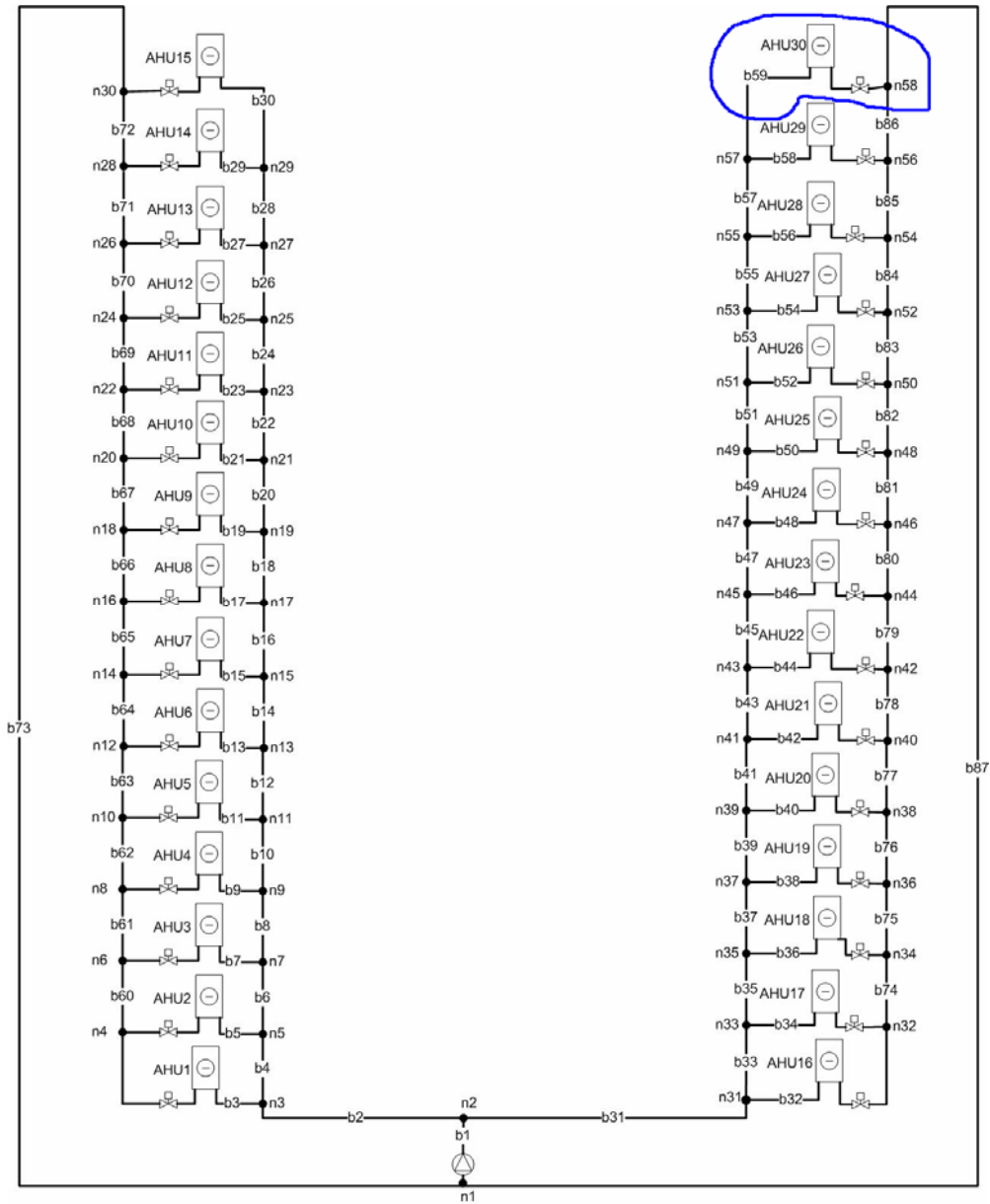
Figure 5.18. Schematic diagram of the reverse-return system for AHUs

Figure 5.18 shows 30 AHUs instead of 50 AHUs, as introduced before, due to an issue in running TRNSYS. The TRNSYS executable file has a limited size, while the size of an executable TRNSYS file with the flow balance model is mainly influenced by the number of branches and nodes. Therefore, it was necessary to reduce the number of branches and nodes in the hydronic network. This reduction was done by replacing two parallel AHUs by one AHU, when the total flow resistance of the given branch is divided by the square of two (because two AHUs are replaced by one). Finally, five AHUs are replaced by three, so that the two first and the last

AHUs are presented as one, while the mid AHU is by itself. In Figure 5.18, a branch is noted by "b", while a node is noted by "n". In addition, the further analysis and results are reported according to this schema in Figure 5.18. The pressure difference sensor is located on AHU30, marked in Figure 5.18.

The TRNSYS model of such a system includes six main components. These components are: load model, AHU model, the realistic PID controller for AHU, flow balance model, PID controller for the pump, and the component with the pump and flow resistance model. The general information flow chart of these main components is shown in Figure 5.19. Since there are 50 AHUs and a corresponding number of controllers, the presentation of all the necessary components from the TRNSYS deck file in Figure 5.19 is difficult. Therefore, the components and their relationships are shown generally in Figure 5.19 so that the system work concept can be recognized clearly.
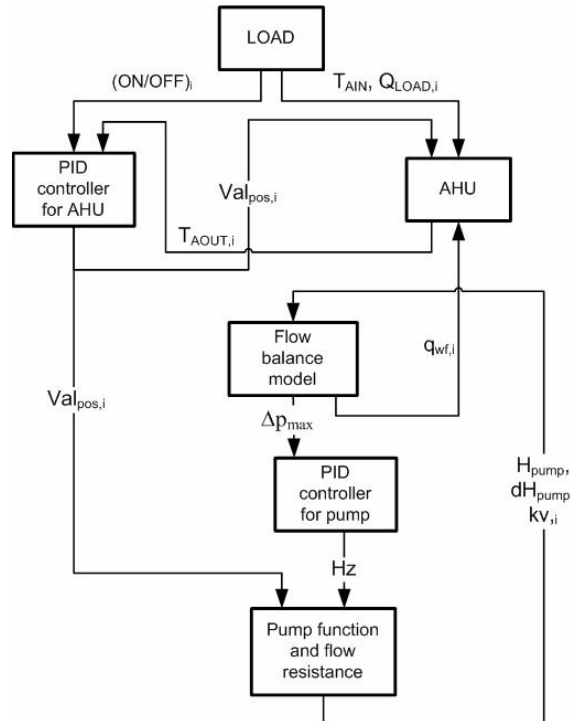

Figure 5.19. General information flow for the TRNSYS model

Figure 5.19 shows inputs and outputs among the different components. The load component outputs are: the system status schedule of each coil $(ON/OFF)_i$, the outdoor air temperature, and

the cooling loads. The valve position, $val_{pos,i}$, is an output from the PID controller. This output is used as an input to the AHU model and as an input to the flow resistance function. Flow balance model has as output water flow rates, $q_{wf,i}$, and pressure differences. The PID pump controller uses the pressure difference on the most remote AHU, Δp_{max}, to find the pump frequency, Hz. The outputs of the pump model are the pump head, H_{pump}, and the first derivative of the pump head over the water flow rate, dH_{pump}. In addition, the outputs of the flow resistance component are the control valves flow resistances, $k_{v,i}$. The pump head, the first derivative of the pump head, and the flow resistances are the inputs to the flow balance model, as shown in Figure 5.19.

The described model has been run for the working hours. The cooling load profile and the outdoor air temperature for these hours are shown in Figure 5.20. Such a load profile has been obtained from a previous project work, while here this load is used immediately through the load model. The regime for using the AHUs is the following: from 8 a.m. to 9 p.m. all the AHUs are in use, while outside of this time 10 AHUs are in use.
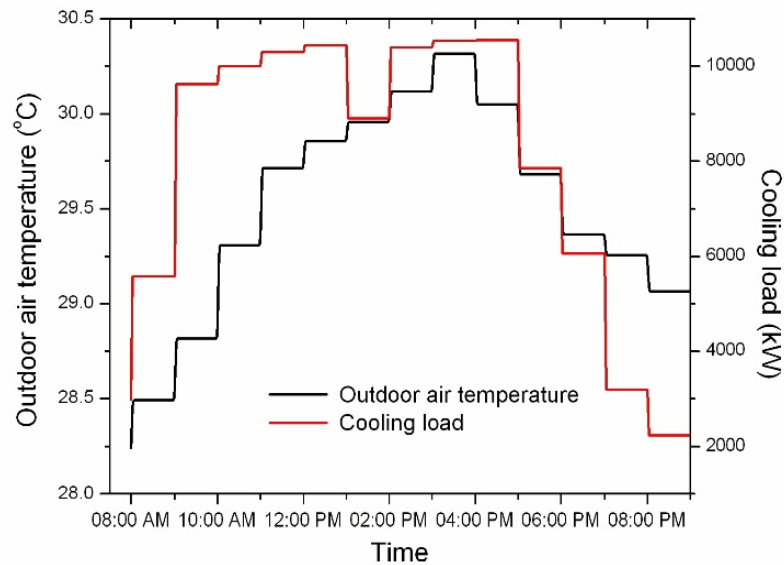

Figure 5.20. Outdoor temperature and the cooling load profile of the AHU system

5.6.2 Involving faults

To establish rules for the FDD in the reverse-return AHU system, it was necessary to test the system performances on a few possible faults. Therefore, the faults are explained first, and then tested.

Old valve

Due to ageing, the control valve cannot achieve the same position as the signal from the valve controller indicates. In that case, the control valve is not opened as the coil PID controller signals. For example, the valve may be opened more in reality than it should be according to the PID controller. Since it is not possible to measure the actual control valve position, this fault can be noted by checking the valve controller signal and the resulting controlled temperature. If the control valve does not have the same position as the signal from the valve controller, then the valve position signal from PID is very low and the controlled temperature has many high oscillations.

Such a fault was involved in the model by biasing the input from the coil PID to the real valve position by 50%. Actually, the input from the PID controller to the flow resistance model is multiplied by 1.5.

Fouled return pipe fault

This fault can appear due to system ageing and use of poor quality water in the hydronic system. In addition, such a fault can appear in a new system due to metal particles after pipe welding. Such a fault means that the flow resistance of the pipes is increased. If the flow resistance of the return pipe is increased, then the desired outlet air temperature of AHU cannot be achieved.

This fault was involved by increasing the flow resistance of the pipes in the return branches.

Fault in the outlet air temperature sensor

The outlet air temperature sensor is a sensor that measures the air temperature after the AHU, actually, after the cooling coil. Sometimes this sensor for the coil outlet air temperature can be

placed on the wrong place or due to ageing the sensor can measure the temperature incorrectly. If the sensor for the coil outlet air temperature measures an incorrect temperature, then it influences the control loop for the outlet air temperature. Therefore, the control will be poor and the system will perform poorly.

This fault was involved by biasing the coil PID controller input from the AHU output by 20%.

Fault in the temperature sensor for the inlet air temperature

The measurement of the inlet air temperature was used for the model calculation of AHU. In this simulation model (Figure 5.19), the inlet air temperature measurement does not influence any control loop. A bias in the inlet air temperature sensor, however, can be influenced by taking the inlet air flow that is not the same as the real environment air. For example, if there is an obstacle, or energy source, in front of the inlet AHU damper, then the AHU is taking air with the increased outdoor air temperature.

This fault was involved by biasing the AHU input from the load model output by 20%.

Bad position of the sensor for pressure difference

The position of the pressure difference sensor is important in the direct-return system, and this sensor must be located at the most remote AHU. Such a position is also recommended for the reverse-return system. The sensor for the pressure difference can measure an incorrect pressure difference, and some of the control valves will not get correct water flow to achieve the set-point outlet air temperature. This fault can appear in the case when the system is upgraded, while the sensor for the pressure difference is not moved to the correct place. Also, in the case of very different load distribution, some branches closer to the pump can show a higher pressure drop than in the most remote ones.

This fault was modeled by setting the pressure measurement on AHU8 instead on the most remote one, AHU30, while the load on this AHU8 is only 25%. The load is 25% on AHU1 to AHU9, while the rest have a load of 100%.

5.6.3 Diagnosing the faults in the AHU hydronic system performances

The effects of the involved faults were observed on the following system performances: the total cooling coil rate, the pump rate, and the outlet air temperature of AHU1 and AHU30. These two AHUs were chosen because they are the first and the last in the riser, respectively, so it can be useful to check the effects on them. The total cooling coil rate implies the rate of all the coils in the network. The effects of the faults on the total cooling rate and the pump rate are shown in Figures 5.21 and 5.22, respectively.
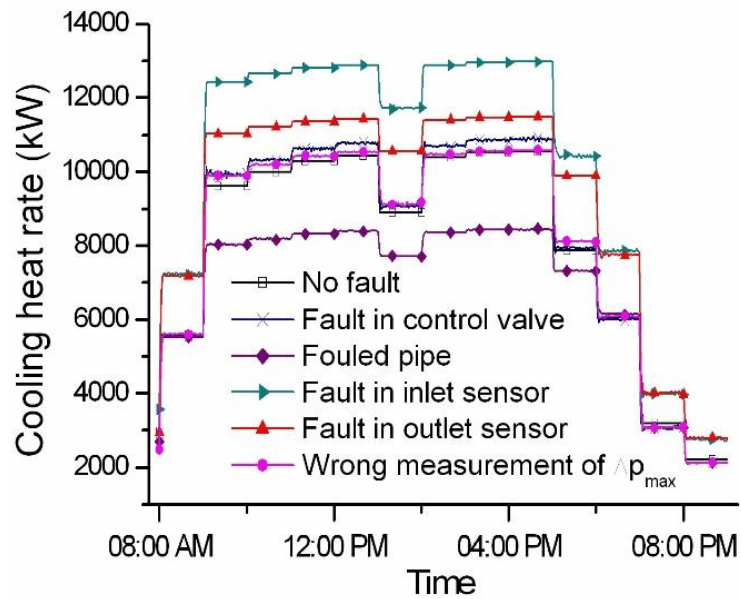

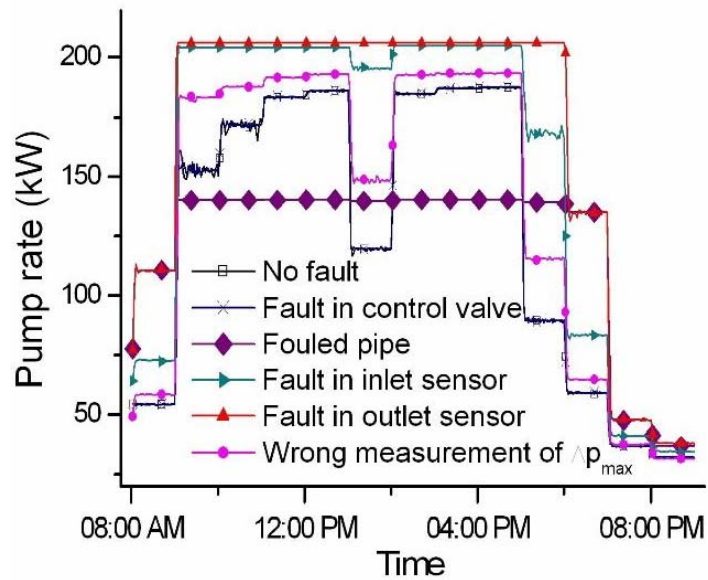Figure 5.21. The fault effect on the total cooling rate

Figure 5.22. The fault effect on the pump rate

The fault in the control valve and the wrong measurement of the pressure difference do not give a large change in the cooling rate compared to the state without the faults, as shown in Figure 5.21. Therefore, the total cooling energy consumption is not increased in the case of these two faults. The fault in the control valve does not influence pump performance, as shown in Figure 5.22. The wrong measurement of the pressure difference increases the pump rate. Both faults in the inlet sensor and the outlet sensor increase the cooling coil rate and the pump rate. The fouled return pipes increase the pump power consumption, while there is a decrease in the cooling energy consumption.

The fault effects on the AHU1 and AHU30 outlet air temperatures are shown in Figures 5.23 and 5.24.
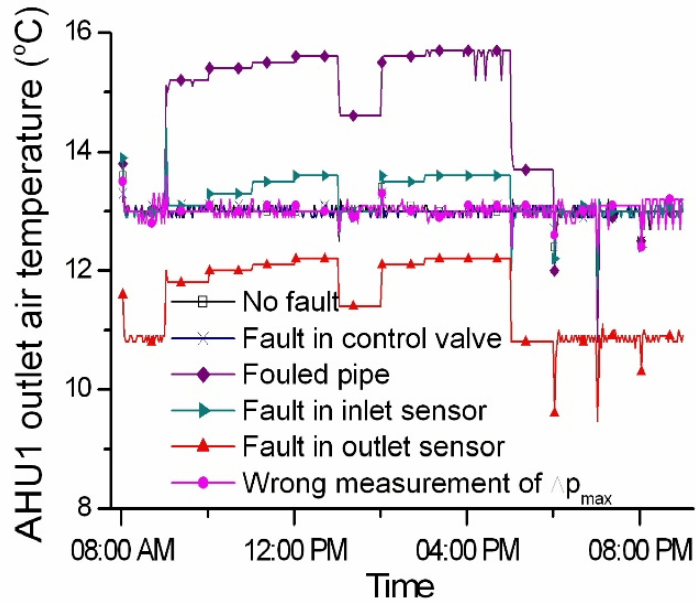
Figure 5.23. The fault effect on the AHU1 outlet air temperature
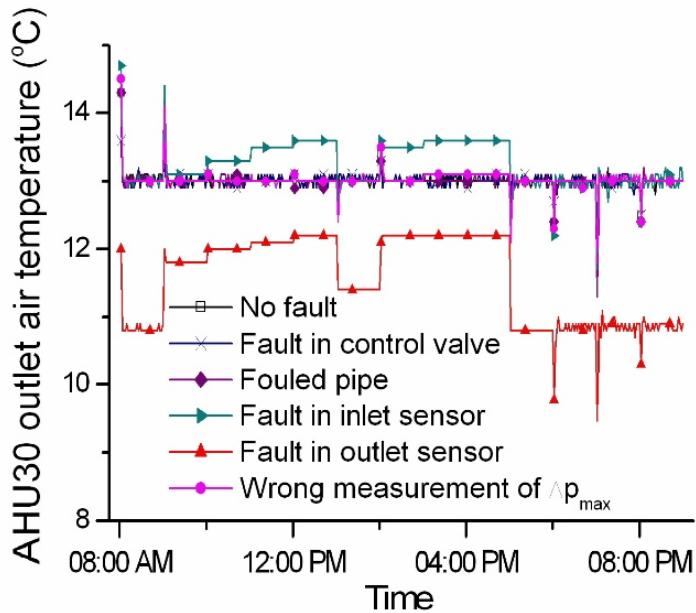
Figure 5.24. The fault effect on the AHU30 outlet air temperature

The inaccurate measurement of the pressure difference and the fault in the control valve do not affect the AHU outlet air temperatures, as is shown in Figures 5.23 and 5.24. The effect of the fouled return pipes is the increased AHU1 outlet air temperature. Since the water flow from the AHU1 is very low, it is not possible to achieve the set-point outlet air temperature when most of

the AHU1 circulation is fouled. This fault does not have a large effect on the AHU30 outlet air temperature (Figure 5.24) because this does not have so long fouled circulation. A positive bias in the AHU outlet air sensor affects a negative bias in the AHU outlet air temperatures, while a positive bias in the AHU inlet sensor affects a small positive bias in the AHU outlet temperatures.

The performance indices were calculated for the above four performances. The performance indices for the cooling rate and the pump rate were calculated based on Equation 5.9, while the indices for the temperatures were calculated based on Equation 5.10. The set-point outlet air temperature is $13^{o}C$. These performance indices of the AHU hydronic system are given in Figures 5.25 to 5.29. The abbreviation TOA in the following figures means the temperature of the outlet air. So, PI_{TAO1} is the performance indices for the AHU1 outlet air temperature. PI_Q is the index for the cooling coil rate, while PI_P is the performance index for the pump rate.
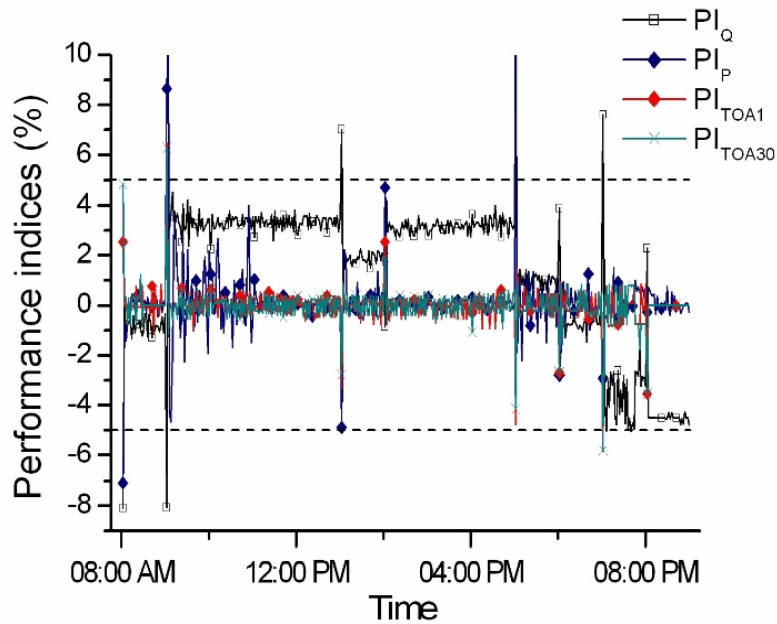
Figure 5.25. PIs for the fault in the control valve
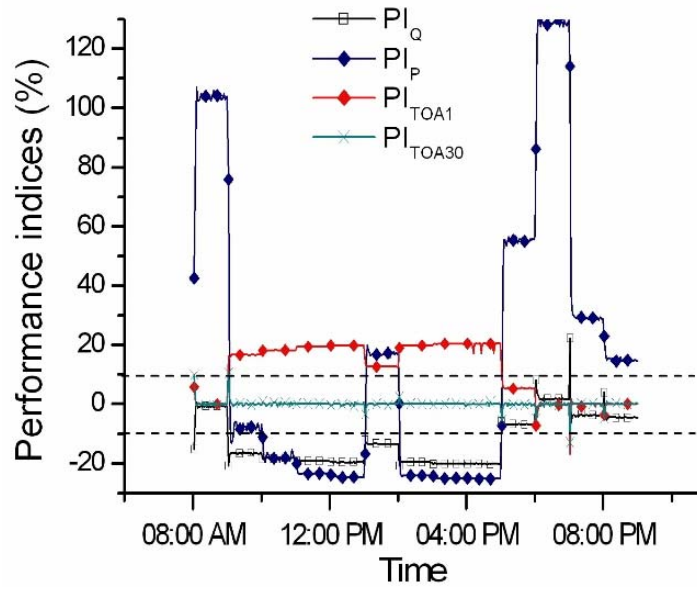
Figure 5.26. PIs for the fouled return pipes
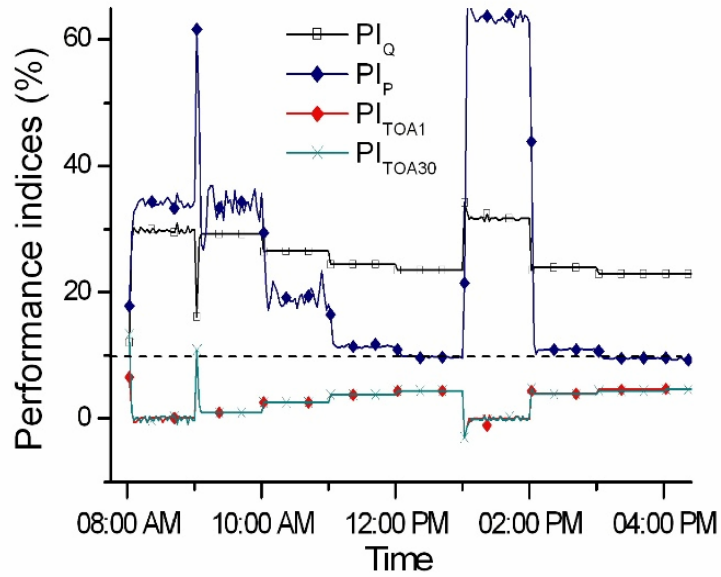
Figure 5.27. PIs for the fault in the inlet sensor
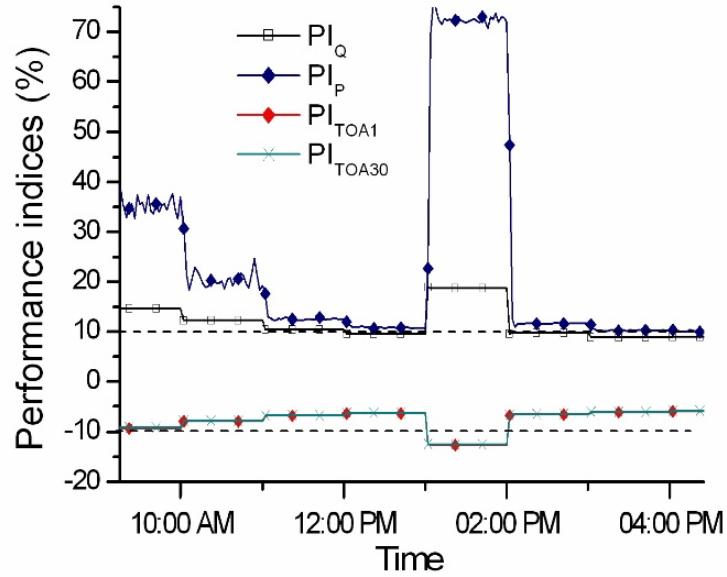
Figure 5.28. PIs for the fault in the outlet sensor
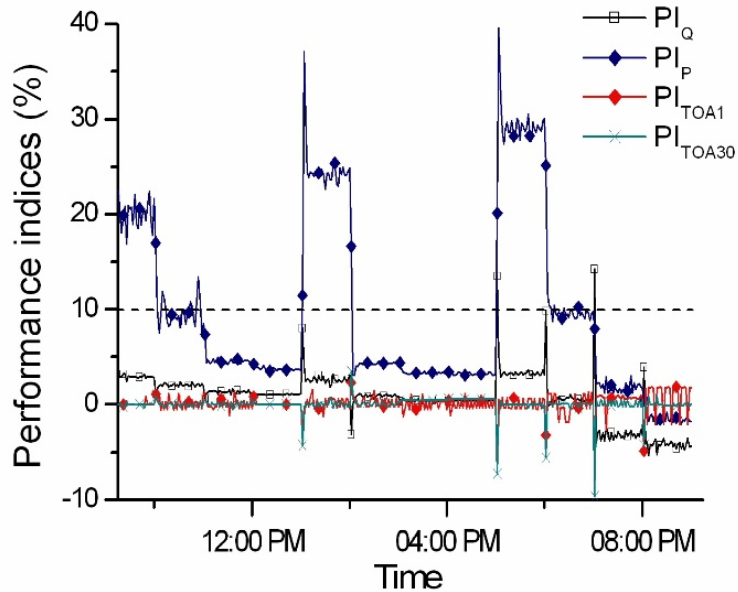
Figure 5.29. PIs for the fault in the measurement of Δp_{max}

In Figures 5.26 to 5.29 there are the horizontal lines at ±10% of the performance indices to show the threshold from where it can be considered that there might be a fault in the system. In Figure 5.25, this line is at ±5% because, in that case, there is not such a large bias in the performance indices.

The results show that faults can affect the AHU outlet air temperature, the pump rate, and the cooling coil rate. The system is quite resistant to the fault in the control valve, while more oscillations in the achieved air temperature can appear. In the case of the incorrect measurement of the pressure difference, it is shown that this reverse-return system is self-balanced. Since the pressure drops in all the branches should be similar, the pressure difference sensor can be placed anywhere. As the results for this fault show, the controllability of this system is still good.

In Figure 5.26, the PI_P for the fouled return pipes has both positive and the negative values, so it is difficult to label this index. The average daily value of the PI_Q is higher than 10%. In the case of this fault, the pump head reaches the pump head maximum. Therefore, under the low cooling loads, the water flow rate is low, while the pump head can be high. In contrast, under the high cooling load at mid-day, the water flow rate should be high, while the pump head is also high. Since the pump head cannot be increased over the pump maximum, the flow rate is decreased, so the pump power appears to be decreased. Therefore, the label for PI_P for this fault is P. This fault shows that additional performance indices should be involved for better fault detection, for example the pump head and the water flow rate.

Using the involved index labeling in Chapter 5.4 and the performance indices values in Figures 5.25 to 5.29, several FDD rules can be established. Finally, a logic diagram of the rules is given in Figure 5.30.
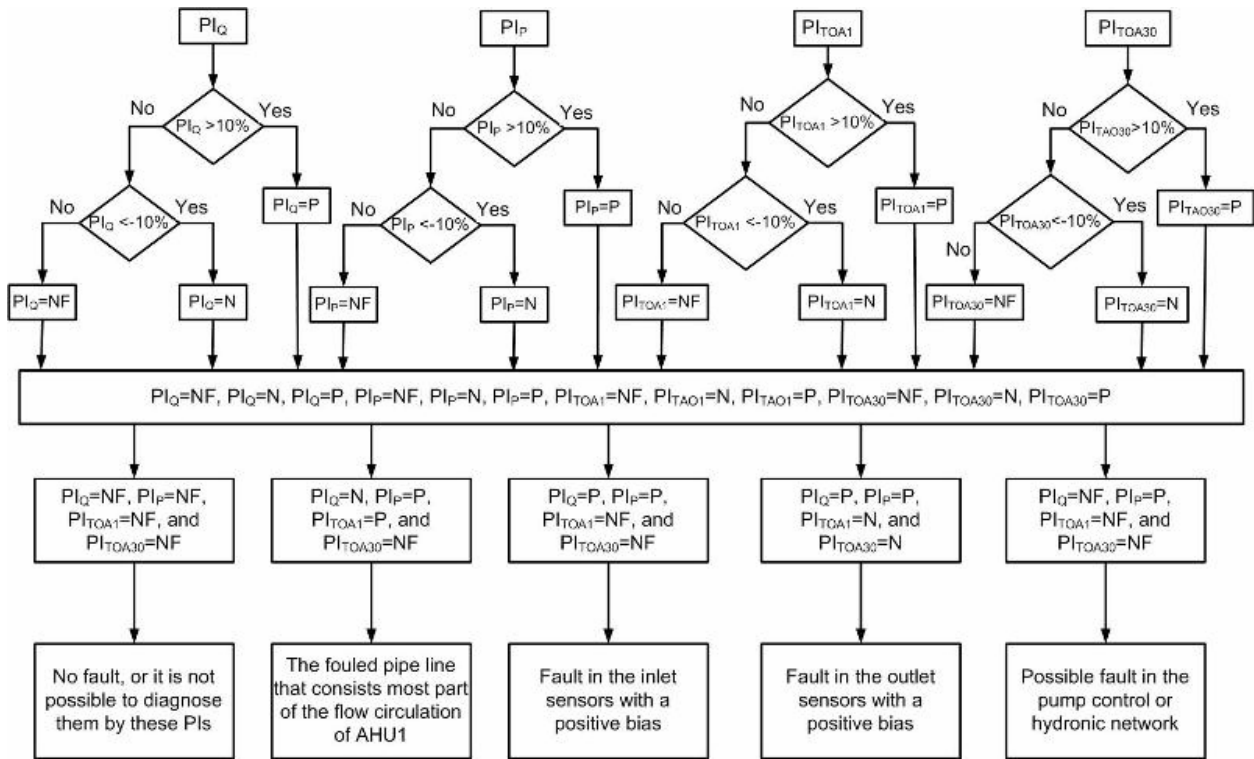
Figure 5.30. FDD rules for the AHU hydronic system

The FDD strategy in Figure 5.30 consists of two parts, fault detection in the top part and fault diagnosis in the lower part. The fault detection implies the performance indices classification before the five fault diagnosis rules were developed. The rules for the fault diagnosis are the following:

− Most of the pipe circulation to and from AHU1 is fouled: if there are positive biases for the pump power and the AHU1 outlet air temperature but a negative bias for the cooling rate and no change in the AHU30 outlet air temperature.

− Fault in the inlet sensor: if the energy consumption and the pump power have a positive bias, but there is no fault in the achieved air temperature.

− Fault in the outlet sensor: if the energy consumption and the pump power have a positive bias, but there is a negative bias in the achieved air temperature.

− Fault in the pump control: if there is a positive bias in the pump power, but there is no fault in the energy consumption and achieved air temperature.

By testing new faults, new FDD rules can be established. Currently, multiple faults have not been examined.

5.7 Closing remarks regarding the model calibration and the fault detection

The most important remarks regarding the model calibration and generating the FDD rules using the simulation tool are the following:

- For a successful model calibration, it is necessary that the system model performs in the same way as the real system.
- EnergyPlus can be used for establishing the FDD rules for the component faults in the heating system.
- TRNSYS can be used successfully for establishing the FDD rules in both the control system and the component faults.
- The FDD rules in this study have been established in three steps: testing different faults, calculating the performance indices, and classifying the observed PIs.
- A cause-effect rule can be correct as the baseline for the performance indices is a performance without faults. In addition, the rules can be affected by the value of the chosen threshold.
- Some faults do not affect all the observed system performances because the system is capable of overcoming such a fault and achieve the desired performances. Therefore, it is necessary to analyze a few important performances so that a certain fault can be diagnosed. For example, the bias in the inlet AHU sensor does not affect the achieved air temperature, while the energy consumption is increased.
- If it is necessary, a new FDD rule system can use several performance indices than suggested here. For example, the pump head or the water flow can be beneficial for the pump performance estimation. However, the use of several indices gives more complex FDD rules.
- Different faults in nature, but caused at the same place, cause the same effects in the performances. For example, the poor building envelope insulation and the open window

give the same effects on the indoor air temperature and the energy consumption. Therefore, it can be difficult to diagnose each of these faults separately, except to recognize that there is a change in the building envelope.

6   CONCLUSIONS

6.1 Main conclusions

The particular conclusions for each chapter are given in the closing remarks. Therefore, only the general conclusions are presented here.

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

An important means for the practical application of any commissioning tool in existing building is BEMS. Sometimes, however, it can be difficult to make the connection among the building geometry, the HVAC system schema, and the BEMS measurements due to the building modifications through its lifetime. There are now, however, easily available e-data related to a building. Therefore, it is necessary to estimate the validity of the data that are used for any building assessment. Contacts with the maintenance services, the system acquirement, and additional measurements can help in the data quality estimation.

Coupled simulation and optimization programs (EnergyPlus and GenOpt) have been utilized for improving the building performances. These tools have been used for improving the design process and the control strategies in HVAC systems. Buildings with the hydronic heating system have been analyzed for the purpose of improving the design process. The optimization tool helps to utilize all the features of a simulation model. In that way, it was possible to determine the parameter values that lead to optimal system performance. Since it has not always been possible to perform only a direct optimization, it was necessary to establish an alternative approach for handling the problems. The established approaches have taken into consideration the problem objectives, constraints, and the program limits. In addition, the approach for handling the conflicting objectives in the building design has been elaborated. The total annual cost has been

estimated by the simplified annuity method. Therefore, the final results in Chapters 3 and 4 are not highly valid, while the methods are recommended.

Using EnergyPlus and GenOpt, the control strategies in two different HVAC systems have been analyzed. These systems were the hydronic heating system and the ventilation system with the recovery wheel. Two approaches have been developed for these two systems, and include the examination of possible strategies until improvements have been achieved. The strategies were easily examined using the optimization tool because a huge range of the values can be tested with little effort. The developed approaches for the strategy optimization include: involving the optimization variables and the objective function and developing information flow for handling the optimization process. To simplify the optimization problem, the optimization variables were classified. The variable classification has given the framework for the optimization approach: directly by optimization program or by manual rerun.

Chapter 5 elaborated the system faults for the AHU air cooling system and the hydronic heating system. For that purpose, two approaches were developed. The first is a heat balance model approach, while the second is rule-based that was generated using the simulation tools.

MATLAB was used to model the heat balance for the building and the heating system. Therefore, the MATLAB optimization toolbox was used to calibrate this model. To couple real data and the simple heat balance model, the procedure for the model calibration by use of an optimization algorithm has been purposed. Using this model, three operating faults in the heating system were elaborated.

EnergyPlus and TRNSYS were used to generate several FDD rules. EnergyPlus was used for modeling the hydronic heating system, while TRNSYS was used for the AHU cooling system. Comparison of the expected and deviated performance is fault detection, while diagnosis means fault identification. Therefore, different FDD tools have diversity in a fault classifier. FDD rules in this work use a threshold value of ±10% for the performance indices as the classifier. These FDD rules have been established in three steps: testing different faults, calculating the performance indices (PI), and classifying the observed PIs. The reason for using these different

simulation tools lies in fact that EnergyPlus can be used for establishing the FDD rules for the component faults in the heating system, while TRNSYS can be used for establishing the FDD rules in both the control system and the component faults.

Since the presentation of the results to the final user is important, a data model has been suggested for that purpose. The final user of the results can be a building operator or manager. A data model for a certain example has not been developed in this work but rather suggested as an idea. The data model as a framework can be used for developing the operator guidelines. The data model for that purpose has to include the necessary information for the fault diagnosis and the building improvement.

6.2 Practical applications

Some of the results can be used for practical applications, while some results cannot be used directly as they are presented in this work. The conclusions obtained from the real environment contacts, the ideas for the control strategy improvements, and the FDD rules can be used practically.

The instructions and ideas for improving the control strategies in the heating and the ventilation system can be used practically. Also, the main instructions in the building design can be used practically.

The conclusions regarding the used data and the practical issues in collecting them can be used as instructions to avoid the mentioned issues. These findings should help the building maintenance communication.

The established FDD rules can be used as manual instructions for the building operators. In addition, these rules can be used as a framework for the automated FDD algorithms that can be directly programmed in the BEMS.

7 SUGGESTIONS FOR FUTURE STUDIES

Based on the research and conclusions, the following suggestions for the future work can be made:

- As shown in the practical surveys, both the maintenance contracts and the maintenance structure influence the building performances. Therefore, it can be useful to make new surveys with the aim of estimating and establishing relationships between the suggested and applied measures, and the final benefits. The results of such surveys can be used practically in selling the commissioning projects.

- As shown in Chapter 4, the control strategies can always be improved and tuned to the actual building demands. Therefore, future work should upgrade the current BEMS programs by implementing different algorithms for the real building control strategy improvements. In addition, the first step in this improvement can be testing new strategies on the real building until an improvement in the performances is achieved.

- Based on the study in Chapter 5, many different FDD rules for HVAC systems can be developed. These rules should be first tested manually on the real building. Consequently, such rules should be directly programmed in BEMS.

- Since a cause-effect rule can be correct as the baseline for the performance indices is a performance without faults, additional work in developing the performance baseline guideline is necessary. Such a study should deal with the baseline energy consumption and the parameter settings. In addition, such a guideline should be related with an energy standard implementation, for example EPBD.

- Since a control can be only as accurate as the sensor measurements, it is necessary to develop methods for measurement assessment. As shown by the additional measurements and testing the biases in sensors, the measurement accuracy and quality significantly

influence the energy consumption. Therefore, research in the measurement quality and sensor deployment can be beneficial for HVAC systems. Such research should also cover the mathematical methods for the measurement assessments.

- Finally, an information system guideline for building operators should be developed. Such a guideline should consist of the necessary objects for the building performance assessment and improvement. As shown in Chapter 2, a data model should be used for that purpose. Such an information system should encourage communication among the building participants.

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Appendix I – Questionnaire

Please, find some minutes to fill out this form - it will be a big help!

Company:

1. Information about building

1.1 Name of the building and address:

1.2 Contact Staff Person	
1.3 Tel. num of Contact Staff Person	
1.4 Building type (e.g., office, warehouse, hospital)	
1.5 Number of occupants	
1.6 Net Total Area	
1.7 Number of floors	
1.8 Year of construction	
1.9 Year of last renovation	
1.10 Do you plan renovation within 2 years?	Yes ☐ No ☐

2. Building Equipment

2.1 Building has central heating/cooling	*Heating* ☐	*Cooling* ☐
2.2 Building is district supplied	Yes ☐	No ☐
2.3 Building has BEMS	Yes ☐ No ☐	Num. controllers

2.4 Which type of system is used as heating and cooling in this building?[1]

	Ventilation	*Heating*	*Cooling*
	Heating water coil ☐	Radiator ☐	Air cooling ☐
	El. Heating coil ☐	Floor heating ☐	Ceiling cooling ☐
	Cooling coil ☐	Electric heater ☐	Other[2]
	Other[2]	Radiation ☐	Other[2]
	Other[2]	Other[2]	Other[2]
2.5 Num. of system			
2.6 Year of the oldest system			

3. Indoor environment

Frequently occurred problems that are reported to caretakers

Ventilation	*Heating*	*Cooling*
Draft ☐	Too warm ☐	Too warm ☐
Noise ☐	Too cold ☐	Too cold ☐
Other	Unstable temperature ☐	Unstable temperature ☐
Other	Other	Other

4. Documentation

Do you have[3]	Yes	No
4.1 Design intention	☐	☐
4.2 Ordinary Operation Step	☐	☐
4.3 As-built records	☐	☐
4.4 Testing, Adjusting and Balancing	☐	☐

5. Energy expenses

	Yes	No
5.1 Do you have energy bills for the last 2 years?[3]	☐	☐
5.2 Do you practice energy efficiency in this building?	☐	☐
5.3 Do you follow some of authority measures in energy use?	☐	☐
5.4 Do you use some of Enova tools?		

6. Measuring

	Yes	No
6.1 Can we have a survey in this building?	☐	☐
6.2 Can we do measurements in the building?	☐	☐

7. Maintenance

	Yes	No
7.1 Do you have steadily employed operator?	☐	☐
7.2 Does the operator attend training for the equipment?	☐	☐
7.3 Do you hire a company for maintenance?	☐	☐
7.4 If yes, does the company have the obligation to maintain all HVAC systems in building?[4]	☐	☐

8. Commissioning

Commissioning is a systematic process of ensuring that all building facility systems perform interactively in accordance with the design documentation and intent. It implies accepting the different methods, guidance and procedures. Process eliminating the need for costly capital improvements, and can give short a payback time.

Are you interesting in commissioning of this building?	Yes☐	No☐

Questionary is submitted by _____

Thank you for your answers!

Some tips:
1. Cross over for systems that are used in the building.
2. Here you can add some another systems for ventilation/heating/cooling.
3. Cross over "Yes" if you have these documentation and if we can get access in these documentation.
4. The question is relevant if your answer on the previous question is "Yes".

Appendix II - Logged points

Num	Point	Data	Unit	Period	Time step	Comments
1	WM01	Energy consumption	kWh		hourly	
2	TUR	Temperature	^{o}C		hourly	
3	RETUR	Temperature	^{o}C		hourly	
4	TF02 t	Temperature	^{o}C		hourly	
5	TF03 v	Temperature	^{o}C		hourly	
6	TF03 t	Temperature	^{o}C		hourly	
7	TF04	Temperature	^{o}C		hourly	
8	TF05	Temperature	^{o}C		hourly	
9	TF06	Temperature	^{o}C		hourly	
10	TF07	Temperature	^{o}C		hourly	
11	TF08	Temperature	^{o}C		hourly	
12	SM02	Water flow	m^3		hourly	
13	DP01	Pressure difference	Pa		hourly	
14	PF01	Pressure	Pa		hourly	
15	AA01	Valve opening	/		hourly	
16	AA03	Valve opening	/		hourly	

Appendix III - Temperature logger list

Logger Name	Place (Office Num)	Period	Comments
CT1		7 days	
CT2		7 days	
CT3		7 days	
CT4		7 days	
CT5		7 days	

Appendix IV - Papers

Paper I	N. Djuric, F. Frydenlund, V. Novakovic, J. Holst, Preliminary Step in Collecting Data for Commissioning of Existing Buildings (Characterization of buildings, systems and problems), 2007.
Paper II	N. Djuric, V. Novakovic, J. Holst, Optimization of energy consumption in building with hydronic heating system by use of computer based tools, 2005.
Paper III	N. Djuric, V. Novakovic, J. Holst, Optimizing the building envelope and HVAC system for an inpatient room by using simulation and optimization tools, 2006.
Paper IV	N. Djuric, V. Novakovic, J. Holst, Z. Mitrovic, Optimization of energy consumption in buildings with heating systems considering thermal comfort by use of computer-based tools, 2007.
Paper V	N. Djuric, V. Novakovic, F. Frydenlund, Existing building commissioning using computer based tools, 2007.
Paper VI	N. Djuric, V. Novakovic, Review of possibilities and necessities for building lifetime commissioning, 2007.
Paper VII	N. Djuric, V. Novakovic, F. Frydenlund, Heating system performance estimation using optimization tool and BEMS data, 2007.

Paper I   N. Djuric, F. Frydenlund, V. Novakovic, J. Holst, Preliminary Step in Collecting Data for Commissioning of Existing Buildings (Characterization of buildings, systems and problems), 2007.

Preliminary Step in Collecting Data for Commissioning of Existing Buildings (Characterization of buildings, systems and problems)

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SUMMARY
This paper deals with the current results in the survey for collecting data for building commissioning. The first aim of the survey was to make an overview of the most typical buildings, HVAC equipments and their related problems. The second aim was to establish the criteria for both choosing the buildings in the further research and establishing the existing building commissioning tools. The survey is carried out by developing the questionnaire for the building caretakers. The current results could give some of the criteria for commissioning of the existing buildings. The paper gives the list of the buildings, equipments, and problems, for which the commissioning tools should be developed.

INTRODUCTION
Commissioning tools for existing buildings should be developed to be useable in the most common cases of buildings. Actually, commissioning tools should give the solution for the most typical problems in the most common buildings. Therefore it is important to make an overview of the most common buildings in Norwegian building facilities. A questionnaire is developed as the preliminary step in an overview of the building facilities. The idea of the questionnaire is to give as much as possible straightforward answers. In addition, the idea of the questionnaire is to check which and how much of the building data can be obtained for our further studies.

METODS
The questionnaire is developed as a tool for the survey, and consists of eight groups of the questions. Since the questions are defined to be as straightforward as possible, the answers should be either "yes", "no", or some numbers. Together with the questionnaire a short guide is attached, too. The questionnaire has to be filled out by the person who is in charge of the building administration, e.g. it could be the caretaker.

The first round of the survey was to send the questionnaire to the caretakers. After getting the answers, a second round was performed based on the unanswered questions. The second round was performed by sending the e-mails to the persons, which filled out the questionnaire.

The survey is still in progress, because it is necessary to have as good as possible overview of building facilities in Norway.

The content of the questionnaire

Building information

These questions have the aim to get general data about the buildings. The most important questions from this group are about: net total area, year of construction, year of the last renovation and if a renovation is planed in the next two years [1].

Building equipment

This group of the questions should show the most used equipment and type of HVAC system in the buildings. Most of the questions in this group should be answered by ticking off. The questionnaire gives the possibility to tick off the most common HVAC equipments, but there is also possibility for additional equipment. Besides the information about equipment, this group of questions asks for: the number of substations, the number of the particular type of HVAC system, and the age of the oldest HVAC equipment in the building. The guide for fill out the questionnaire gives the explanation of HVAC system based on the following definition: "An HVAC system is functional assembly of equipment for air treatment. The assembly of equipment is connected by a net-work that is determined by the system nature (for example radiators are connected by pipes, air-distribution units by ducts, etc.). An HVAC system is one in which energy is transformed from a source of energy through a distribution net-work to spaces to be conditioned [2]."

Indoor environment

These questions deal with the most common problems in the buildings. The most typical problems concerning the indoor environment are suggested in the questionnaire, but also there is a possibility for additional problems. The suggested problems are noted generally, as the following: too warm or cold, unstable temperature, draft and noise. There is no emphasis on when problems occur. These questions should be answered by ticking off, too.

Documentation

The questions treat the building documentation. All the terms in this group of questions were defined based on the Norwegian translation of the commissioning terms [3]. The aim of this part of the questionnaire is to show how much of building documentation are available. The questionnaire asks for the following documentation: design intention, ordinary operation step, as-built records, and (TAB) testing, adjusting and balancing documentation.

Energy use

These questions aim at energy use and the attitude of the building owners in practicing energy efficiency. A question from this group asks about using *Enova* energy efficiency tools. Enova SF is a governmental agency established to deal with the implementation of energy efficiency and renewable energy policy in Norway. This is a pro-active agency that has the capacity to stimulate energy efficiency by motivating cost-effective and environmentally sound investment decisions. Enova SF advises the Ministry in questions relating to energy efficiency and new renewable energy [4]. The questions about energy efficiency attitude among building owners are important for an overview if the buildings need some additional tools for energy efficiency. There are four questions in this group, and they ask about the following: energy bills during the last two years, practicing the energy efficiency measures in the building, practicing some of the authority measures in the energy efficiency, and using the Enova tools.

Measuring

Since access to a building is necessary to measure, these questions ask about it.

Maintenance

These group of the questions aims at maintenance in the buildings. The aim of this part is to connect the problems and maintenance service. There are questions either the building owners have in company an employed maintenance service or a hired company for maintenance service. There is a question if the caretakers attend training for HVAC equipments. In addition, there is a question about the responsibility of a hired company for the maintenance.

Commissioning

The last question is if they would use some of commissioning tools. A short explanation about commissioning is given additionally to this question. Commissioning is a systematic process of ensuring that all building facility systems perform interactively in accordance with the design documentation and intent. It implies accepting the different methods, guidance and procedures. Process eliminating the need for costly capital improvements, and can give short payback time [5].

RESULTS

The following building owners took part in the survey: Forsvarsbygg (the Norwegian Defense Estates Agency), Telenor (Governmental telecommunication company), and NTNU (Norwegian University of Science and Technology) campus. The questionnaire was completely answered by *32* building caretakers from *15* towns in two months through two rounds. Some of the caretakers sent photos, which are given in Table 1.

Table 1. Photos of some of the buildings participating in the survey.

NTNU-Main building (96 years old)

NTNU-Realfabygget(137 HVAC system)

NTNU-Materialteknisk

Military office building - Rena

Telenor Kolstad - Bergen

Military office building - Bodø

Based on the answers, some of the starting criteria for future research can be established. The age of buildings that participated in the survey is from *1* to *96* years. The answer to this question

should be straightforward, but in some cases there are few years of construction. The reason for this is because the buildings have been extended through the entire life time, and there is no any regularity how it happens. The question about the year of the last renovation was not answered in *21* cases. The reason is that the caretakers do not know the exact date. Using the available data about year of the last renovation, the rate of renovation during the building life time can be explained. The relation is shown in Figure 1.
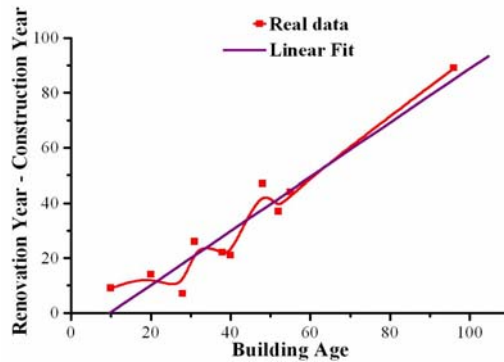
Figure 1. The rate of building renovation during the life time

Figure 1 shows that the buildings had the first renovation approximately *10 years* after the construction. The equation of the fitted line in Figure 1 is:

$$Last\ renovation\ Year - Construction\ Year = -9.52 + 0.98\ Building\ Age\,. \qquad (1)$$

The multiplier of the building age is *0.98*. This implies that the building owners invest in the buildings throughout the entire life time. Therefore the building commissioning would be necessary on a continuous basis.

The age of HVAC system is important information for the building commissioning. According to the answers, the relation between the age of building and the age of the HVAC system can be established as in Figure 2.

Figure 2. Building Age vs. Age of the oldest system

For *41%* of all buildings there is a linear relation between the age of building and the age of the oldest system. Figure 2 shows that the buildings, which age is less than *50 years*, have at least one of the HVAC equipment of the same age as the building age. The complete data about the year of the construction, year of the last renovation and the age of the oldest system were obtained for *18* buildings. Using this data, the relation between the system age and year of renovation can be established as in Figure 3.
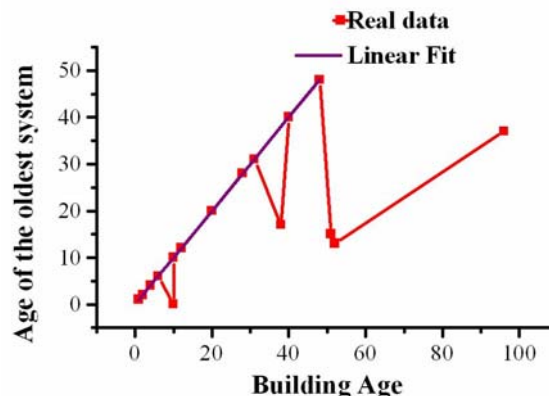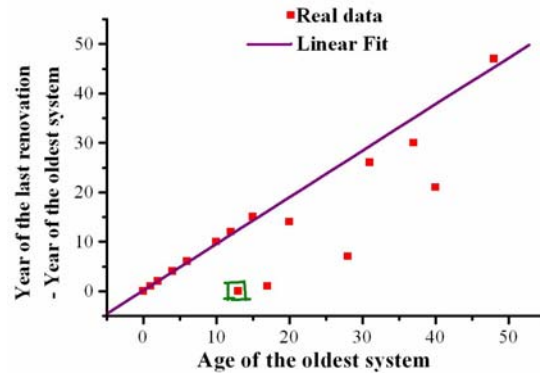

Figure 3. System age vs. Renovation

Figure 3 shows that for 11 buildings there exists a relation between the difference of the year of the last renovation and the year of the oldest system, and the age of the oldest system. Figure 3 shows that the HVAC systems are not replaced after each renovation. This shows that the HVAC systems might be renovated, but not changed completely, because some of the components are still kept. Only in the case of one building, with the green square, (Kaserne Setermoen) the HVAC equipment has been changed completely when the renovation was undertaken. Since most of the buildings are renovated partly, the estimation of the retrofit benefit would be necessary. Therefore the commissioning protocol of a suggested improved measure is necessary.

The answers about the HVAC systems are important for defining the conditions for which the commissioning tools will be developed. *84 %* of all the buildings have a central heating source. 59% of the buildings have both the central heating system and the district heating. Since there is BAS (Building Automation System) in *91 %* of the participated buildings in the survey, the further study will treat buildings with BAS. The obtained results can be used to establish the relation between the number of controllers and the number of HVAC systems as it is shown in Figure 4.

Figure 4. Number of substations vs. Number of systems

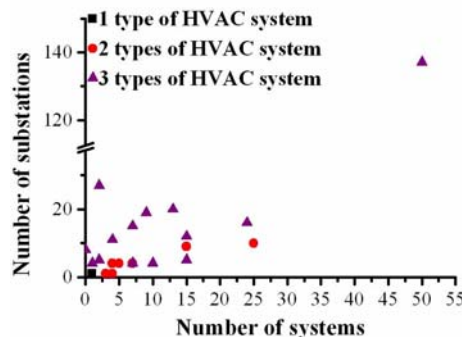Still it is not possible to give the strict criteria for the number of the systems and the number of the substations, but there is a trend that several different types of HVAC systems imply higher number of the substations. The buildings with all three types of HVAC systems (ventilation, heating and cooling) have a higher number of substations than the other, as Figure 4 shows. BAS gives a possibility for the indirect measurements. Therefore a possibility of use the BAS data is valuable for the commissioning procedures.

The question about number of systems was not answered in *22 %*. Some of the answers were obtained through the second round. However, some of the participants in this survey have in the building data base the exact data about the number of the systems (a good example is NTNU Gløshaugen campus). The operation management at NTNU campus uses the data base program LYDIA [6]. Also, they have their own data base in Excel format, which has been developed over seven years.

The results concerning the number of HVAC systems and net total area are shown in Figure 5 and 6.
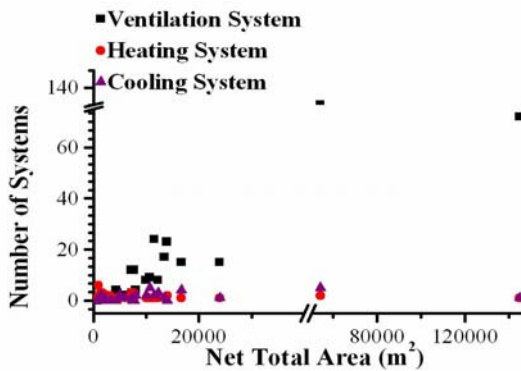

Figure 5. Number of Systems vs. Net Total Area   Figure 6. The Subplot of Figure 5
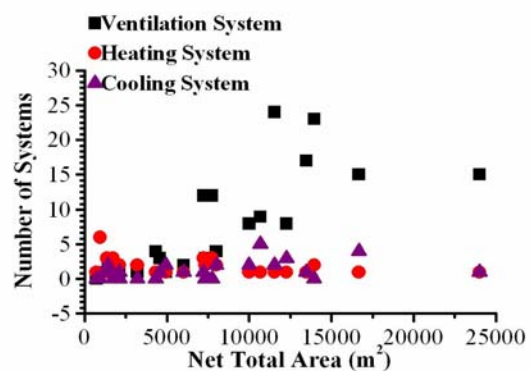
Figure 5 shows a certain relation between the number of the particular type of the system and net total area, but still it is not possible to establish any criteria. In addition, it is obvious that a larger net total area of the building implies a higher number of the ventilation systems. Figure 6 is subplot of Figure 5, so it gives an enlarged view of the narrow area in Figure 5. In Figure 6 is easier to note that the number of the heating and the cooling systems are mostly the same regardless of net total area. Information about building area and the position of HVAC system are important for developing the building models. In addition, the knowledge of the BAS measurements gives a possibility for better understanding of a building performance. Therefore the relation among both the building net total area, number of systems and the number of the substations if beneficial for establishing the commissioning protocols for the building estimation.

The fourth group of the questions should show which building documentation can be obtained. Most of the caretakers have never heard of the term "design intention". This is the reason why only in *19 %* of the answers were "yes". As-built records and TAB documentation can be obtained from *78 %* of the buildings participated. The ordinary operation step documentation exists in *91 %* of buildings. The above information about documentation implies the commissioning criteria that the future studied buildings should have as-built records and TAB documentation and ordinary operation step available.

Energy bills for the last two years are available in *81 %* of the buildings. In most of the buildings, the owners practice some measure for energy efficiency, either on their own way or following the authority measures aimed to the energy efficiency. Enova tools are used in *41 %* of the buildings. These results show that the owners of the buildings practice the energy efficiency measurement in some way, but they also need several tools for that purpose.

Each building in the survey has their own maintenance service employed in the company and all of them attend some courses about the equipment in the building. *69 %* of buildings hire outside company for maintenance. The hired companies have the responsibilities for all HVAC equipments only in *19 %* of the cases, because they are hired only for the particular equipments. This implies the conclusion that for some issues in the building only the employed staffs are in charge. Since there are a few levels of the maintenance services, a discrepancy between their strategies can appear. Consequently, some faults or issues can appear in a building, and therefore a commissioning protocol for the maintenance service can be useful.

For developing and application of the commissioning tools in their buildings, all the participants except one are interested. This is also proven by the fact that in all the buildings we can do research and measuring.

DISCUSSION
For the future study and for developing the commissioning tools, it is necessary that the specific type of equipment exist in at least *50 %* of the buildings. The overview of the most used equipment is given in Table 1.

Table 1. Summarization of the most typical building, HVAC equipment and problems

Type of building	Num.of Buildings	Type of HVAC	Equipment	Problem
Office building	13	Ventilation	Water heating coil	Draft
			Cooling coil	
		Heating	Radiator	
		Cooling	Air cooling	Too warm
				Too cold
				Unstable temperature
Hospital	1	Ventilation	Water heating coil	Noise
			Cooling coil	
		Heating	Radiator	
			Floor Heating	
		Cooling	Air cooling	
Barrack	3	Ventilation	Water heating coil	
		Heating	Radiator	Too cold
			Floor Heating	
Multipurpose	12	Ventilation	Water heating coil	Draft
				Noise
			Cooling coil	Bad air
				High air temperature
		Heating	Radiator	Too warm
				Too cold
				Unstable temperature
		Cooling	Air cooling	Too warm
				Unstable temperature

Mess hall	1	Ventilation	Water heating coil	
		Heating	Radiator	
Repair shop	1	Ventilation	Water heating coil	
		Heating	Radiator	
			Floor heating	
			Ceiling Heating	
		Cooling	Air cooling	
Training center	1	Ventilation	Water heating coil	
		Heating	Radiator	

The future study in developing the existing building commissioning tools will deal with the occurred problems for the particular type of building and the appropriate HVAC equipments. Based on the answers, for the most used equipments in the particular type of buildings, the occurred problems are found. For each of these problems in the particular type of building and for the particular type of HVAC equipment, commissioning tools should be developed. The summarization of the most typical problem and equipment in the particular type of building is given in Table 1. The questionnaire is still in progress, and list below will be extended.

CONCLUSION
The survey is a useful tool to start research for the building commissioning. The presented results give a few criteria for the commissioning of the existing buildings. In the future study, the building documentation will be required. The age of both building and equipment will not be strict criteria, but persistence in building renovation would be a required criteria. Therefore, the commissioning protocols should estimate the retrofits benefits. Since BAS give a possibility for the indirect measurements, the future studies will consider buildings, which have HVAC systems with BAS. Even though the relation among both the number of the systems, net total area and the number substations is not established, the further work should find such a relation, since it is important to utilize BAS data for a good understanding of the building performance. The actual summarization the most typical building, HVAC equipment and problems should be spread in the future.

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Paper II   N. Djuric, V. Novakovic, J. Holst, Optimization of energy consumption in building with hydronic heating system by use of computer based tools, 2005.

OPTIMIZATION OF ENERGY CONSUMPTION IN BUILDING WITH HYDRONIC HEATING SYSTEM BY USE OF COMPUTER BASED TOOLS

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ABSTRACT

The paper deals with energy simulation and optimization processes. The simulation process is performed by the simulation program *EnergyPlus*[1] while the optimization process is performed by the generic optimization program *GenOpt*[2].

The simulation is performed in order to analyze energy consumption, indoor temperature and thermal comfort during the design day for variations in the insulation thickness of building envelope and the supply water temperature. The optimization process is used to determine the optimal values of insulation thickness that gives the lowest sum of investment and energy costs, under the condition that the thermal comfort is satisfied.

The simulation results show the influence of the considered parameters on the diurnal variation of indoor temperature and thermal comfort. The optimization processes show the mutual influence of actual parameters on the total cost.

KEY WORDS: optimization, simulation, energy demand, thermal comfort, hydronic heating.

INTRODUCTION

The computer-based simulation and optimization tools are recognized as a very promising tool in designing buildings. Also, the simulation and optimization programs can be used for determining and analyzing the parameters that govern the energy consumption and thermal comfort in buildings.

In order to satisfy the demand for rational use of energy, the analysis and optimization were performed for some important parameters, which influence the energy consumption for the building with hydronic heating system. The energy analyses and optimization were performed for the school building with hydronic heating system. The school building with the heating system was modeled in *EnergyPlus* by using weather data for the heating season in Belgrade (Serbia and Montenegro).

The aim of the study is the analysis and optimization of parameters that influence both energy consumption and thermal comfort by use of computer-based tools. The objective function for optimization takes into account energy consumption and investment cost considering also

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[2] Copyright by Lawrence Berkeley National Laboratories, Berkeley, CA, USA

obtained thermal comfort. The influence of the following parameters was analyzed: the insulation thickness of the building envelope and the supply water temperature.

METHODS

The software package *EnergyPlus* was applied for simulation, while the optimization was performed by use of the generic optimization program *GenOpt*.

EnergyPlus is a simulation program that performs simultaneous calculation of building and HVAC system by using a suitable mathematical model for each building consisting element (construction of building, HVAC system and plant). *EnergyPlus* deals with different building data, which include weather data, the construction of building envelope, the geometry of building, internal loads (people, lights, etc.) and HVAC system. *EnergyPlus* performs transient calculation of building envelope and because of that it is possible to obtain results for each hour or time step [1].

GenOpt is a generic optimization program that must be connected to some simulation program such as SPARKE, *EnergyPlus*, TRNSYS or DOE-2, to be able to conduct an optimization of parameters from simulation programs [2]. *GenOpt* allows the possibility of using one-parametric and multi-parametric optimization algorithm [3].

Description of School Building

The energy analysis will be performed for a school building located in Belgrade. The weather data for Belgrade, for year 1995, given by ASHRAE are used [4]. The school, that is located on the inclined terrain, has two floors. The building has the shape of the Greek letter P, with half-atrium yard oriented to the south. The building consists of 134 rooms. The building envelop is a light construction, with the outside walls made of wood. The partition walls are of light concrete. The windows consist of three glass layers with air between them. The outside doors are of glass with triple glass layers, while the inside doors are wooden.

For defining the zones for sake of calculations, we have to consider the function, the orientation and the air-conditioning system of the included rooms. For the given building, 21 calculation zones are involved. After simulations by *EnergyPlus* and based on calculated heat losses, thermal comfort and considering the most occupied zones, the radiators are proposed for nine zones [5].

Forming the Objective Function for Optimization of Insulation Thickness

To be able to find the optimal values of some parameters it is necessary to define the objective function. The aim is to find the optimal value of insulation thickness but not only to accomplish the minimal total cost yet to satisfy the thermal comfort, too. Satisfactory thermal comfort means that the *PPD* (Predicted Percentage of Dissatisfied) value has to be lower then a particular given value [6], [7]. In order to solve the problem, both the total cost and thermal comfort will be followed through the optimization process. During the optimization process, the optimization program (*GenOpt*) passes several times through the simulation program (*EnergyPlus*) for different combinations of given parameters, calculating energy consumption and thermal comfort for every combination. During the optimization, calculated values of total cost are analyzed only in the area where *PPD<10%*. This means that the sizing is done for boundary values for B class of thermal comfort [8].

The objective function for the optimization of insulation thickness will be created as a sum of the energy cost and the cost of insulation:

$$C = C_E + C_I \tag{1}$$

where $C\left(dinar\right)^3$ is the total cost, $C_E\left(dinar\right)$ is the cost of energy, and $C_I\left(dinar\right)$ is the cost of insulation. The cost of energy is calculated by using the price given by the "Belgrade Power Plant" for consumers with the heat consumption meter. The energy cost for whole heating season will be determined by using the degree-day method because the optimization is performed for the design day. The energy cost for whole heating season is calculated as [9]:

$$C_E = \frac{Q_{DD}}{3600 \cdot 1000} \cdot \frac{DD \cdot y \cdot e}{t_i - t_o} \cdot c_E + P \cdot c_P \tag{2}$$

where $Q_{DD}\left(J\right)$ is energy consumption for the design day; $c_E = 2,71\,dinar/kWh$ is the price of energy per $1kWh$, $P\left(W\right)$ is the installed power of heating equipment [9]; $c_P = 993,6\,dinar/kWyear$ is the price for $1kW$ of installed power equipment per year; $SD = 2520\ ^0C \cdot day$ is degree-day for Belgrade; $e = e_t \cdot e_b$ is the coefficient of limitation, ($e_t = 0,75$ is coefficient of temperature limitation and $e_b = 0,75$ is coefficient of exploitation limitation); $y = 0,6$ is the coefficient of simultaneously load of unfavorable conditions, adopted based on [10]; $t_i = 19\ ^0C$ is indoor temperature; $t_o = -11,5\ ^0C$ is the outdoor design temperature for Belgrade, adopted from ASHRAE [4].

The insulation cost is calculated as follows:

$$C_I = 1,4\frac{A_I \cdot c_I}{n} \tag{3}$$

where $A_I\left(m^2\right)$ is the surface of the insulation in all outside walls; $c_I\left(dinar/m^2\right)$ is the insulation price per unit of surface, that depends on the insulation thickness; $c_I = 15,18316 \cdot \delta - 11,9742$, where $\delta\left(cm\right)$ is insulation thickness; $n\left(year\right)$ is number of years for paying the insulation. In this case n is 10 years and the additional expanses for installment are estimated to by 40%. The rate of interest and the inflation are not taken in consideration during this optimization [9].

SIMULATION RESULTS

Analysis of influence of the insulation thickness on radiator heat rate and the thermal comfort during the design day, in this paper will be shown only for one of 21 calculation zones of the school building [5]. The "Class Zone 2" is oriented south-west. The desired value of the indoor temperature (T_z) is 20^0C during the occupancy period from 0700 to 1900 while outside this period it is 15^0C. The supply water temperature is 60^0C and the radiators are in use whole day. The radiator surface areas are the same for the different values of insulation

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[3] 80dinars=1 € or 1dinar=0,0125€.

3

thickness and they were calculated based of analysis of the heat losses [9]. Variations of the indoor air temperature in the zone during the design day, for different insulation thicknesses, are given in *Fig. 1*, while the radiator heat rate (Q) are given in *Fig 2*.
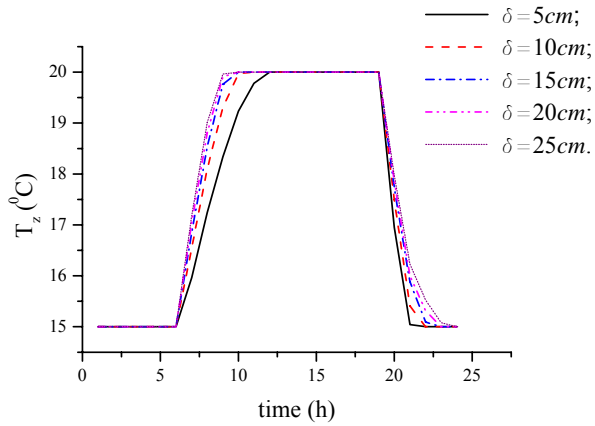

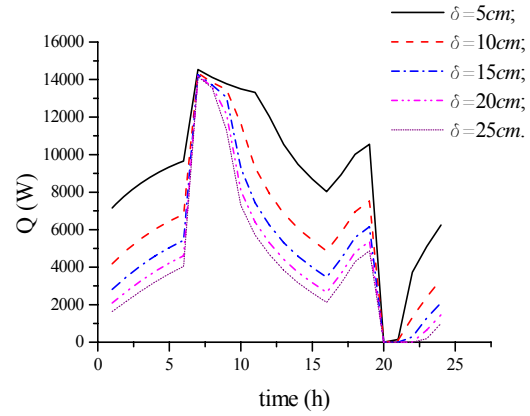Fig. 1 Influence of insulation thickness on indoor temperature

Fig. 2 Influence of insulation thickness on radiator heat rate

Fig. 1 shows that the desired value of the indoor temperature is reached sooner with bigger insulation thickness than with lower insulation thickness of the building envelop. The influence of the insulation thickness on the thermal comfort can be explained by using the *fig. 1*. When the indoor temperature is equal or almost equal to the desired indoor temperature the thermal comfort is satisfied. Using the value of indoor temperature to calculate the PPD value, we can find out that the *PPD* value is about *10%* during almost whole working period. Also, as the insulation thickness increases the thermal comfort will be reached sooner.

Fig. 2 shows that the radiator heat rate decreases when the insulation thickness increases. When the desired indoor temperature increases suddenly, T_z at *0700*, the radiator responds by increasing the heat rate. The rise is almost the same for different insulation thicknesses because the radiator surface area and the supply water temperature are the same for different insulation thicknesses. When the indoor temperature is almost constant, the radiator heat rate decreases when the insulation thickness increases.

The supply water temperature has influence on both the energy consumption and the time necessary to reach desired indoor temperature. The time necessary to reach desired indoor temperature diminishes when the supply water temperature increases. The influence of the supply water temperature on the indoor temperature, during the design day, for the insulation thickness of *9,8 cm* and the radiator surfaces area are the same as in the above analysis, this is shown in *Fig. 3* [9]. The desired indoor temperature is reached after one hour for the supply water temperature of 90^0C, while the desired value is not reached at all for the supply water temperature of 40^0C.
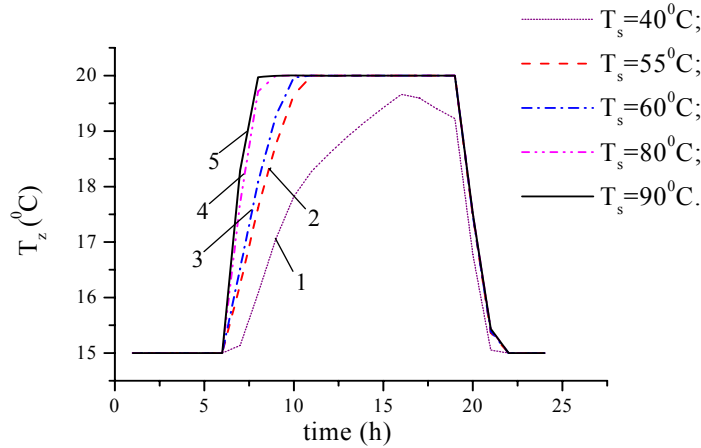
Fig. 3 Influence of the supply water temperature on the indoor temperature

The radiator heat rate is highest during the transition period (at *0700*) for the highest supply water temperature of 90^0C. The desired indoor temperature in the zone is maintained during the whole occupancy period for the highest supply water temperature. In this case, the heat losses toward the outside are at its highest because of the high indoor temperature [9].

OPTIMIZATION RESULTS

The optimization of the insulation thickness of the building envelop was done for the objective function (1). In this case only one parameter was optimized and the Golden Section method was used as optimization method [3]. Because of the one-parametric optimization the relations between both the total cost and the insulation thickness, and the *PPD* value and the insulation thickness can be established. The relations between the energy cost, the insulation cost and the total cost, and the insulation thickness of the building envelop are given in the *Fig. 4*, while the relation between the *PPD* value and the insulation thickness is given in the *Fig. 5*.
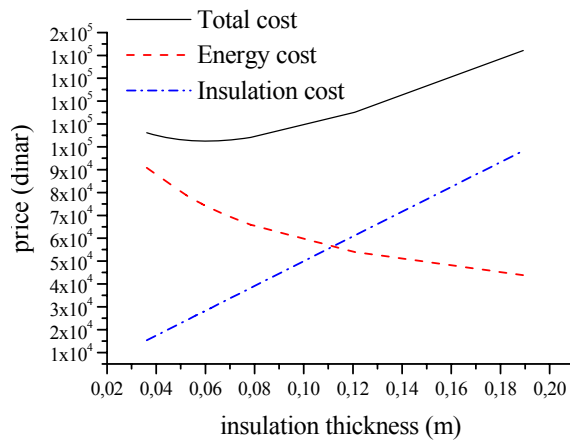

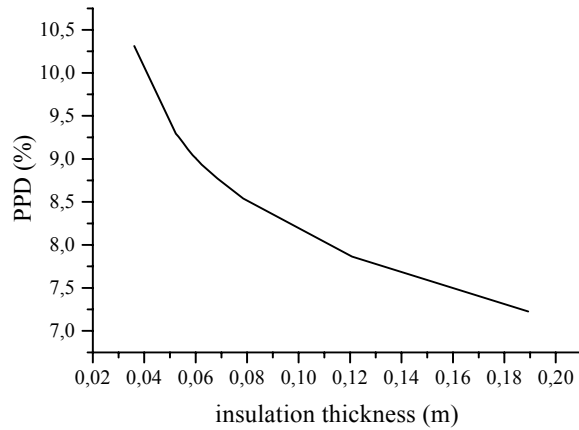*Fig. 4 The relations between different costs and the insulation thickness*

Fig. 5 The relation between the thermal comfort and the insulation thickness

The performed optimization shows that the insulation thickness has influence both on energy consumption and on thermal comfort. Energy consumption i.e. energy cost is decreasing when insulation thickness is increasing. For given prices of energy and insulation we can find the minimum of total cost from the *Fig. 4*. Also, if the insulation is thicker the better is thermal comfort.

CONCLUSIONS

The paper shows that mathematical optimization is a cost-effective tool that supports the designer in creating better buildings and HVAC systems. It will often provide lower operating costs and higher comfort for the building occupants. The simulation shows that the insulation thickness has influence both on energy consumption and on thermal comfort. It shows also that the supply water temperature has influence on the time necessary to reach the desired indoor air temperature.

The optimization process gives the direction in which the actual parameters have to be chosen to be able to diminish energy consumption and to satisfy the thermal comfort demands. The optimization also gives the designer a better understanding of the building and the HVAC system behavior.

ACKNOWLEDGEMENTS

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Paper III   N. Djuric, V. Novakovic, J. Holst, Optimizing the building envelope and
HVAC system for an inpatient room by using simulation and
optimization tools, 2006.

OPTIMIZING THE BUILDING ENVELOPE AND HVAC SYSTEM FOR AN INPATIENT ROOM BY USING SIMULATION AND OPTIMIZATION TOOLS

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Keywords: Thermal Comfort, Design, Simulation, Optimization

ABSTRACT

The evaluation of building performance is a multi-parametric problem with some objectives, which can be conflicting. Sometimes, there are several methods to calculate particular objectives. This paper deals with comparing two different models for predicting thermal comfort. Optimization of parameters, which influence energy consumption and thermal comfort in an inpatient room, is the case study. The analysis is done for the heating period. The response of the models for predicting thermal comfort is shown by analyzing the influence of indoor humidity and indoor temperature. Also, the response of models is shown by analyzing supply water temperature and insulation thickness of the building envelope. The influence of investment period on total cost is shown, too. Each relation between influenced parameters is established by using the optimization tools. The optimization results are different, depending on defined objective function.

INTRODUCTION

The objective of the study is to design an inpatient room at the St. Olavs Hospital in Trondheim, Norway, by using the computer based tools. The optimization aim is to establish the relations between both energy consumption and design parameters, and thermal comfort and design parameters. Two different models for predicting the thermal comfort sensation are compared. The models for predicting thermal comfort are the *Fanger* and *Pierce* model.
For purpose of the study, two models of inpatient room are made in *EnergyPlus[1]*. The first model is made for determining the heat losses. This model is developed for exploring the response of thermal comfort models on changing the indoor humidity and indoor temperature. The second model is made for hydronic

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heating system with radiator heaters. The optimizations for both models are performed for the winter design day in Trondheim.

The optimizing parameters in the analyses are the insulation thickness of the building envelop and the *UA* value of radiator.

METHODS

The simulation process is performed in the simulation software *EnergyPlus*, while the optimization is performed in the generic optimization program *GenOpt*[2]. The inpatient room is modeled in *EnergyPlus*. The optimizations are performed considering the total cost and thermal comfort.

Thermal comfort models

The models for predicting thermal comfort are the *Fanger* and the *Pierce* model. The difference between these two models is in used temperature for determining the thermal sensation index. The *Fanger* model uses the operative temperature, while the *Pierce* model uses the effective temperature. Operative temperature combines three parameters and these are the mean radiant temperature, the mean air temperature and the water vapor pressure in ambient air. The effective temperature (*ET*) is the dry-bulb temperature of a hypothetical environment at 50% relative humidity and the uniform temperature that results in the same total heat loss from the skin as from the actual environmental. The *Fanger* thermal sensation index is labeled *PMV* (Predicted Mean Vote), while the *Pierce* thermal sensation index is labeled *PMVET* (Predicted Mean Vote modified by *ET*). After estimating the thermal comfort index, either using the *Fanger* or *Pierce* model, the predicted percentage of dissatisfied (*PPD*) can be established as follows:

$$PPD = 100 - 95 \cdot \exp\left(- 0.03353 PMV^4 - 0.2179 PMV^2\right) \qquad (1)$$

For determining *PPD* we can use either *PMV* or *PMVET* or some other thermal sensation indexes. In the following analysis the response of these two thermal sensation indexes will be compared. *PPD* will be calculated for both thermal sensation indexes. The recalculating of both thermal sensation indexes in *PPD* is necessary because *PPD* is a more convenient parameter for practical use.

Objective functions

Thermal comfort and total cost are analyzed. For the purpose of the study, objective functions are established. The objective functions have to consider thermal comfort and total cost per year.

For analyzing the response of thermal sensation indexes, the objective function is *PPD*, which takes either the *PMV* (*Fanger* model) or *PMVET* (*Pierce* model). Since the room is an inpatient room, it is important that thermal comfort is satisfied. This means that the *PPD* value calculated by using the *Fanger* model should be close to value of 5%, which implies that almost all room occupants are satisfied.

Total cost is the objective function for optimizing the parameters that influence on energy consumption and investment cost. Total cost considers either the cost of energy and insulation or the cost of energy, insulation and radiators. This depends on the model used for defining the inpatient room in *EnergyPlus*.

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The total cost is formed as a sum of energy and insulation cost if the implemented model for inpatient room in *EnergyPlus* is a model for determining the heat loss. This objective function is used for analyzing the insulation thickness, considering the number of years for paying back the insulation. The objective function in this analysis is as follows:

$$C = C_{en} + C_{in} \tag{2}$$

The total cost in Equation (2) is determined per year. The energy cost for the heating period is calculated by using the degree-day method, because performed simulations are for the design day. However total cost is needed for the heating period. The energy cost is determined as:

$$C_{en} = \frac{Q}{3600 \cdot 1000} \cdot \frac{DD}{t_i - t_o} \cdot c_{en} . \tag{3}$$

The energy consumption is calculated for the design day. The number of degree-day for Trondheim is $4003\ ^{\circ}C \cdot day$. The indoor design temperature for inpatient room is $24^{\circ}C$, while the outdoor design temperature for Trondheim is $-14^{\circ}C$. The energy price per *kWh* is $0.75\ NOK$. The insulation cost is defined as:

$$C_{in} = 1.4 \cdot \frac{A_{in} \cdot c_{in}}{n} . \tag{4}$$

The insulation cost takes into consideration insulation surface, insulation price per unit of surface, and number of years for paying for the insulation. Additional expenses for installation are estimated at *40%* of investment for materials. The insulation price per unit of surface for mineral wool depends on the insulation thickness as: $c_{in} = 413.44 \cdot \delta + 0.144$. The rate of interest and the inflation are not taken in consideration in this study.

The objective function for the optimizing the parameters that lead the performance of the hydronic heating system is created same way as in Equation (2) and with the additional item that considers the radiator surface area. This gives the following equation:

$$C = C_{en} + C_{in} + C_R . \tag{5}$$

The additional item in Equation (5) is the cost for radiators per year, which can be calculated as follows:

$$C_R = \frac{UA}{U} \cdot \frac{1}{n} \cdot c_R . \tag{6}$$

The radiator cost takes in consideration radiator surface, price of radiator per unit of surface and number of year for paying for the radiator. The mean value of the overall heat transfer coefficient for radiator is $8\ W/m^2 K$. The number of years for paying the radiator is 10. The radiator price per unit of surface is $333\ NOK/m^2$.

OPTIMIZATION RESULTS

In the inpatient room, the thermal comfort is the most important, because it is one of the conditions for well recovering patients. There are several models for predicting the human thermal sense. The response of the model on the variable parameters that influence thermal comfort is the most important in analyzing the thermal comfort of inpatients. This can be established by using the optimization process. In the following analysis the insulation thickness is optimized while the humidity is a parameter. Since only one parameter is optimized, the one-parametric optimization method, Golden Section, can be used. The objective function is Equation (1). In this analysis the model for determining the heat loss is used as the simulation model of the inpatient room. The response of the *Fanger* and *Pierce* model on the changing of humidity are shown in Figure 1 and Figure 2, respectively.
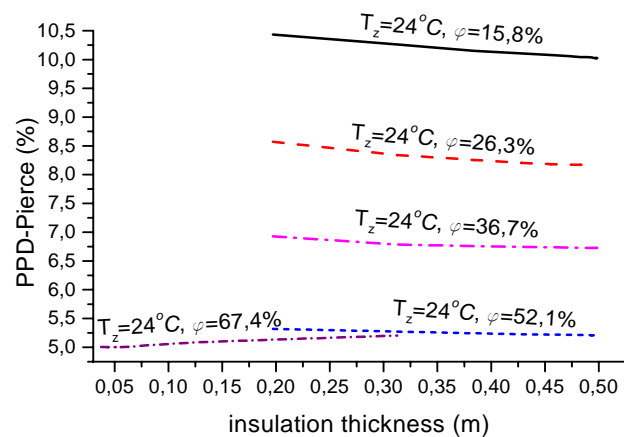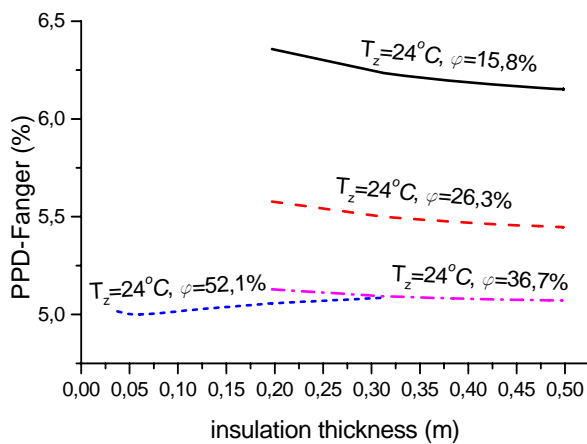

Figure 1. The response of Fanger model on humidity   Figure 2. The response of Pierce model on humidity

Comparing the above figures we can conclude that the *Pierce* model is more responsive on changes in humidity. If relative humidity is changed *10%* with constant indoor temperature, the *PPD* calculated by using the *Fanger* model is changed for *1%*, while the *PPD* calculated by using the *Pierce* model is changed *2%*. Also, when relative humidity is higher then *50%* and indoor temperature is *24°C*, the *Fanger* model decreases the insulation thickness while the *Pierce* model still leads to increasing the insulation thickness. The *Pierce* model starts to decrease insulation thickness when relative humidity is higher than *65%* at indoor temperature of *24°C*. Both thermal comfort models start decreasing the insulation thickness after some value of relative humidity because people would feel sweater.
The important issue in determining the optimal values of parameters that influence energy consumption is the number of years for paying the investment. The influence of number of year on the total cost per year is analyzed by using the Equation (2). The analysis is done considering the insulation thickness. This means that the Golden Section method is used. The influence of year on the relation between the total cost and insulation thickness is shown in Figure 3.
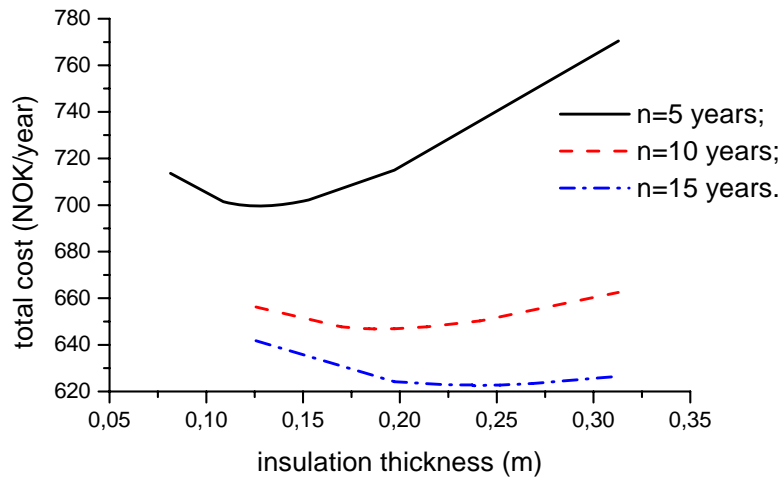
Figure 3. The influence of years on the total cost regarding the insulation thickness

Figure 3 shows that for the least number of years for paying the investment, the annual cost for insulation is the highest. This leads to thinner insulation thickness. When the number of years for paying the insulation investment is higher, the optimal insulation thickness is thicker. If there is *10* years for paying the insulation investment, then total cost has wider minimum than for *5* years.

Influence of parameters, which influence the performance of hydronic heating system, on thermal comfort, can be analyzed by connecting the simulation model for the hydronic heating system and a suitable optimization algorithm. If the *UA* value is set up to be constant, then we can perform a one-parametric optimization with insulation thickness. The influence of supply water temperature on the thermal comfort and total cost can be established if the one-parametric optimizations are performed for different supply water temperature (*50^oC-90^oC with steps of 10K*). In this analysis, $UA = 10\,\text{W/K}$ for radiator and objective function is Equation (1). The response of the *Fanger* and *Pierce* model on changing the supply water temperature considering the insulation thickness is shown in Figure 4.
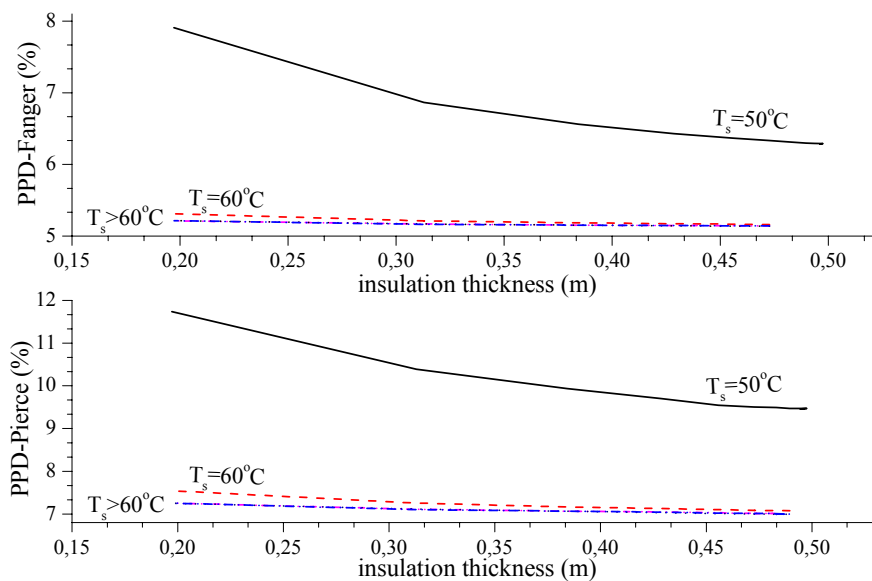

Figure 4. The response of thermal comfort models on supply water temperature

Figure 4 shows that the *Pierce* model is more responsive to variations in the supply water temperature than the *Fanger* model. Also, Figure 4 shows that for $T_S > 60^\circ C$, there is no more influence of supply water temperature on thermal comfort, and because of that, it is difficult to see difference between lines for higher temperature a *60°C*. For each of these supply water temperatures the indoor relative humidity is about *33.95%*, which is satisfactory because the recommendation for inpatient room is *30%* at indoor temperature of *24°C* in winter period. The influence of the supply water temperature on the total cost (for $UA = 10\,\text{W/K}$) considering the insulation thickness is shown in Figure 5. The total cost is calculated with Equation (5).
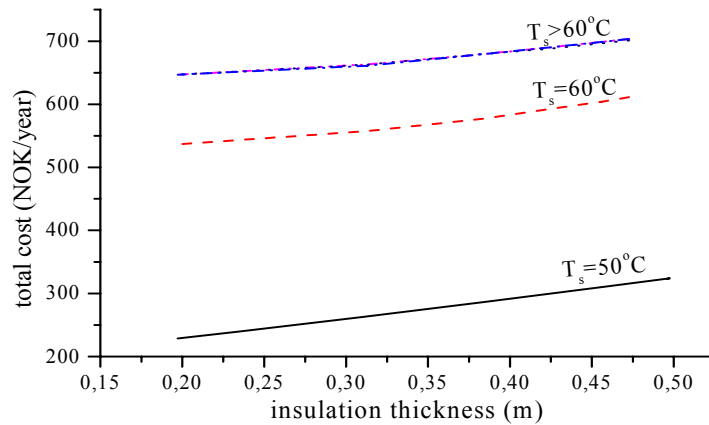
Figure 5. The influence of supply water temperature and insulation on total cost

Each value of total cost for different values of supply water temperature in Figure 5 is calculated for the same value of parameters as thermal comfort in Figure 4. Figure 5 shows that the total cost is almost the same for $T_S > 60^\circ C$.

If the optimization is performed for radiator surface area and insulation thickness, then the Hybrid algorithm is used as multi-parametric optimization algorithm. In this analysis the objective function is Equation (1), while the total cost, Equation (5), is calculated simultaneously. The influence of supply water temperature on thermal comfort and total cost is established in Figure 6.

Figure 6. The influence of supply water temperature on thermal comfort and total cost

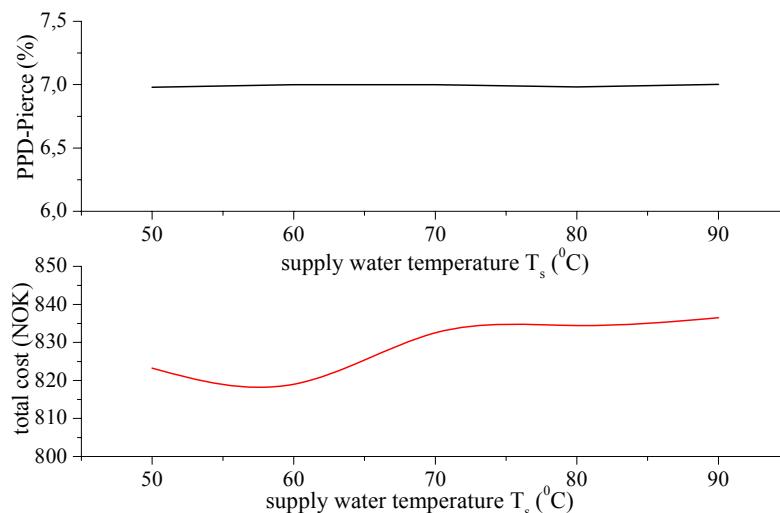The optimizations for the above analysis were performed for different supply water temperature (50^oC-90^oC with steps of $10K$). The data in Figure 6 are valid for the minimum value of *PPD*. Figure 6 shows that the thermal comfort is the same because it is satisfied for each combination of parameters, but total cost is not same. Total cost is not same because lower supply water temperature (50^oC) requires higher investment in insulation and radiators, while higher supply water temperature (90^oC) yields higher energy consumption.

If the same optimization as above is performed, but with the objective function as Equation (5), while Equation (1), thermal comfort, is calculated simultaneously, the results would be as in Figure 7. This optimization leads optimized parameters in the lowest total cost. This means that thermal comfort would maybe not be satisfied for some parameters. The aim, however, is also to satisfy the thermal comfort. In order to accomplish thermal comfort, the optimization results are analyzed in the area where *PPD<7.5%*.
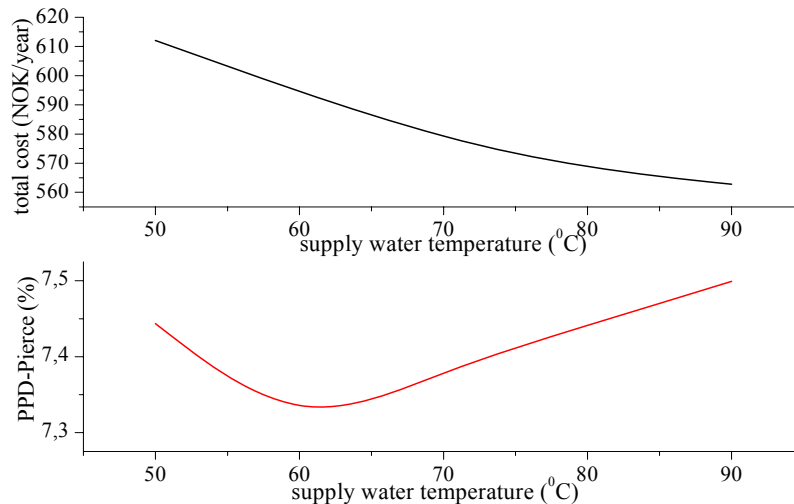

Figure 7. The influence of supply water temperature on total cost and thermal comfort

Figure 7 shows that the total price is lowest for the highest supply water temperature for the given parameters, because the radiator surface is the smallest. The lowest supply water temperature needs the biggest radiator and the thickest insulation. Comparing the Figures 6 and 7, we can see difference in the total price depending on what is set as objective function. Also, we can conclude, if the thermal comfort was changed *0.5%*, the total cost is changed *200 NOK/year*.

CONCLUSIONS

This paper shows that optimization tool connected with simulation tool gives the possibility for establishing the relations between the objectives and the design parameters. Also, the paper gives the procedure for how to deal with the optimization program connected with simulation software.

The study shows that the *Pierce thermal comfort model* is more responsive to changes in the relative humidity than the *Fanger* model. Also, the *Pierce* model is more responsive to changes in the supply water temperature. Both models do not respond to changing the supply water temperature above 60^oC. The number of year for paying back the insulation investment influences on the insulation thickness. If the number of years for paying the investment is higher, then thicker insulation can be implemented. Choice of objectives has the main point of the obtained optimal results. This implies that the results are determined by choosing the objective function.

Computer based tools support the designing of better buildings and HVAC system. Optimization also gives the designer a better understanding of the building and the HVAC system behavior.

ACKNOWLAGEMENT

NOTATION

- $C\left(\text{NOK/year}\right)$ - total cost per year;
- $C_{en}\left(\text{NOK/year}\right)$ - cost of energy per year;
- $C_{in}\left(\text{NOK/year}\right)$ - cost of insulation per year;
- $Q\left(J\right)$ - energy consumption for design day;
- $DD\left(^{o}C\cdot day\right)$ - degree day;
- $t_{i}\left(^{o}C\right)$ - design indoor temperature;
- $t_{o}\left(^{o}C\right)$ - design outdoor temperature;
- $c_{en}\left(\text{NOK/kWh}\right)$ - energy price per 1kWh;
- $A_{in}\left(m^{2}\right)$ - insulation surface;
- $c_{in}\left(\text{NOK/m}^{2}\right)$ - insulation price per unit of surface;
- $n\left(year\right)$ - number of year for paying the credit for insulation;
- $\delta\left(m\right)$ - insulation thickness;
- $C_{R}\left(\text{NOK/year}\right)$ - the cost for radiator per year;
- $UA\left(W/K\right)$ - the overall heat transfer coefficient multiplied with surface;
- $U\left(W/m^{2}K\right)$ - the mean value of the overall heat transfer coefficient;
- $c_{R}\left(\text{NOK/m}^{2}\right)$ - the radiator price per unit of surface.

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ENERGY
and BUILDINGS

Optimization of energy consumption in buildings with hydronic heating systems considering thermal comfort by use of computer-based tools

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Abstract

The paper deals with an optimization of parameters, which influence the energy and investment cost as well as the thermal comfort. The parameters considered in this study are: the insulation thickness of the building envelope, the supply-water temperature and the heat exchange area of the radiators. A combination of the building energy simulation software *EnergyPlus*[1] and the generic optimization program *GenOpt* (see footnote 1) has been used for this purpose. The paper presents the application of a one-objective optimization algorithm solving the problems with two objectives, because the optimization algorithm is one-objective and the problem has two objectives, which are minimal total costs and satisfied thermal comfort. The total costs represent the sum of energy consumption and the investment costs. The thermal comfort is represented by Predicted Percentage of Dissatisfied (PPD) in this study. The optimization is used to determine the values of parameters that give the lowest sum of investment and energy cost, under the condition that the thermal comfort is satisfied. In addition, the optimization processes show the mutual influence of parameters on both the total cost and the thermal comfort.
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Keywords: Building energy optimization; Simulation; Thermal comfort; Hydronic heating

1. Introduction

The application of simulation and optimization tools for solving a variety of energy management problems in HVAC system or building design problems is shown through works of Wright et al. [1], Fong et al. [2], and Cai and co-workers [3]. The example of insulation optimization in order to minimize the Life-Cycle Cost is shown in [4]. The design of building is a multi-parametric problem with few objectives or constraints. Usually, the objectives and constraints do not have the same physical meaning.

For the rational energy consumption, the analysis of the energy cost considering the thermal comfort is necessary. Building energy analysis is done for a school building with a hydronic heating system. The school building and its heating system is modeled in *EnergyPlus* software by using the weather data for the heating season in Belgrade.

The aim of the study is optimization of several parameters that influence both the total costs in the school building and thermal comfort by use of computer-based tools. The parameters optimized in the study are: the insulation thickness of the building envelope, the supply-water temperature and the heat exchange area of the radiators. In addition, the aim is to show how to proceed with two objectives using the one-objective optimization algorithms. The first objective function for optimization is the total cost that takes into account the energy consumption and the investment cost. The second objective function deals with the resulting thermal comfort. The thermal comfort is represented by Predicted Percentage of Dissatisfied (PPD), which is lower if thermal comfort is better.

2. Methods

For the purpose of energy analysis, the software package *EnergyPlus* is connected with the generic optimization program *GenOpt*.
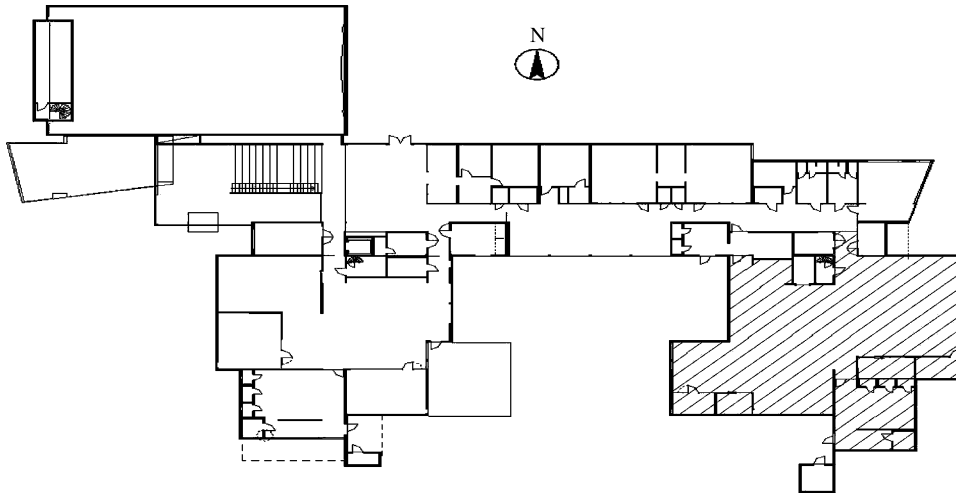

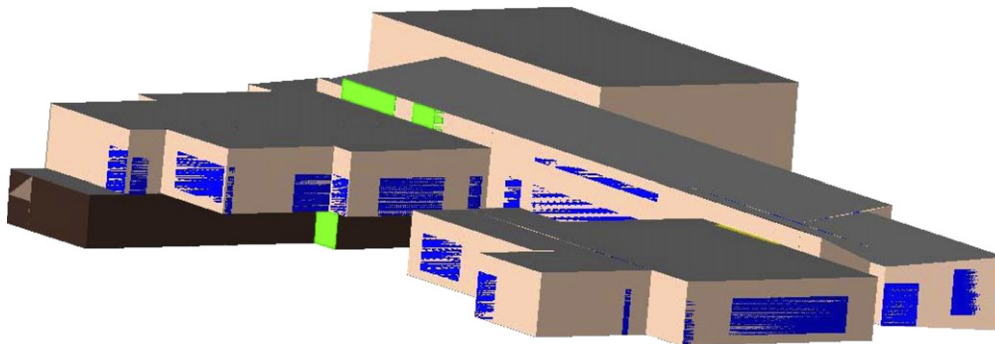Fig. 1. A general plan of the school building.

Fig. 2. The school building facade.

EnergyPlus is a building energy simulation program that calculates the building heating and cooling loads and simulates the operation of HVAC systems and central plant equipment. *EnergyPlus* deals with different building data, which include weather data, the building envelope, the geometry of the building, internal loads (occupancies, internal loads, etc.) and the HVAC system. There are other simulation programs such as BLAST[2] or DOE-2, which are sequential simulation, while *EnergyPlus* is integrated simulation [5].

GenOpt is a generic optimization program that must be connected to some simulation program such as SPARK, *EnergyPlus*, TRNSYS or DOE-2, in order to conduct an optimization of parameters from simulation programs [6]. *GenOpt* allows one-parametric and multi-parametric optimization [7].

The coupling of *EnergyPlus* and *GenOpt* is only one example in solving the simulation–optimization problems of energy management in the HVAC systems. The energy management problems could be solved using evolutionary programming as it is done in [2], or using adaptive neuro-fuzzy algorithms as in [3]. In addition, a trade-off problem between investment costs, operating cost and occupant thermal comfort could be solved using the genetic algorithm as in [1]. *GenOpt* is chosen in this study because it is developed for the optimization of the objective function from an external simulation program, such as SPARK, *EnergyPlus*, TRNSYS or DOE-2.

2.1. Description of the case study building

The case study is performed for a school building located in Belgrade. The building consists of 134 rooms. The building envelope is a light construction, with the outside walls made of wood, while the windows and outside doors consist of three-layer glass with air filling. The partition walls are of light concrete, while the inside doors are wooden. A general plan of the first floor of the school building is shown in Fig. 1.

In Fig. 1 the north orientation is noted by "N". For hatched zone in Fig. 1 ("Class Zone 2" in the below text) the results are given in the below text. The building facade is shown in Fig. 2.

Weather data for Belgrade, for the year 1995, given by ASHRAE are used in this study [8]. These data imply that the minimal temperature in wintertime is $-11.5\,^{\circ}$C and the maximal temperature in summertime is $33.4\,^{\circ}$C.

For defining the building geometry in *EnergyPlus*, it is necessary to define the zones. The purpose, the orientation and the air-conditioning system of the rooms must be considered in defining the zones. For the given building, 21 zones are

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[2] BLAST—Building Loads Analysis and System Thermodynamics.

identified. After simulations by *EnergyPlus*, using the algorithm for determining the heat loads, the analysis of the results is done. Based on the heat loads, the thermal comfort and considering the most occupied zones, the radiators are proposed for nine zones [9].

2.2. Forming the objective function

To determine the optimal values of some parameters, it is necessary to define the objective function. The objective function should be defined so that the total cost is the lowest and at the same time the thermal comfort is satisfied. The thermal comfort is represented by PPD [10,11] in this study. PPD is calculated using predicted mean vote (PMV), which can be obtained easily from *EnergyPlus* as an output. In addition, the PPD is convenient for results representation, because the lower the PPD, the better the thermal comfort.

GenOpt allows that only the first function defined in the initial file can be the objective function to be minimized or maximized. The range of values for optimized parameter is defined in the command file [7]. Considering the command and the initial file, *GenOpt* makes the input for *EnergyPlus*. The objective function and the paths that define the connections between the simulation and the optimization files are defined in the initial file. If there are more functions defined after the first one, they are just calculated for particular combinations of parameters. This means that if we want to calculate the minimal value of certain function, it should be the first function to be defined in the initial file. However, if we have some constraints (for example: satisfying the thermal comfort, the sum of some parameters should be lower than some given value, etc.), it can be defined as the second function in the initial file. The minimums of these second or third functions are not sought. For solving the above problem, both the total cost and thermal comfort are calculated through the optimization process, but the total cost is the objective function. During the optimization process, the optimization program (*GenOpt*) passes several times through the simulation program (*EnergyPlus*) for the different combinations of the given parameters, calculating the total cost and the thermal comfort for every combination of parameters.

The supply-water temperature is the parameter defined as the schedule type. The option schedule type in *EnergyPlus* is used for defining the parameters that change hour by hour (for example: supply-water temperature, desired indoor temperature, zone occupancy). The optimization, considering the supply-water temperature, is performed in the following way: the optimizations are performed for the insulation thickness of the building envelope and the heat exchange area of the radiators, but with constant supply-water temperature through one optimization. Each optimization is performed for the different values of the supply-water temperature, covering the range from 35 to 90 °C with steps of 5 °C. The minimum of the total cost is determined for each value of the supply-water temperature by considering the thermal comfort. After the optimizations are performed, the post-processing of the results is done by analyzing the total cost in the range where
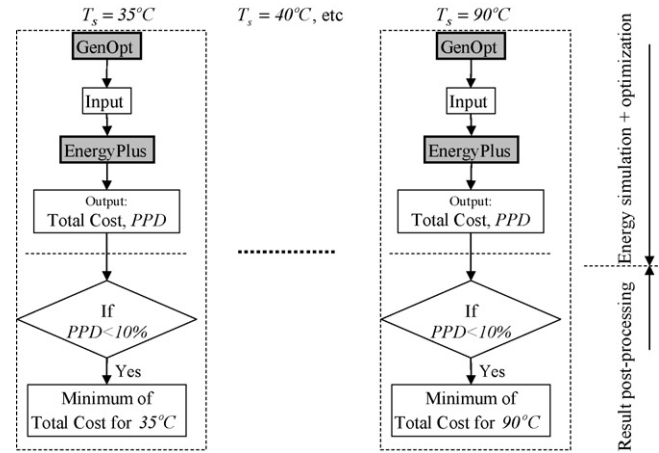

Fig. 3. The information flow between energy simulation and optimization.

PPD < 10%. This means that the sizing is done with boundary values for B class of the thermal comfort based on [12]. The procedure for solving the above problem is given in Fig. 3.

The objective function for this optimization will be formed as a sum of the energy costs, the insulation cost and the radiator cost:

$$C = C_E + C_I + C_R \tag{1}$$

where C (€) is the total cost, C_E (€) the cost of energy, C_I (€) the cost of insulation, and C_R (€) is the radiator cost.

Since the optimization is performed for the design day, energy cost for the whole season will be calculated by using the degree-day method. It is calculated as in [13]:

$$C_E = \frac{Q_{DD}}{3600 \times 1000} \frac{DD \times y \times e}{t_i - t_o} c_E + P c_p \tag{2}$$

where Q_{DD} (J) is energy consumption during the design day; c_E (€/kWh) is the price of energy per kWh, the used value is 0.034 €/kWh given by the "Belgrade Power Plant"; P (W) is the installed power of heating equipment (*EnergyPlus* does not calculate the maximum power for certain period of time during performing the optimization and because of that the mean power for design day is used for this optimization); c_p (€/kWyear) is the annual energy price for kW of installed power equipment (€12.42 for kW per year given by the "Belgrade Power Plant"); DD (°C day) is the number of degree-days, which is 2520 for Belgrade, based on [14]; $e(-)$ is the coefficient of limitation, which consists of both coefficient of temperature limitation (e_t) and exploitation limitation (e_b), adopted values for the coefficient are: $e_t = 0.75$ based on [14] (Table 9.III) and $e_b = 0.75$ based on [14] (Table 9.IV); $y(-)$ is the coefficient of simultaneous effect of unfavorable conditions, which is 0.6 for normal windy terrain and open terrain situation of building, based on [14]; t_i (°C) is the indoor temperature, in this case $t_i = 19$ °C; t_o (°C) is the outside design temperature which is −11.5 °C for Belgrade, adopted from ASHRAE [8].

The insulation cost is calculated as follows:

$$C_I = 1.4 \frac{A_I c_I}{n} \tag{3}$$

where A_I (m^2) is the insulation surface of all outside walls; c_I (€/m^2) is the insulation price per unit of surface that depends on the insulation thickness: $c_I = 0.19\delta - 0.15$, where δ (cm) is the insulation thickness; n (year) is the number of years for purchasing the insulation. In this case n is 10 years. The additional expense for installation is estimated at 40% of insulation cost.

The radiator cost is as follows:

$$C_R = \frac{c_{R1}}{A_1} \frac{UA}{U} \frac{1}{n} \qquad (4)$$

where c_{R1} (€/section) is the radiator price per one section; adopted in this study is €10.5, A_1 (m^2) is the surface of one section, in this case is 0.3 m^2, adopted from [14] (Table 7.III); UA (W/K) is the radiator characteristic in *EnergyPlus*; $U = 8$ W/m^2 K is the mean value of the overall heat transfer coefficient for radiators, based on data from [14] (Table 7.III). UA value is the optimized parameter in this analysis and it represents the sum of all UA values from all nine zones. The interest rate and the inflation are not taken into consideration in this analysis [13].

The thermal comfort is calculated by using the Fanger model:

$$PPD = 100 - 95 \exp(-0.03353 PMV^4 - 0.2179 PMV^2) \qquad (5)$$

where PMV is predicted mean vote on the Fanger thermal sensation scale.

Nine parameters are set for the heat exchange area of the radiators in each zone with radiators and one parameter is for the insulation thickness of the building envelope. This gives the total number of 10 parameters in this study.

3. Simulation results

The influence of the supply-water temperature on the indoor temperature and the radiator heat rate during the design day is shown for one of the 21 calculation zones of the school building [9]. The "Class Zone 2" is shown in Fig. 1 by hatch. The desired value of the indoor temperature is 20 °C during the occupancy period from 07:00 to 19:00, while outside of this
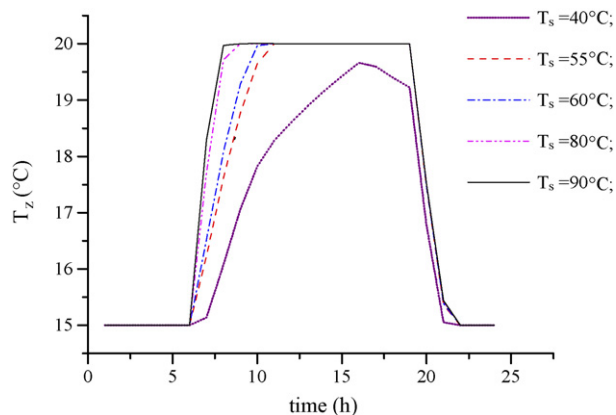

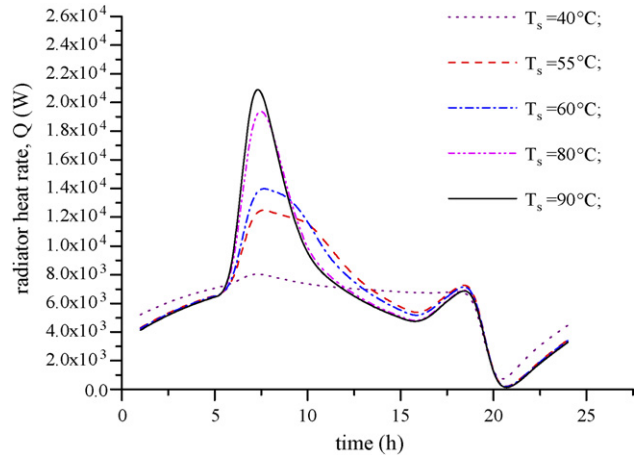Fig. 4. Influence of the supply-water temperature on the indoor temperature.

Fig. 5. Influence of the supply-water temperature on the radiator heat rate.

period it is 15 °C. The radiators are in use the entire day. The influence of the supply-water temperature on the obtained indoor temperature (T_z) in the zone during the design day for the insulation thickness of 9.8 cm is shown in Fig. 4 [13]. In addition, the heat exchange area of the radiators is the same for different supply-water temperature.

Fig. 4 shows that the supply-water temperature has influence on the time necessary to reach the desired indoor temperature in the zone. The time diminishes when the supply-water temperature increases. The set point is reached after 1 h with the supply-water temperature of 90 °C, while it is not reached at all for the supply-water temperature of 40 °C.

The diurnal variation of the radiator heat rate in "Class Zone 2" for the design day, for different supply-water temperatures and for the insulation thickness of 9.8 cm, is shown in Fig. 5.

The radiator heat rate is the highest during the transition period (at 07:00) for the highest supply-water temperature of 90 °C. The heat exchange area of the radiator is oversized for the supply-water temperature of 90 °C and because of that the radiator heat rate is the highest in the transient period. The indoor temperature in the zone is maintained at the desired value during the whole occupancy period for the highest supply-water temperature. In this case, the heat losses are the highest because the indoor temperature is high [13].

4. Optimization results

The optimizations of the insulation thickness of the building envelope and the heat exchange areas of the radiators were done, for constant supply-water temperature, by using the objective function (1). As the number of the optimization parameters is 10, the hybrid algorithm was used as the optimization method. Since the objective function was the total cost, the optimization algorithm minimized the function (1), while function (5) was calculated for the same combinations of parameters. Twelve optimizations of the insulation thickness and the heat exchange area of the radiators were made for the different values of the supply-water temperature. The optimization results for some values of supply-water temperature are given in Fig. 6a–j. The numbers of simulations at each
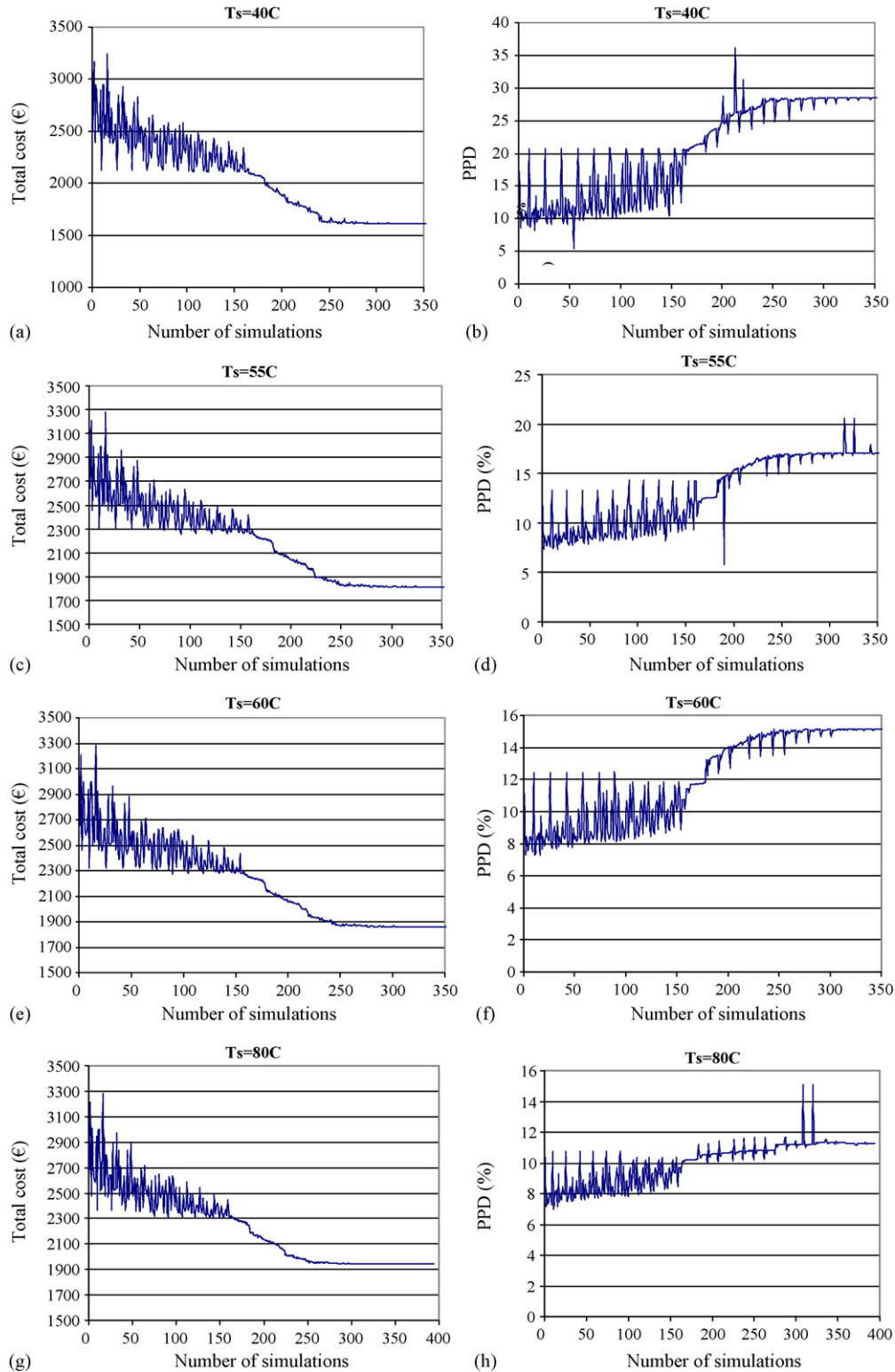
Fig. 6. (a) Total cost for T_s = 40 °C; (b) PPD for T_s = 40 °C; (c) total cost for T_s = 55 °C; (d) PPD for T_s = 55 °C; (e) total cost for T_s = 60 °C; (f) PPD for T_s = 60 °C; (g) total cost for T_s = 80 °C; (h) PPD for T_s = 80 °C; (i) total cost for T_s = 90 °C; (j) PPD for T_s = 90 °C.

optimization are different, because for the different values of the supply-water temperature, the optimization algorithm converges differently. If the supply-water temperature increases, the optimization algorithm needs more iteration steps to terminate. The figures show the values of the total cost

and PPD at each simulation. Considering each couple of figures (from Fig. 6a and b to Fig. 6i and j), the minimum of the total cost can be found for the satisfied thermal comfort.

For each value of the supply-water temperature, the minimum of total cost was sought, but just for particular
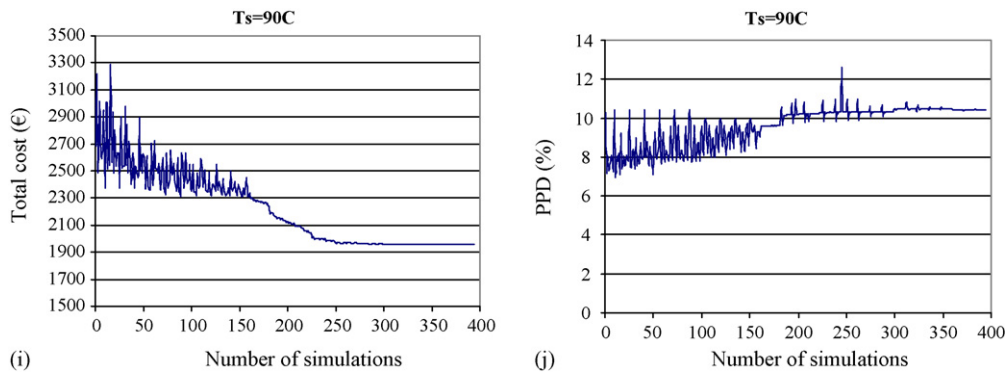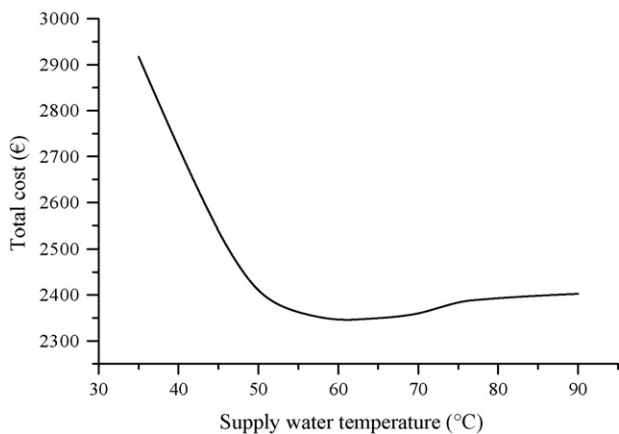
Fig. 6. (*Continued*).

Fig. 7. The relation between the total cost and the supply-water temperature.

simulations, where PPD < 10%. This means that for the supply-water temperature of 60 °C, the minimum of total cost was sought between the 1st and the 150th simulation, because in that range PPD occurs to be lower than 10% (Fig. 6e and f). It is necessary to perform each optimization to its end, which includes 350 or 400 simulations in each optimization, but the minimum of total cost was sought only in the range where the thermal comfort is satisfied. After determining the minimum of
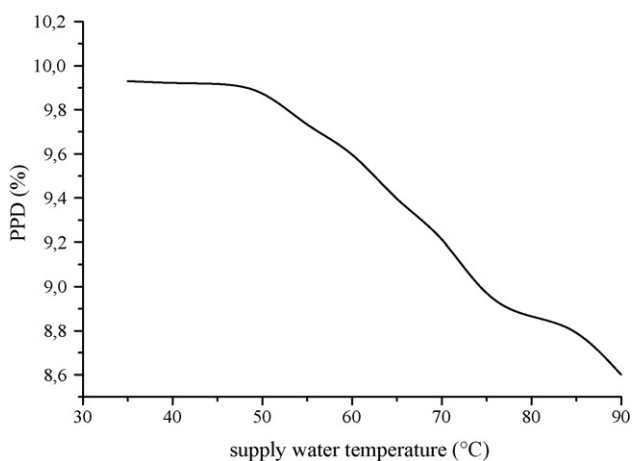

Fig. 8. The relation between the thermal comfort and the supply-water temperature.

the total costs for each value of the supply-water temperature in the above explained way, the relations between both the total cost and the supply-water temperature, and the thermal comfort and the supply-water temperature could be established.

The relation between the total cost and the supply-water temperature is shown in Fig. 7 [13].

Fig. 7 shows that the highest total cost can be expected for the lowest supply-water temperature because larger insulation thickness and the heat exchange area of the radiators are necessary. The total cost reaches minimum at the temperature of 60 °C, for the given conditions. For higher temperatures of the supply-water, the total cost increases because the higher indoor temperature in the zone is maintained for longer period of time, and energy consumption is higher.

The relation between the thermal comfort and the supply-water temperature can be established by using the corresponding values of PPD for each value of total cost from Fig. 7. This relation is shown in Fig. 8.

Fig. 8 shows that the value of PPD is satisfied for each value of the supply-water temperature. Consequently the constraint is fulfilled. The thermal comfort is better when the supply-water temperature is higher, because the desired indoor temperature is maintained almost through the entire occupancy period.

5. Conclusion

The design of buildings and HVAC systems is a multi-parametric problem with both objectives and constraints. The objectives and constraints usually have different natures. This paper shows how to analyze the problem of two physically different objectives by using one-objective problem and the practical use of mathematical optimization connected to simulation software.

The analysis shows that the supply-water temperature has influence on the time necessary to reach the desired indoor air temperature. In addition, the optimizations show that the highest total cost is expected for the lowest supply-water temperature. The optimization gives the overview of results obtained by the different combinations of parameters. This is useful in choosing the solution to a given problem. The optimization process gives the direction in which the considered parameters have to be chosen considering the objectives and constraints.

Acknowledgements

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Paper V   N. Djuric, V. Novakovic, F. Frydenlund, Existing building
             commissioning using computer based tools, 2007.

Commissioning in Existing Building Using Computer-Based Tools

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SUMMARY

This paper deals with a ventilation system with a recovery wheel and several related operation parameters. The first aim was to develop a commissioning tool using computer-based tools. The second aim was to find a better energy management control strategy for the ventilation system. The problem in the ventilation system could imply both too warm air and poor air quality. The simulation and optimization tools used in the study are *EnergyPlus[1]* and *GenOpt[1]*. To evaluate the performance of the ventilation system components, it is important to establish the relations between the components. The result of the study suggests measures for retrofit in overcoming a part of the problem of too warm air. In addition, the results indicate energy savings from *15* to *30 %*.

INTRODUCTION

A survey among Norwegian building facilities shows that there is a problem of too warm air and poor air quality in the buildings [1]. This study gives an example how to start an analysis for developing a commissioning tool. In addition, few retrofit measures are tested using *EnergyPlus*.

The heat recovery efficiency is usually studied separately from buildings themselves. Considering significant influence of the heat recovery wheel on the indoor air temperature, it is necessary to study together with the building and HVAC equipment as mentioned in [2]. This study shows how to deal with such a challenge by using computer-based tools. The existing energy management control strategies are mostly heuristic, so there is a necessity for systematically examining the existing energy management control functions and improving them [3]. The study develops the control strategy for the supply-water and tests it.

The building model is developed in *EnergyPlus*. The building has a ventilation system with a heat recovery wheel and a water heating coil. The simple configuration of the equipment is chosen for establishing a basic overview of such a ventilation system. The weather data for Trondheim (Norway) are used in this study.

BUILDING AND VENTILATION SYSTEM DESCRIPTION

The model in this study is developed in *EnergyPlus*. The base of the building is shown in Figure 1. Figure 1 shows the building zoning such that the exterior zones extend six meters inside from the exterior surface as recommended in [4]. Such a way of zoning implies two exterior zones,

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[1] Copyright by Lawrence Berkeley National Laboratories, Berkeley, CA, USA

which are ventilated. Hatched zones are ventilated (Figure 1). The ventilated zones have a common ventilation system. In Figure 1, "N" implies the north direction.
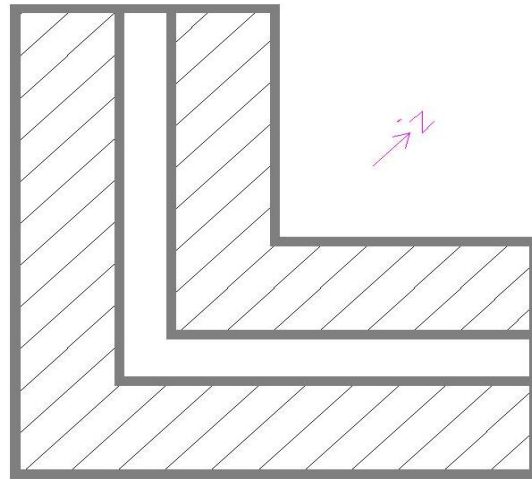
Figure1. Ventilated zones are hatched in building base

The building facades are shown in Figure 2 and Figure 3. The total area of the building is *1350 m²*. The attic and the core zone (non-hatched zone) are assumed to be unconditioned zones. This study treats only the external zones at the first floor, the hatched zones in Figure 1. The total area of these zones is *546 m²*.
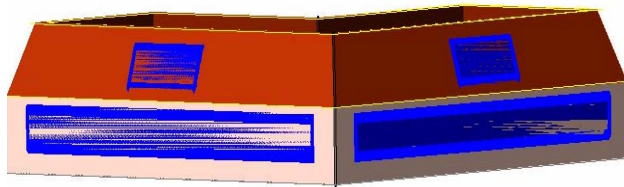
Figure 2. South side of the building   Figure 3. North side of the building
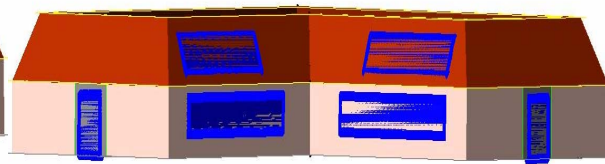
A sketch of the ventilation system is shown in Figure 4. One of the objectives of this study is to find the mutual influence between the heat recovery wheel and the water heating coil. The air flow through the system is *3.3 m³/s*, the larger zone consumes *2 m³/s*, while the smaller consumes *1.3 m³/s*. The amount of air is chosen according to ASHRAE recommendations for air changing per hours in office buildings [5].
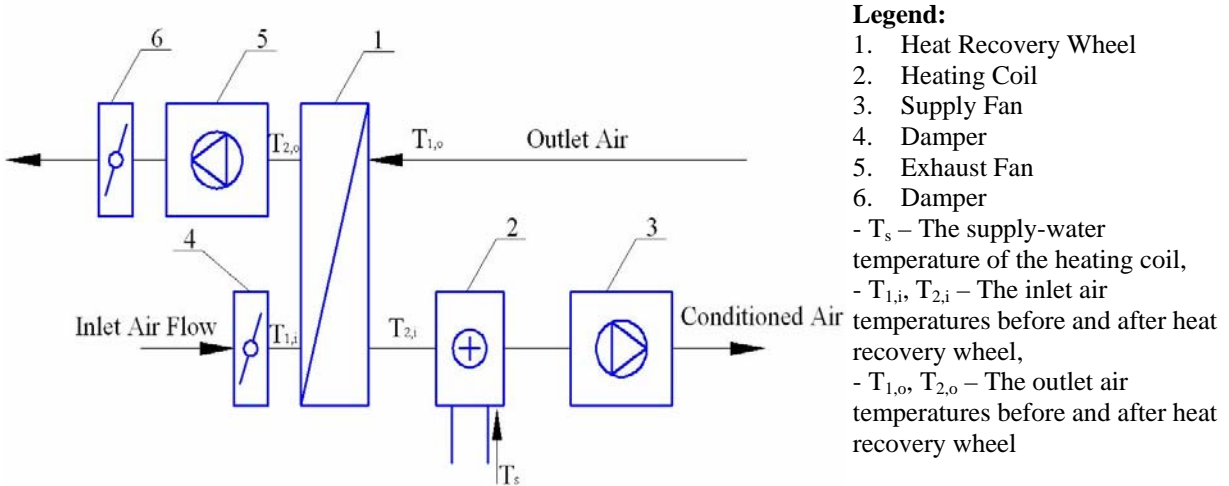
Figure 4. Ventilation system

Legend:
1. Heat Recovery Wheel
2. Heating Coil
3. Supply Fan
4. Damper
5. Exhaust Fan
6. Damper
- T_s – The supply-water temperature of the heating coil,
- $T_{1,i}$, $T_{2,i}$ – The inlet air temperatures before and after heat recovery wheel,
- $T_{1,o}$, $T_{2,o}$ – The outlet air temperatures before and after heat recovery wheel

The only internal loads are assumed to be the loads from occupants. The density of people is *0.1 persons/m²* [6]. This implies *32* persons in the larger zone and *22* persons in the smaller zone.

The supply-water temperature of the heating coil is shown in Figure 5. Figure 5 is obtained from BEMS (Building Energy Management System) for the actual building.
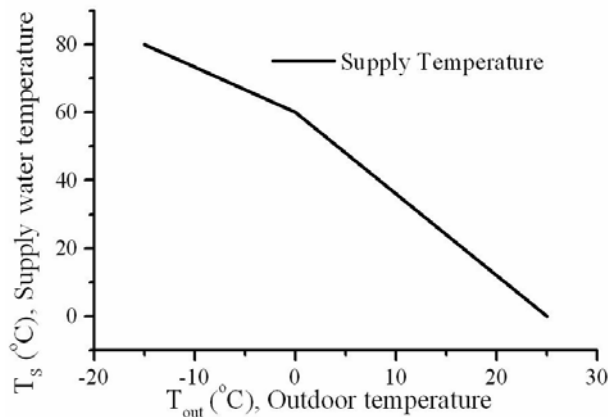
Figure 5. Supply-water temperature curve

The curve in Figure 5 is the same for all the equipment that are using heating energy, except that the heating coil does not operate when the outdoor temperature is above 5^oC. Therefore, the outdoor temperature range from -15^oC to 5^oC is actual for this study, and the baseline energy use is calculated in the same outdoor temperature range. This outdoor temperature range implies 190 days for the weather data for Trondheim.

METODOLOGY
To find a better energy management control strategy for the ventilation system, it is important to find the mutual relationships between the important parameters. This study finds these relationships by establishing an optimization problem and post-processing the optimization results. Before the optimization problem is defined, the heat recovery model is involved.

EnergyPlus model for the heat recovery wheel

The sensible energy efficiency of the heat recovery unit, ε, in *EnergyPlus* is:

$$\varepsilon = \frac{T_{2,i} - T_{1,i}}{T_{1,o} - T_{1,i}}. \tag{1}$$

The notation in Equation 1 is according to Figure 4, where $T_{1,i} \left(^{o}C \right)$ is the air temperature of inlet air before the heat recovery wheel, $T_{2,i} \left(^{o}C \right)$ is the air temperature of the inlet air after the heat recovery wheel, and $T_{1,o} \left(^{o}C \right)$ is the air temperature of the outlet air before it enters the recovery wheel.

The capacity of the heat recovery wheel is:

$$\dot{Q} = \dot{V} \cdot c_p \cdot \rho \cdot \left(T_{2,i} - T_{1,i} \right), \tag{2}$$

where $\dot{Q} \left(W \right)$ is the heat recovery rate of the wheel, $\dot{V} \left(m^3/s \right)$ is the volumetric air flow rate, which is defined by the user in *EnergyPlus*, $c_p \left(J/kgK \right)$ is the specific heat capacity of air, and $\rho \left(kg/m^3 \right)$ is the air density. The surface area of the heat recovery wheel is not taken into consideration in this *EnergyPlus* model.

Optimization Problem

The optimization problem is defined in *GenOpt*. Since the aim is to increase the heat recovery rate of the wheel, the objective function is defined to be the maximum of the heat recovery rate of the wheel, Q_{rec}. Therefore the optimization problem is defined as:

$$\max Q_{rec}, \tag{3}$$

$$\text{and the variables are } \begin{bmatrix} UA \\ T_S \end{bmatrix}. \tag{4}$$

The variables in this problem are: the *UA* (W/m^2) value of the heating coil and $T_S \left(^{o}C \right)$, the supply temperature of the heating coil. The *UA* value is multiply of the overall heat transfer coefficient, U (W/m^2K), and the area of a heat exchanger. The water flow rate of the heating coil is not considered in this optimization problem, because the defined value of the maximum flow rate in *EnergyPlus* is only a limit for the simulation. The water flow is calculated at each time step, so that the load requested of the coil is met at a flow rate which is less than the defined flow rate. This implies that changing the maximum flow rate will not change any results. The entire optimization process is performed for the volumetric air flow of *3.3 m³/s*. In addition, the same optimization process is repeated for the different values of the outdoor temperature. The range of the outdoor temperatures in this optimization problem is from *-15ºC* to *0ºC*.

The optimization problem is shown in Figure 6. The optimization variable is the *UA* value, but *NTU*, the number of transfer units, is more used in practice to express a characteristic of heat exchangers. The *NTU* value is defined as:

$$NTU = \frac{UA}{\dot{m}c_p}, \tag{5}$$

where $\dot{m}(kg/s)$ is water mass flow rate and $c_p(J/kgK)$ is the specific heat capacity of water.

Figure 6 gives the optimization results for the volumetric air flow of *3.3 m³/s* (*11880 m³/h*). The results are obtained for the range of the outdoor temperature from *-15°C* to *0°C*. For the particular couple of *NTU* and the supply-water temperature, the heat recovery rate of the wheel can be obtained from Figure 6. This heat recovery rate gives a particular value of the inlet air temperature after the heat recovery wheel, $T_{2,i}$, for a particular value of the outdoor temperature.
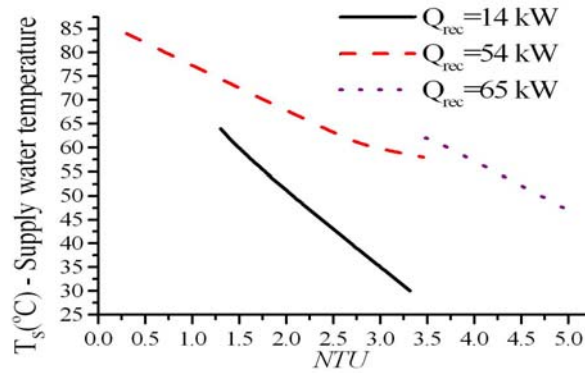
Figure 6. Curves of constant wheel capacity

Figure 6 shows that if the supply-water temperature of the heating coil increases and the value of *NTU* increases, then the heat recovery rate of the wheel increases. Similar figures could be established for the heat rate of the heating coil, Q_{coil}, and zone indoor temperature, T_i.

Post-processing of the optimization results
By using the optimization results from the above problem, the appropriate relations for minimizing energy use can be established.

The optimization results are used to establish two relations:
1. Heat recovery rate of the wheel vs. heat rate of the heating coil, and
2. Indoor temperature vs. heat rate of the heating coil.

The above relations are established for the different values of the outdoor temperature, T_{out}, and in this case they are: *-15°C*, *-10°C*, *-5°C*, and *0°C*. The results are shown in Figure 7. All the results are valid for the optimal combinations of the optimized parameters.

Figure 7. Heat recovery rate of the wheel and
Indoor temperature vs. Heat rate of the heating coil

Figure 7 shows that the relationships between the heat recovery rate and the heating coil rate are different depending on whether the heat recovery wheel recovers en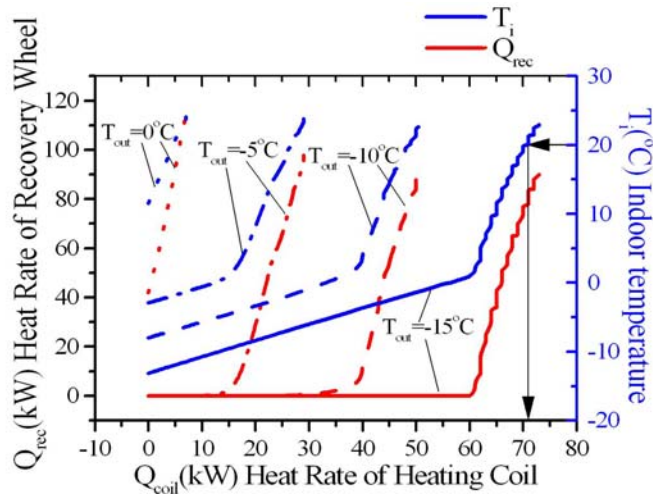ergy or not. For example, for $T_{out} = -15^oC$, the heat recovery rate of the wheel is negligible until the heat rate of the heating coil reaches $60\ kW$. In addition, the slope of the indoor temperature line is different depending on whether the recovery wheel recovers energy or not. If the heat recovery wheel recovers energy the slope is steeper. This appears because when the recovery wheel recovers the energy, then the reached indoor temperature is higher. Figure 7 shows that when the outdoor temperature increases, the heat rate of the heating coil is negligible comparing to the heat recovery rate of the wheel.

RESULTS

The results in Figure 7 show that it is possible to use a lower supply temperature and to shut down the coil when the outdoor temperature is higher than 0^oC. Based on the optimization results, it is possible to obtain the new values for the new supply temperature curve. Both the new and the current supply temperature curves are given in Figure 8. The consequences of such a measure on energy consumption are shown in Figure 9.
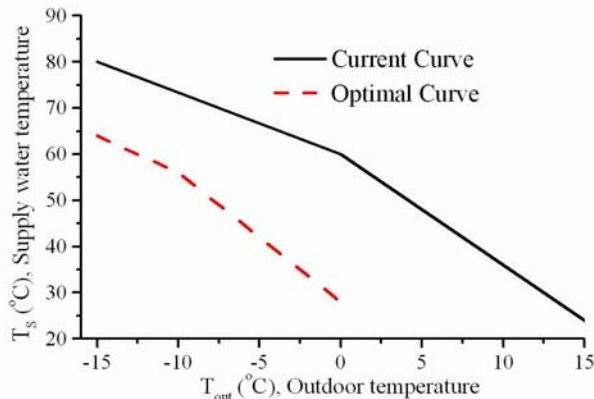

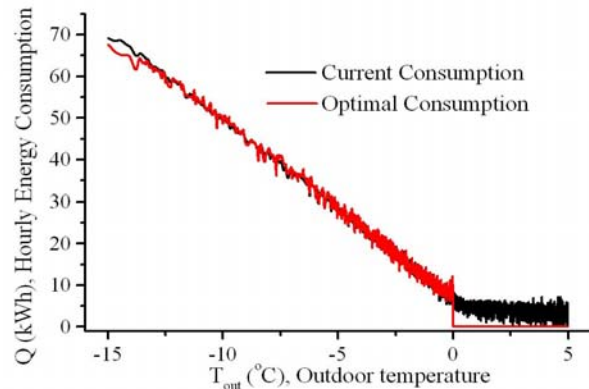Figure 8. Optimal and Current supply temperature

Figure 9. Hourly energy consumption

Figure 8 shows that it is possible that the supply temperature is lower, while the achieved indoor temperature is the same. Figure 9 gives the hourly energy consumption for the outdoor temperatures from $-15^{o}C$ to $5^{o}C$. In addition, when the coil uses the supply-water temperature as in Figure 5, it works until the outdoor temperature is $5^{o}C$. While, when the coil uses the new curve, it works until the outdoor temperature is $0^{o}C$. The results in Figure 9 are normalized by the outdoor temperature. The highest energy saving by using this measure is archived after the coil is shut down. The energy consumption of the coil is slightly lower when using this optimal supply temperature curve. The reason is that the same amount of the energy is necessary to achieve the desired indoor temperature regardless to the level of the supply temperature.

The energy saving can be determined based on [7] by using an equation, which compares the difference between the continuous end-use baseline and continuous post-retrofit energy use measurement. In this study the energy saving is calculated as:

$$ES = 100 \cdot \left(Q_b - Q_{pr} \right) / Q_b \tag{6}$$

where *ES (%)* is the energy saving, $Q_b \left(kWh \right)$ is the total baseline energy consumption, and $Q_{pr} \left(kWh \right)$ is the total post-retrofit energy consumption. The energy savings are calculated in the same way for both heating and electric energy. In this study the post-retrofit consumption is possible energy consumption, if the measure would be implemented.

Figure 9 shows that the system shut down implies the highest energy saving, so different cases are tested to estimate when it is possible to achieve the highest energy saving. The cases are the following:
    - case 1: the current supply temperature (the supply temperature as in Figure 5);
    - case 2: the new supply temperature (the supply temperature as the red-dashed curve in Figure 8) is applied and the coil is shut down when $T_{out}=0^{o}C$;
    - case 3: the current supply temperature and the coil is shut down when $T_{out}=0^{o}C$;
    - case 4: the new supply temperature, the coil is shut down when $T_{out}=0^{o}C$, and the entire system is shut down in four hours after *20:00*;
    - case 5: the current supply temperature, the coil is shut down when $T_{out}=0^{o}C$, and the entire system is shut down in five hours after *20:00*.

The resulting energy savings from the above measures are given in Table 1. Table 1 gives the energy savings in both the heating and the electrical energy. The energy consumption in Table 1 is the total energy consumption when the outdoor temperature ranges from $-15^{o}C$ to $5^{o}C$. The heating energy, Q_{coil}, is the energy consumed by the heating coil, while the electric energy, Q_{el}, is the energy for the fans, pump, and the motor for the heat recovery wheel.

Table 1. The energy savings implied by each measure

Case	Q_{coil}(MWh)	Q_{el}(MWh)	Heating Energy Saving (%)	Electric Energy Saving (%)
1	55.6	26.2	0	0
2	44.7	26.2	19.6	0
3	47.0	26.0	15.5	0
4	38.2	21.7	31.0	17.1
5	38.2	20.5	31.0	21.8

The largest part of the total power consumption is made by the fans. Therefore there is no big difference in the electric consumption between the first three cases. When the entire system shut down is applied, there is also a significant energy saving in the electric energy. The energy saving is *19.6 %* when the new curve is applied for the supply temperature. In addition, it is possible to save *15.5 %* of energy by using the current curve for the supply temperature, but shut down the coil when the outdoor temperature is higher than 0^oC. The highest possibility of the heating energy saving of *31 %* is possible when the entire system is shut down during non-working hours.

The results of the study show that the supply-water temperature, as in Figure 5, is high when the outdoor temperature is above 0^oC. The supply-water temperature of the heating coil could be controlled in different way than in Figure 5. In addition, the heating coil works until the outdoor temperature is 5^oC, while the heating coil should be shut down then according to the results. This can be proved from Figure 7, which shows that for the outdoor temperature of 0^oC the heat rate of the heating coil is negligible compared to the heat recovery rate of the wheel.

CONCLUSION
The paper gives the better energy management control strategy for the ventilation system developed by using the computer-based tools. In addition, it defines the optimization problem, and gives the procedure how to post-process the optimization results to get the useful relationships. The results show that the current controlling strategy is one of the causes for too warm air. The results show the possibilities for energy savings from *15 to 30%*. The study did not treat the size of the heating coil, because it was not available. The future work should treat the size of the equipment, and should apply similar measures on a real building.

ACKNOWLEGEMENT

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Paper VI N. Djuric, V. Novakovic, Review of possibilities and necessities for building lifetime commissioning, 2007.

Review of possibilities and necessities for building lifetime commissioning

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Abstract

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

Contents

1. Introduction

Commissioning is a systematic process of ensuring that all building facility systems perform interactively in accordance with the design documentation and intent. Therefore, commissioning methods and tools have to ensure that buildings reach their technical potential and operate

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

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

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

2. Commissioning as a help tool for improving building performance

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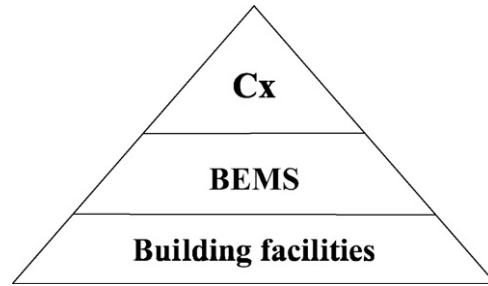

Fig. 1. The hierarchy of building needs.

the participants and the building elements during the building life is poor.

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

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

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

3. Why commissioning is necessary?

3.1. Faults in building operation

There is an increasing realization that many buildings do not perform as intended by their designers. Reasons include faulty construction, malfunctioning equipment, incorrectly configured control systems and inappropriate operating procedures [7]. On

the other hand, due to abnormal physical changes or ageing of HVAC components, inadequate maintenance, HVAC components easily suffer from complete failure (hard fault) or partial failure (soft fault) [8]. Even though building performances are normally supervised by BEMS, when a fault enters in the system the BEMS programs currently available do not adequately assist in finding the underlying cause of the fault. Therefore diagnosis of the defect is thus left to the operator [9]. However, both increase in energy consumption and degradation in the indoor environment follow each fault regardless of source.

Research on fault detection and isolation in automated processes has been active over several decades. The HVAC process has also been a subject of interest during the last 10 years. Annex 25 [9], organized by International Energy Agency (IEA) and its Energy Conservation in Buildings and Community Systems (ECBCS) was a leading forum in this field in the beginning of 1990s. A number of methodologies and procedures for optimizing real-time performance, automated fault detection and fault isolation were developed in the Annex 25. Many of these diagnostic methods were later demonstrated in real buildings in Annex 34 [10] (also organized by IEA-ECBCS), which concentrated on computer-aided fault detection and diagnosis [11].

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

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

3.2. Legislative force

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

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

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

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

The LEED Green Building Rating System was developed by the United States Green Building Council (USGBC) to further the development of the high-performance, sustainable buildings in the United States. LEED provides a framework for assessing a building's performance and for achieving sustainability goals. Commissioning is a requirement to achieve LEED

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

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

certification for both new and existing commercial buildings. In addition to commissioning being a fundamental requirement, additional credits towards certification can be earned through additional commissioning activities [16].

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

3.3. Commissioning benefit

Commissioning benefits can be defined as

- energy benefit and
- non-energy benefit.

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

Some of the most important non-energy commissioning benefits are

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

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

4. How does a commissioning tool work?

4.1. Assessment, fault detection and diagnosis

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

There are two levels or stages of 'diagnostics':

- fault detection and
- fault diagnosis.

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

4.2. Methods for fault detection and diagnosis

Commissioning tools for building performance assessment can be defined as

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

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

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

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

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

The statistical methods indicate a fault based on an index value of faulty conditions. An index can have different background depends on the method. For example, the FDD application of PSA method uses the squared sum of the residual, named the Q-statistic or squared prediction error (SPE), as an index of faulty conditions. Consequently, the Q-contribution plot can be used to diagnose the fault. The variable making a large contribution to the Q-statistic or SPE is indicated to be the potential fault source [8]. In MBFDD

method combined with SVM method, an SVM method is used to design a fault classifier, which is based on the statistical learning theory that transforms the signal to a higher-dimensional feature space for optimal classification [25].

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

4.3. Commissioning tools application

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

There have been developed two user interfaces for a commissioning tool under Annex 40, diagnostic agent for building operation (DABO) in Canada and Cite-AHU tools in France [28]. DABO is a software tool running in the central building operator station. It analyses data from the BEMS in order to identify faults in the operation of energy consuming equipment and systems. DABO uses expert knowledge to identify these faults through the use of a hybrid knowledge-based system composed of an Expert System and a Case-Based Reasoning module [29]. DABO and Cite-AHU tools have been devoted for the building operator, maintenance company and the energy service company [28].

A practical barrier to the adoption of commissioning tools is the difficulty of setting up communications between the tool

Table 2
FDD tools comparison

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

and the control devices. Technologies for carrying out automated commissioning are still in their infancy and very few tools are available for practitioners to use [28].

5. Commissioning users

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

6. Conclusion

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

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

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

Acknowledgement

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Paper VII   N. Djuric, V. Novakovic, F. Frydenlund, Heating system performance

estimation using optimization tool and BEMS data, 2007.

Heating system performance estimation using optimization tool and BEMS data

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Abstract

Causes and effects of a few real faults in a hydronic heating system are explained in this paper. Since building energy management system (BEMS) has to be utilized in fault detection and diagnosis (FDD), practical explanations of faults and their related effects are important to building caretakers. A simple heat balance model is used in this study. The model is calibrated using the optimization tool. Site data from the BEMS of a real building are calibrated against the model. Desired and real data are compared, so that the effects of the following faults are analyzed: faults in an outdoor air temperature sensor, fault in the time schedule, and a water flow imbalance problem. This paper presents an overview of the real causes of the faults and their effects both on the energy consumption and on the indoor air temperature. In addition, simple instructions for the building caretakers for fault detection in the hydronic heating systems are given.
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1. Introduction

There has been much interest in the development of FDD techniques that are suitable for use in building control systems. There are many different diagnosis techniques and listed faults for the different HVAC systems [1]. A practical algorithm for diagnosing control loop problems of an air-handling unit (AHU) is provided in [2]. Deviations in the indoor temperature and energy consumption caused by different faults are explained practically, using an easy-to-use tool for FDD in [3]. Therefore, it is important to utilize the FDD techniques and algorithms more efficiently for the practical explanation of deviations in the indoor temperature and energy consumption. This study aims at the practical explanations of the operating faults in a hydronic heating system.

Most simulation models are based on first principles, such as *EnergyPlus*[1] [4]. A large number of parameters are needed as inputs for the simulation model. In addition, using optimization with *EnergyPlus* requires a whole lot of effort on pre-processing input files and post-processing results. The work of Wang and Xinhua [5] shows that kind of simplified models that can represent the physical properties of the building system are preferred for diagnosis, optimal control, etc. In addition, the 'grey box' approach, based on the laws of physics and a limited number of parameters, shows to be simple and flexible for the building performance estimation [6]. Therefore, this study uses the simplified heat balance model to describe the building and the hydronic heating system.

The calibration process compares the results of the simulation with measured data and tunes the simulation until its results closely match the measured data. A number of researchers have made progress in this topic [7]. Depending on the HVAC systems or building model, several different approaches for the model calibration have been found. The model calibration of the building stock that tunes the model to the average energy consumption involving a calibration coefficient, gives the low quality of validation data [8]. This study gives an approach for the calibration of the model on hourly basis using the optimization tool. There are often significant uncertainties associated with the definition of the

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Nomenclature

C_b	overall conductance of wall (W/K)
C_r	overall conductance of radiator (W/K)
n	total number of time steps
Q	energy consumption (kWh)
T	temperature (°C)

Subscripts

h	heating branch
i	time step
in	indoor
k	element index
r	return
out	outdoor
s	supply
t	hot tap water heating branch
v	ventilation

models used to predict the performance. The nonlinearity in the HVAC system models makes the accurate model prediction difficult [9]. Therefore, sequential quadratic programming (SQP) [10] is necessary to use in this study. The successful use of SQP algorithm for the model calibration of a lumped simulation model is shown in [11]. The MATLAB optimization toolbox is used in this study to solve the optimization problem.

Effects of AHU sensor fault on total energy consumption are shown in the work of Wang and Xiao [12]. This paper gives the effects of two practical sensor faults in the hydronic heating system: a disconnected sensor and a faulty measurement of outdoor air temperature sensor. Two types of faults, an open window and a defective radiator valve, are studied by using the model-based FDD in [13]. This paper gives few additional faults in the same system. Usually it is difficult to find the examples of real faults, so in the work of Pakanen and Sundquist [14], a few artificial faults are introduced for on-line diagnostic tests of AHU. All the faults in our study are found in the case study building. Even though there have been lots of works in the building maintenance area, a combination of the optimization application and practical explanation in the hydronic heating system for these faults has not been reported.

The aim of this study is to utilize BEMS data, so that faults in a hydronic heating system can be detected. First, the paper gives the building and the heating system description. Afterwards, a brief overview of the necessary data, including the explanation of the BEMS data and the additional measurements, is presented. Since the model is calibrated against the real data, the optimization application for the model calibration is explained. Based on the developed approach, the main part of the paper gives the effects of four found faults. Besides the two faults mentioned above, fault in the time schedule and a water flow imbalance problem are described.

2. Building description

This building description consists of: the general building data, the heating system description, a brief description of a heating system control strategy and a maintenance service structure for the BEMS.

The buildings are located at the University campus in Trondheim, Norway, and they consist of offices and laboratories. Two buildings have a common substation and they are connected. Therefore, they will be treated as one aggregate building in this study. The building has three floors and basement, and the total area is 13,700 m^2. Heat is supplied by district heating, indirectly connected to a heating network through the heat exchangers. The hydronic heating system has the central control provided by BEMS. Since the building is divided into four zones, there are four main branches in the substation. The building base with the orientation is shown in Fig. 1. The schematic diagram of the hydronic system is given in Fig. 2.

Fig. 2 shows the system with the measurement points that are logged in the BEMS. The Main Block, in Fig. 2, consists of the North, the Mid and the South Block, all shown in Fig. 1. The supply-water temperature, T_{hs}, is controlled by the valve AA01 (Fig. 2), while the valve AA01 stroke is controlled by two temperature sensors, the outdoor temperature and the supply-water temperature sensor. The outdoor compensation curve, shown in Fig. 3, defines the desired supply-water temperature as the function of the outdoor temperature. Such control implies that an increase in the supply-water temperature must cause an opposing change in valve stroke, so as to bring back this temperature to the desired value. In addition, an increase in the outdoor temperature must cause the valve to reduce the supply-water temperature according to Fig. 3. This control can only be as accurate as the sensor measurements.

The supply-water temperature follows the curve from Fig. 3 during the period 5 a.m. to 4 p.m., while during the period 4 p.m. to 5 a.m. this temperature is decreased by 10 °C. The same rule with the decreased supply-water temperature is implied during the weekends, except on Mondays, the rule from Fig. 3 starts at 1 a.m. The desired indoor air temperature during working hours is 22 °C. The desired supply hot tap water temperature is 70 °C.

There are two levels of the maintenance service for the BEMS. The first level is provided by an internal maintenance personnel hired by the building maintenance service, and the second is provided by the BEMS supplier technical support.
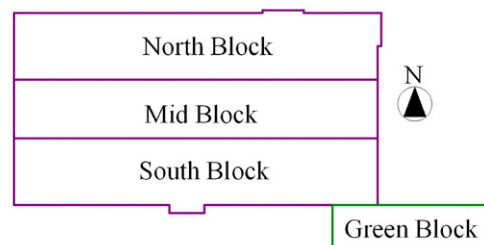

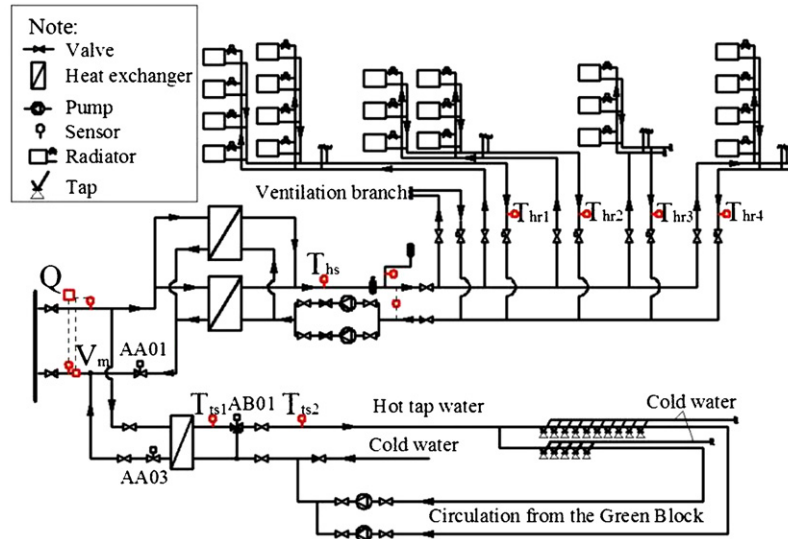Fig. 1. Sketch of the general building plan.

Fig. 2. Schematic diagram of the hydronic system.

3. Data collection and measurement

The aim of data collection was to get as many data as possible that can be used in the building performance estimation. In addition, these data should be used for a building model calibration, and for establishing a kind of rules for the faults detection. Data collecting includes: on-site survey, data available from BEMS and additional measurements.

The on-site survey was done by one person during 1 week. The radiators had been counted during the survey. These data are necessary for the model calibration.

The measurement adopted from BEMS includes the hourly log of the data. The additional measurement includes the following: the indoor air temperature in four offices, the outdoor air temperature, and the energy consumption of the hot tap water system by using thermocouples and an ultrasound flow meter. In addition, the outdoor temperature is downloaded from Norwegian Meteorological Institute [15]. Since the energy consumption for the hot tap water is not measured by the BEMS, it was necessary to measure it to establish the heat balance of the substation. The supply-water

Fig. 3. The outdoor temperature compensation curve.

temperature is controlled by the outdoor air temperature sensor, so the sensor function test is useful for fault detection. Therefore the outdoor air temperature is measured and downloaded in addition to the BEMS data. All the other data are used both for the model calibration and the fault detection.

4. Model and model calibration

4.1. Model approach

The model approach in this study is based on the heat balance equations. The heat balance equations include: the zone heat balance and the heat balance for the substation. The ventilation systems are controlled locally, and they are all the simple fan coil units. There are two ways to define the energy consumption of the ventilation system: assuming an additional term in the heat balance equation or establishing the pressure balance model for the parallel branches (the four branches for heating and the branch for ventilation, Fig. 2). Since only the heat balance model is defined, only the total capacity of the ventilation is counted discretely as an additional term for each zone. The model is hourly based. Even though the model is steady-state, the building response is obtained by changing the temperature values.

The heat losses of the zones are described by C_b, the overall conductance of walls, which is a product of the heat conductance and the wall area. The heat capacity of the radiators is calculated by using overall conductance of radiator, C_r, and the mean temperature of the heating water based on [16]. The similar approach for defining the heat energy balance in such a system is applied in the work of Bojic and Trifunovic [17,18]. The heat balance of a zone is shown in Fig. 4.

The dashed-dotted line in Fig. 4 bounds a zone. The heat balance for one zone can be written as:
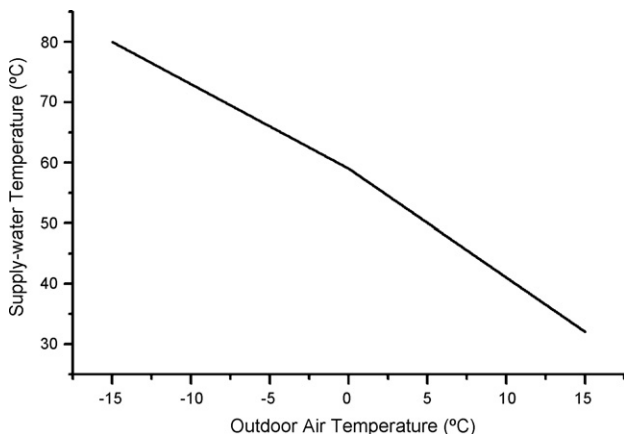
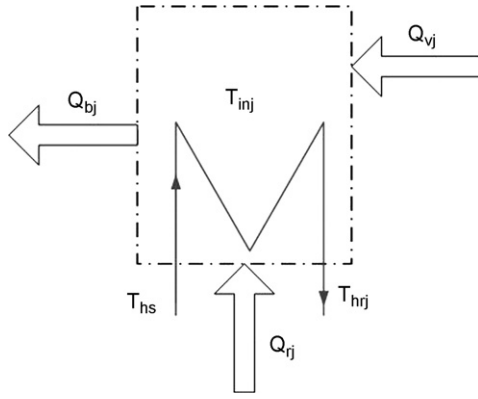$$Q_{bj,i} = Q_{rj,i} + Q_{vj,i} \tag{1}$$

Fig. 4. Heat balance of a zone.

where $Q_{bj,i}$ is the hourly heat loss of a zone, $Q_{rj,i}$ is the heat capacity of the radiators in the zone j, and $Q_{vj,i}$ is the heat capacity of the ventilation system in zone j. Eq. (1) can be written as:

$$C_{bj} \times (T_{inj,i} - T_{out,i}) = C_{rj} \times \left(\frac{T_{hs,i} + T_{hrj,i}}{2} - T_{inj,i} \right) + Q_{vj,i}$$

(2)

where j is the zone index, and i is the time step. As Eq. (2), the heat balance equations are established for each of the four zones in Fig. 1. C_{bj}, C_{rj} and $Q_{vj,i}$ are the model parameters. Since there are four zones with two parameters, C_{bj}, C_{rj}, which are time-independent, there are 8 times-independent parameters. In addition, there is a model parameter for the heat capacity of the ventilation system, $Q_{vj,i}$, which is different in each time step. Since there are four zones with the ventilation system and n time steps, there are $4n$ model parameters for the heat capacity of the ventilation system. Finally, $4n + 8$ parameters are necessary to define the model.

After Eq. (2) is solved, the hourly energy consumption of the radiators in each zone can be calculated as:

$$Q_{rj,i} = \frac{3600}{1000} \times C_{rj} \times \left(\frac{T_{hs,i} + T_{hrj,i}}{2} - T_{inj,i} \right).$$

(3)

The total hourly energy consumption of the building is:

$$Q_i = \sum_{j=1}^{4} Q_{rj,i} + \sum_{j=1}^{4} Q_{vj,i} + Q_{t,i}$$

(4)

where $Q_{t,i}$ is the energy consumption for the hot tap water that is measured.

The model input vector consists of the outdoor air and the supply-water temperature. By solving Eq. (2), the indoor air temperatures, and the return-water temperatures in each time step are obtained. Since there are four zones and n time steps, the output from Eq. (2) gives $8n$ elements. In addition, by solving Eq. (4), the total energy consumption in each time step is obtained, so this output gives n elements. Finally, the model output vector contains $9n$ elements, which are: the total energy consumption, the indoor air temperatures in each block, and the return-water temperatures from each block in each time step.

Such a simple model is suitable for the optimization. Since this model will be calibrated against the real data, there is a necessity for simplifying the model and hence save simulation time, particularly in the optimization process as shown in the work of Fong et al. [19].

4.2. Model calibration approach

The objective of the model calibration is to adjust the model to the related real data. In this case, the model calibration process calculates how close the model output corresponds to the measured data on an hourly basis. For every hour, a percentage difference, in paired data point, is calculated. The sum of squares percentage difference is then calculated for each hour. This sum allows for determination of how well the model fits to the data; the lower the sum, the better the calibration. The model is defined as:

$$Y_m = C \cdot X_m$$

(5)

where Y_m is the vector of the model output, X_m is the vector of the model input, and C is the vector of the model parameters. The objective function for the calibration of the model in Eq. (5) could be defined as

$$\min \sum_{k=1} \left(\frac{Y_{r,k} - Y_{m,k}}{Y_{r,k}} \right)^2$$

(6)

where $Y_{m,k}$ is the model output, and $Y_{r,k}$ is the corresponding measured data. To solve the optimization problem in Eq. (6), it is necessary to use the SQP algorithm. The function 'LSQNON-LIN' in the MATLAB optimization toolbox is employed to solve Eq. (6) in this study.

In order to define an optimization problem, it is necessary to define the upper and lower bounds. The upper and lower bounds for the overall conductance of the radiator, C_r, in each block, are defined based on the on-site survey. The upper and lower bounds for the overall conductance of the walls, C_b, are assumed based on the window size and U value. Considering the lack of information concerning the use of the ventilation systems, the lower and upper bounds for the ventilation capacities are chosen arbitrarily.

The $9n$ elements of the output vector are calibrated against the measured data using Eq. (6). The output vector must have more elements than the model has parameters. In this case it means that $9n > 4n + 8$. An information flow for the model calibration is shown in Fig. 5.

Fig. 5 shows that the optimization algorithm makes new model parameters input until the model outputs are adjusted to the corresponding measured data. The results of the model calibration are shown in Fig. 6.

Models are declared to be calibrated if they produce Mean Bias Error (MBE) within ±10% and Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)) within ±30% when using hourly data [20]. The errors of the used model are given in Table 1.

Table 1 shows that all the errors in the model outputs satisfy the condition from [20], so the model is calibrated.
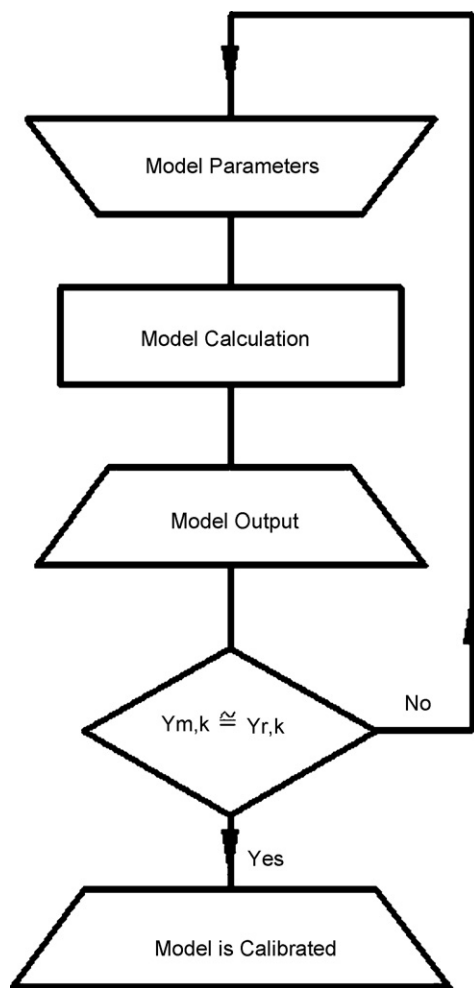
Fig. 5. The information flow of the model calibration.

The model is useable to estimate the change both in the achieved indoor air temperature and energy consumption when there is a bias in the desired supply-water temperature. Since the existing energy management control strategies are mostly heuristic, there is a need for systematically examining and improving them, as mentioned in [21]. In this case, the supply-water temperature should always be tuned to obtain the desired indoor air temperature, so this model can be used to optimize it, too. A new outdoor temperature compensation curve can be found by minimizing the difference between the achieved and desired indoor air temperature. Such an optimization problem can be defined in a similar way as Eq. (6), except that instead of the measured values, the desired values have to be used. Since the hot tap water consumption is measured and the model parameters for the ventilation are assumed, the model is not completely independent to predict the building performance. The model would be completely capable to predict when the model parameters are time-independent. However, since the study includes both measurements from BEMS and additional ones, there are data overlapping, so it is possible to analyze faults and their related effects on energy consumption and the indoor air temperature.

5. Faults in the heating system

Based on the developed approach, simple instruction for fault detection can be given. The following faults are noted: disconnected sensor for the outdoor air temperature, the outdoor air temperature sensor measures a faulty temperature, fault in the time scheduling program and a water flow imbalance problem in the substation. The faults are explained by first giving the cause and then the effects. The effects are shown on the total energy consumption and on the indoor air
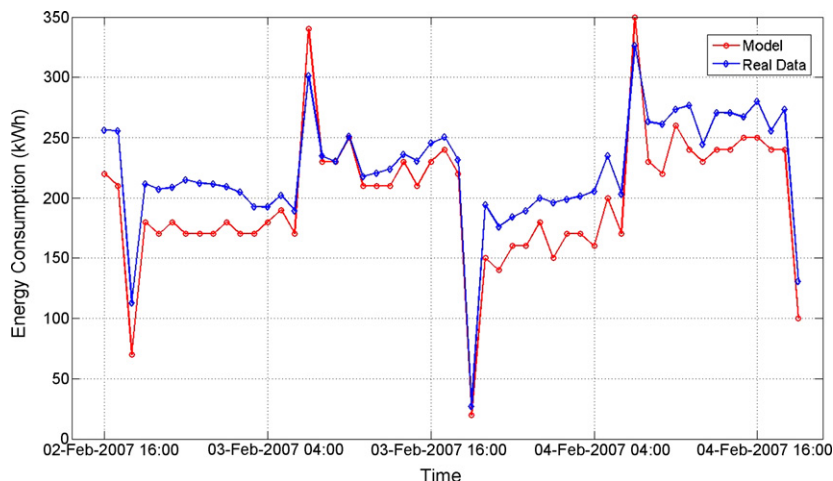

Fig. 6. Results of the model calibration.

Table 1
The error in the model outputs

	Q	T_{in1}	T_{in2}	T_{in3}	T_{in4}	T_{hr1}	T_{hr2}	T_{hr3}	T_{hr4}
MBE (%)	−9.82	−0.84	1.30	−1.87	−1.24	0.081	−0.13	0.20	−0.15
CV(RMSE) (%)	12.5	8.95	8.76	9.54	9.83	0.87	0.90	1.02	1.16

temperature of the Green Block. In the following figures the term "Desired Schedule" is used for the operation schedule described in connection with Fig. 3. The term "Actual Schedule" appears in the following figures, and it implies the operation schedule actually in use. This schedule implies that the supply-water temperature follows the curve in Fig. 3 from 5 a.m. to 5 p.m., Monday to Friday, and from 6 a.m. to 6 p.m., Saturday and Sunday. Outside of this period the supply-water temperature is decreased by 10 °C.

5.1. Disconnected sensor

When the outdoor air temperature sensor is disconnected, the outdoor temperature compensation curve (Fig. 3) is not fulfilled. The effects of such a fault are influenced by the BEMS strategy in the case when this sensor is disconnected.

The BEMS strategy for this heating system is defined so that if the sensor for the outdoor air temperature is disconnected, then the supply-water temperature is equal to the corresponding value at $T_{out} = 0°$ C. Actually, the supply-water temperature would be almost constant regardless of the change in the outdoor temperature. Fig. 7 shows the supply-water temperatures, the desired ones and the ones when the sensor is disconnected, normalized by the outdoor temperature.

Fig. 7 shows the effect on the supply-water temperature when the outdoor air temperature sensor is disconnected during the working hours; the supply-water temperature is almost constant. The effect on the supply-water temperature during the off-working hours is the same as in Fig. 7, except that all the values are approximately decreased by 10 °C. In Fig. 7 the faulty values of the supply-water temperature are higher than the corresponding value for the supply-water temperature at $T_{out} = 0$ °C because there is also a water flow imbalance problem in the system.

Fig. 8 shows the outdoor air temperature and the related supply-water temperatures, the measured and the desired.

The outdoor air temperature in Fig. 8 is downloaded from the Norwegian Meteorological Institute [15]. The effects of the disconnected sensor for the same period are shown in Fig. 9.

The effect of the disconnected outdoor air temperature sensor is shown in Fig. 8, the supply-water temperature is almost constant regardless of the changes in the outdoor air temperature.
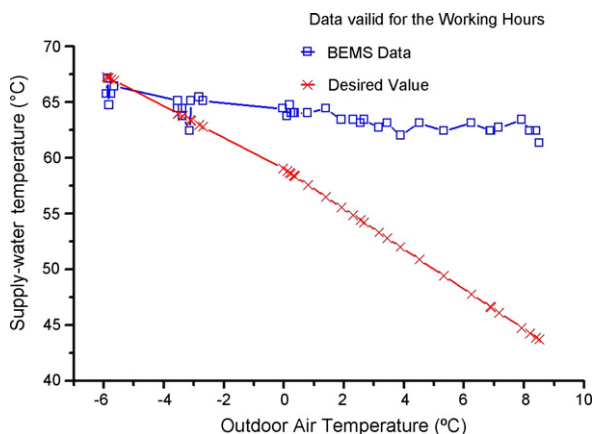
When the outdoor air temperature sensor is disconnected, the indoor air temperature is different from the desired value, and the energy consumption is almost constant outside of the transient time period regardless of the outdoor air temperature changes, as Fig. 9 shows. Since the current BEMS strategy in a case of the disconnected outdoor air temperature sensor is defined by the outdoor temperature of 0 °C, the supply-water temperature has the value close to an appropriate value at 0 °C. For a different BEMS strategy, this offset of the desired supply-water temperature is different. Actually, depending on the BEMS strategy the effects of the disconnected sensor are different. In this case, if $T_{out} > 0$ °C, then both the energy consumption and the indoor temperature are increased, while if $T_{out} < 0$ °C, both the energy consumption and the indoor temperature are decreased.

5.2. Fault in the outdoor air temperature sensor measurement

When the outdoor air temperature sensor measures faulty, the desired indoor temperature is not achieved even though the supply-water temperature seems to be achieved.

Since the outdoor temperature was obtained from three different sources, the sensor function test was possible to be done by comparing these data as shown in Fig. 10.

Fig. 10 shows that the sensor used to control the supply-water temperature measures a faulty temperature. The line with crosses in Fig. 10 represents the measurement done by an additional logger. This additional logger was placed outdoor all the time and logged the outdoor temperature every 10 min. The line named "Met Data" represents data from [15]. Since the Meteorological Institute gives data every 6 h, these data are interpolated. In addition, the meteorological station is located at the different place from the actual building. In the further analysis the data for the outdoor air temperature measured by the additional logger are used as correct data.

If the outdoor air temperature sensor measures a faulty temperature, then the achieved supply-water temperature is faulty. In this case, the BEMS outdoor air temperature sensor measures a higher temperature than the actual one. Therefore, the supply-water temperature is lower than desired for the actual outdoor air temperature. The difference between the outdoor air temperatures and related supply-water temperatures is shown in Fig. 11.

The example in Fig. 11 shows the supply-water temperature when the outdoor sensor measures higher outdoor temperature than the actual one all the time. The corresponding effects of a fault in the outdoor air temperature sensor, both on the indoor air temperature and the energy consumption, are shown in Fig. 12.

Fig. 12 shows that if the outdoor temperature sensor measures a higher temperature than the actual one, then the indoor temperature is decreased and the energy consumption is decreased. Such a fault can be noted by measuring the indoor temperature. If the indoor temperature is lower than desired, even though the supply-temperature achieves the desired value, then the outdoor sensor measures a faulty temperature. The cause of such a fault can be either a bad position of the sensor, an old sensor, or a defected sensor by any reason.

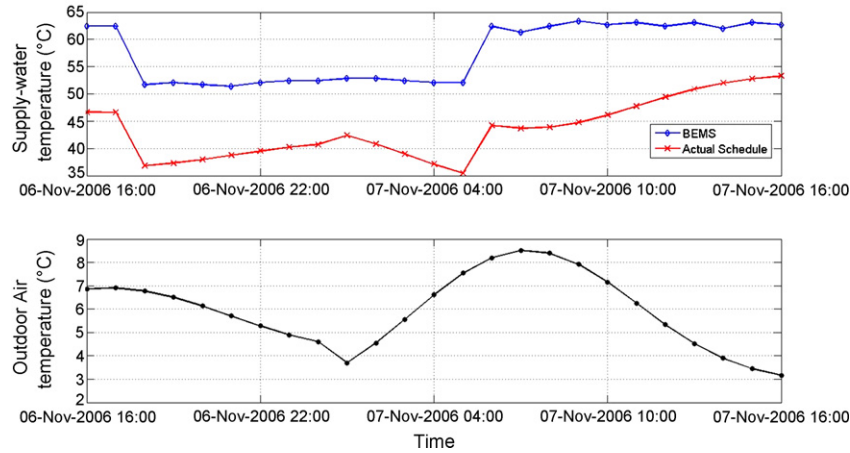Fig. 7. Supply-water temperature during working hours.

Fig. 8. The disconnected sensor causes the constant supply-water temperature.
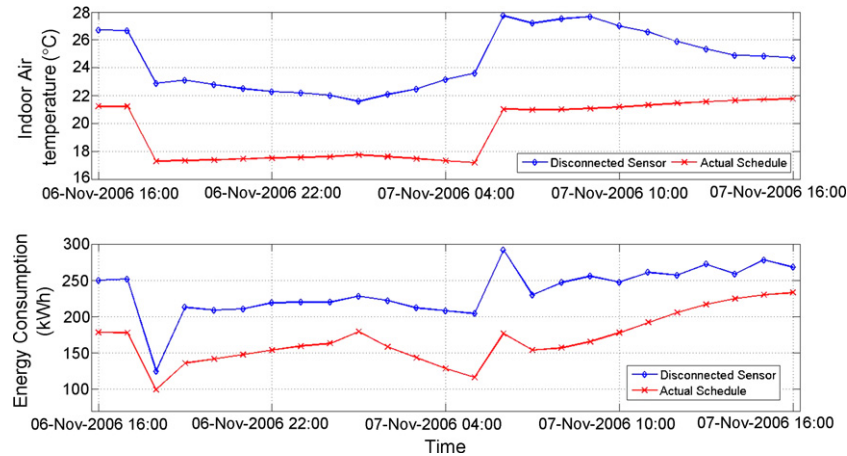

Fig. 9. Effects on the indoor air temperature and the energy consumption when the outdoor air temperature sensor is disconnected.

5.3. Fault in time schedule

A fault in time schedule prevents an energy efficiency measure. Such a fault can be easily detected by checking the hourly energy consumption.

Since there are two maintenance levels that program the time schedule, it is possible that a fault appears. In connection with Fig. 3, the desired operational schedule is given, while the actual is given in the introduction of Chapter 5. The differences in the desired and actual operation schedule are shown in Fig. 13. Since the real data are used in this example, the fault in the outdoor air temperature sensor measurement exists in Fig. 13, as well.
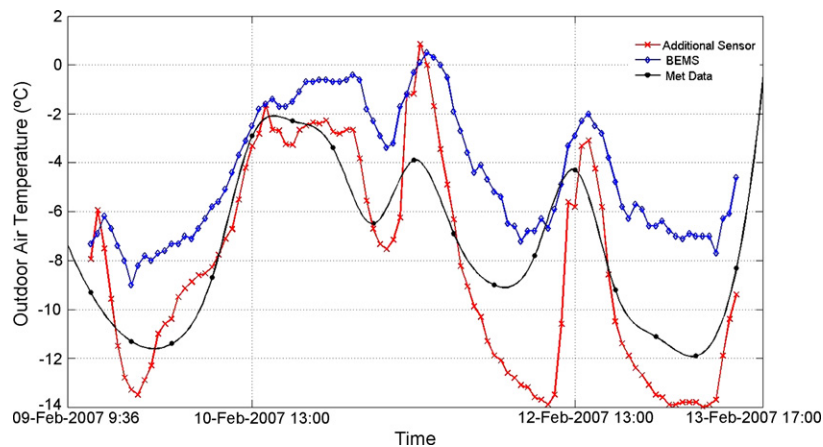

Fig. 10. Different measurements of the outdoor air temperature.

8   *N. Djuric et al. / Energy and Buildings xxx (2008) xxx–xxx*
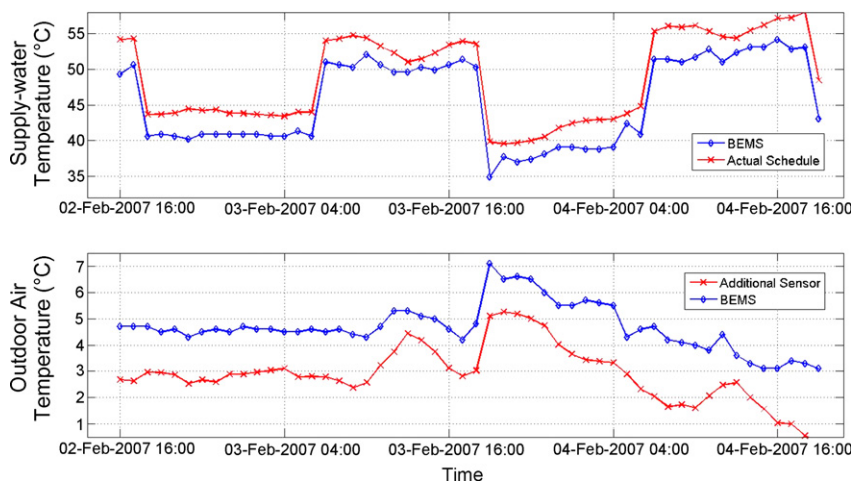

Fig. 11. The BEMS outdoor air temperature sensor measures a faulty outdoor temperature.
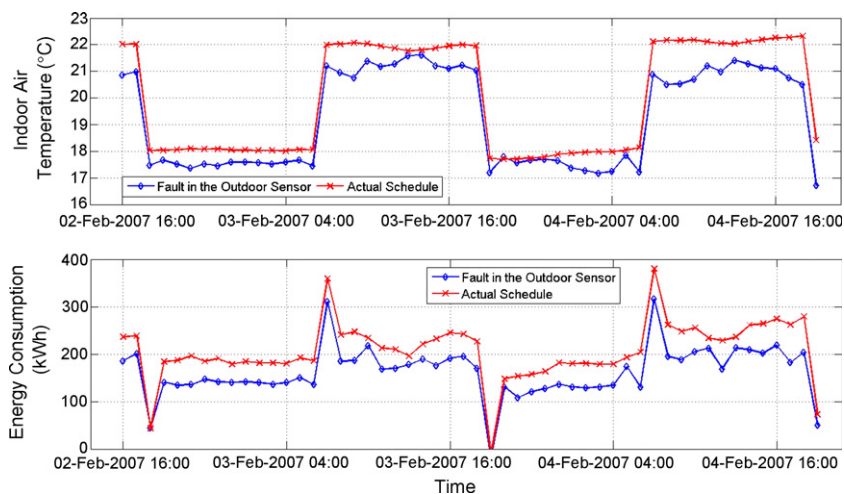

Fig. 12. Effect of the faulty measurements of the outdoor air temperature sensor.

Fig. 13 shows that the desired schedule was not fulfilled. For example, February 9–11 was a weekend, i.e. the off-working hours, so according to the desired schedule the supply-water temperature should be 10 °C decreased. Since the actual schedule is in use, there is a difference in the achieved and desired supply-water temperature. In addition, Fig. 13 shows that even though the outdoor air temperature sensor measures a faulty outdoor temperature, the achieved supply-water temperature is higher than desired, because the desired schedule is not in use. Fig. 13 shows that the actual operational schedule is fulfilled only on February 10, but not at all on February 12 and 13. So in the off-working hours, between both February 11 and 12, and 12 and 13, the supply-water temperature is the same as the desired, but this is because the actual schedule is not fulfilled (circles labeled with ''2 faults'' in Fig. 13). The effects of this difference are shown in Fig. 14.

Fig. 14 shows the effects on the indoor air temperature and the energy consumption caused by the faults in the time schedule. Since the actual schedule was used during the weekend, the energy consumption is higher than it should be with the desired operation schedule. The desired operation schedule aims to be an energy efficiency measure. Since the actual schedule is in use, there is no effect of the energy efficiency measure. This difference in the time schedule can easily be noted by checking the hourly energy consumption. If there is no response in the hourly energy consumption at the moment the supply-water temperature is changed, it means that the desired time program is not in use. The corresponding responses in the energy consumption to the temperature changes in Fig. 13 (labeled with ellipses) are labeled in Fig. 14 (ellipses labeled with ''response''). In addition to these different settings in the time schedule, it is possible that an error appears in the time schedule program, too. Such a fault can cause the resulting operational schedule that is neither actual nor desired, as it is shown for February 12 and 13.

5.4. Water flow imbalance problem

This fault seems to be difficult to explain to the building caretakers. As a brief introduction into this fault a short example is given as follows: if the valve AA01 (Fig. 2) does not close perfectly, the heating branch consumes energy, even

N. Djuric et al. / Energy and Buildings xxx (2008) xxx–xxx
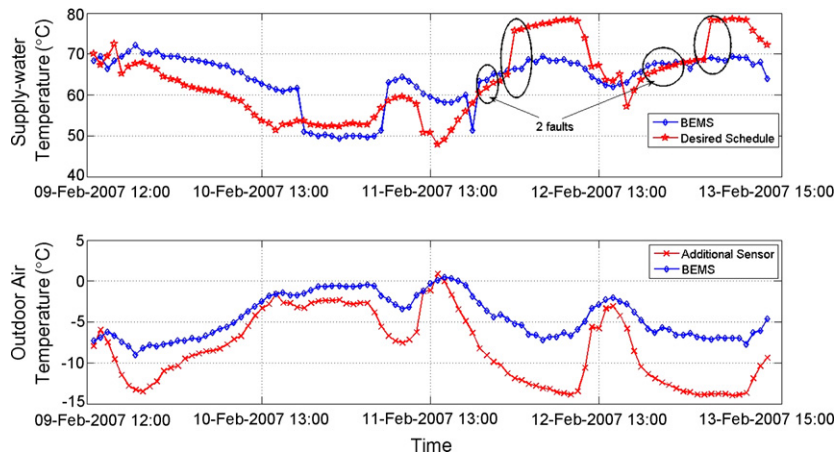
9

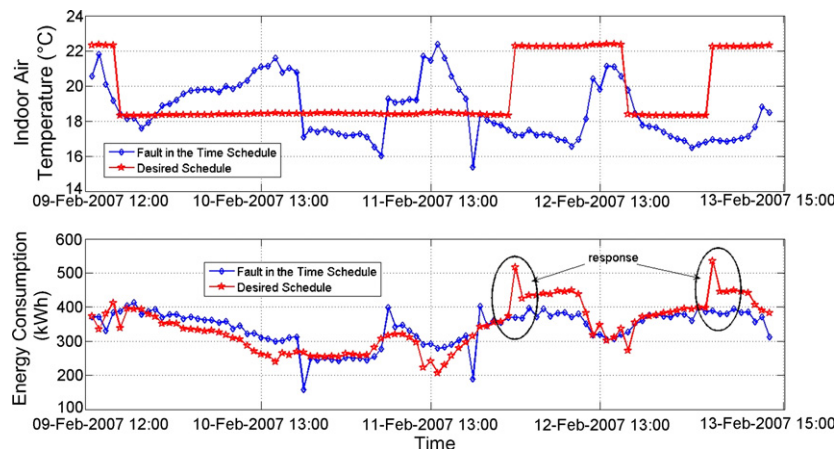Fig. 13. The different settings in the time schedule.

Fig. 14. Effects of the different setting in the time schedule.

though the BEMS data shows that the valve AA01 is closed. Therefore, the total energy consumption is increased.

The supply branches for the heating and the hot tap water system are parallel (Fig. 2). A model for the hydraulic and thermal characteristics of these two branches is not defined in this study. Therefore, the effects cannot be shown as in the above examples, while the problem source is explained. These two branches have different hydraulic and thermal characteristics according to their purpose in the system. Since they are parallel, they influence each other, and a fault can appear. Such a fault is caused by ageing of the valve. The example of such a fault is shown in Fig. 15.
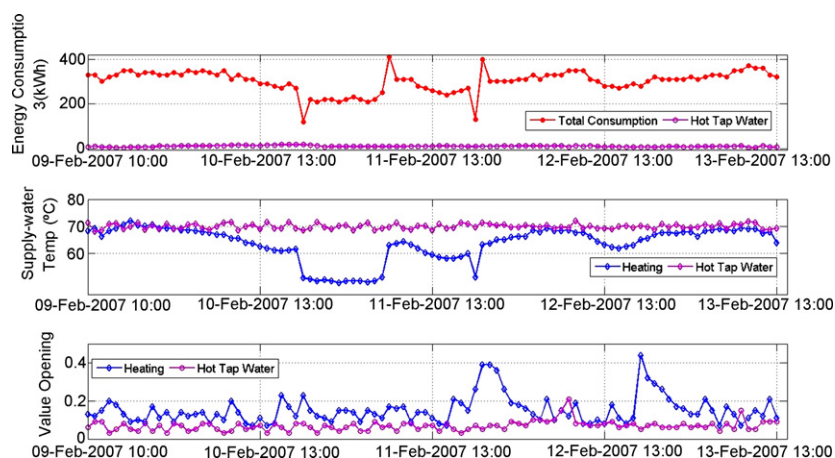

Fig. 15. Problem between two parallel branches for the heating and hot tap water system.

To present such a fault, the valve openings are also given in Fig. 15. To explain this fault, it is necessary to look at the ratio between the hot tap water consumption and the total energy consumption. At the moment when the supply-water temperature is decreased by 10 °C this ratio is high. If the valve opening (AA01) for the heating system is increased at the same moment, the supply-water temperature for the hot tap water would be lower than the desired one, because the heating branch is capable of receiving a higher percentage of the total consumed energy. At the moment when the supply-water temperature is increased by 10 °C, the total energy consumption is the highest, as at 6 a.m. on February 11. Since the entire system consumes a high amount of energy, the bias in the supply hot water temperature appears regardless of the valve position (AA03). Actually, when the supply-water temperature is almost constant for a period, the supply hot water temperature is influenced by the heating control valve (AA01) opening. The effect of this fault was noted during the on-site survey. A radiator at the first floor in the North Block was warm on July 4 2006, when the outdoor air temperature was approximately 25 °C. Even though the BEMS data showed that the valve AA01 opening was 0%, it was possible that a certain amount of the main flow circulated through it, since the valve did not close perfectly. Since the consumption of the hot water was low, a part of the main flow circulated through the heating branch, so even the pump was shut down, the hot water was circulated by itself. Therefore the total energy consumption is increased, even though nobody needs heat in the summer.

6. Conclusion

The simple heat balance model of the building and the hydraulic heating system is calibrated against the real data by using the optimization tool. The obtained model was good enough to detect four faults. Therefore the four detected faults in the hydronic heating system are explained. By using the simple heat balance model the fault effects on the indoor air temperature and the energy consumption are shown. The results show that the faults can cause both increase and decrease in the achieved indoor air temperature and the energy consumption. The effects of the faults are influenced by when and how they appear.

The effects of the disconnected outdoor air temperature sensor are influenced by the BEMS strategy in the case of the disconnected outdoor air temperature sensor. The faulty measurement of the outdoor air temperature sensor influences the indoor temperature and energy consumption. The fault in the time schedule could appear because of both a few levels in the BEMS maintenance services and an error in the time schedule program. Such fault can be easily noted by checking the hourly energy consumption.

Further work should include the water pressure balance model, so that the model is completely independent of the additional measurements to predict the building performance by using BEMS data. Currently and further detected faults and their effect should be summarized and classified, so that a kind of false database would be developed as a help to the building maintenance services.

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