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ENERGY EFFICIENT INDOOR CLIMATE CONTROL

A Practical Approach for Enhanced Implementability

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Building Services Engineering
Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

This work deals with energy efficient indoor climate control in office buildings, with an emphasis on implementability. More specifically, the aim is to suggest and evaluate improvements to building automation systems that are sufficiently simple and efficient to be realistic alternatives to commonly-used systems. The approach is focused on a technology that generates control signals by anticipating the influence of measured indoor climate disturbances, and this principle was evaluated for automating heating, cooling and ventilation on central as well as local building levels.

The work was conducted through a combination of simulations in Simulink® and experiments in a laboratory environment. Each part has its own purpose in the whole, and the procedure follows a systematic and holistic structure. While some studies deal with technologies for measuring disturbances using few standard-type sensors, other focus on finding relevant ways for transforming this information into control signals without involving extensive algorithms or many parameters. Altogether, most practical aspects and relevant applications are addressed in order to provide an as complete picture of the research topic as possible.

The general methodology was to re-create typical working days through office-like activities in office-like environments, and to repeat the same period with a suggested and conventional indoor climate control system. As both control systems were constrained to fulfill a desirable indoor climate, their performances were measured by the associated energy usages of the heating, ventilation and air-conditioning (HVAC) system. Furthermore, the influences of several conditions such as building structure, office room type, working activity and ambient climate are considered in the work. The investigated variants appear in pairs and were selected to cover most relevant configurations regarding some specific aspect. Using this approach, the aim is to spread the investigation so that most real scenarios can be found within the range of results.

The combined results show that realizable technologies are sufficient to reduce the HVAC energy usage considerably, at the same time as a desirable indoor climate is achieved. It was moreover found that the largest potential benefits are allocated to ventilation system automation. Even a simple supply air temperature control strategy has the ability of reducing total energy usage with up to 30 % compared to a conventional outdoor temperature-compensated approach. Further, a single parameter controller for ventilation rate automation on room level can result in that up to 50 % less air is required for maintaining a desirable indoor climate.

Keywords: Heating, ventilation and air-conditioning, indoor climate control, building automation, office buildings, energy efficiency, implementability, model-based control.

This study has been founded by the department of Energy and Environment, Chalmers University of Technology, Göteborg, Sweden.

Till mina allt.
Malin, Teodor och Hilma.

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Göteborg, August 2014

Mattias Gruber

LIST OF PUBLICATIONS

This thesis is based on six peer-reviewed journal articles that are appended and cited according to the following order:

I. M. Gruber, A. Trüschel, J.-O. Dalenbäck, Model-based controllers for indoor climate control in office buildings - Complexity and performance evaluation, Energy and Buildings (Elsevier), 68 (2013) 213-222.

II. M. Gruber, A. Trüschel, J.-O. Dalenbäck, CO_2 sensors for occupancy estimations: potential in building automation applications, Energy and Buildings (Elsevier), 84 (2014) 548-556.

III. M. Gruber, A. Trüschel, J.-O. Dalenbäck, Alternative strategies for supply air temperature control in office buildings, Energy and Buildings (Elsevier), 82 (2014) 406-415.

IV. M. Gruber, A. Trüschel, J.-O. Dalenbäck, Energy efficient climate control in office buildings without giving up implementability, submitted to the journal of Applied Energy (Elsevier).

V. M. Gruber, A. Trüschel, J.-O. Dalenbäck, Combining performance and implementability of model-based controllers for indoor climate control in office environments, Building and Environment (Elsevier), 2014 (82), 228–236.

VI. M. Gruber, A. Trüschel, J.-O. Dalenbäck, Motion sensors for ventilation system control in office buildings, submitted to the journal of Energy (Hindawi).

Additional publications connected to this research project are the following:

1. M. Gruber, Behovsbaserad styrning av inomhusklimat i kontor, Energi & Miljö, 2013 (1), 52-54.

2. M. Gruber, Mätbara störningar ger bättre klimatstyrning, Energi & Miljö, 2012 (12), 20.

3. M. Gruber, P. Fahlén, L. Ekberg, B. Permats, J. Berg, Ventilation kräver samverkan mellan flera yrkesgrupper, Fastighetsförvaltaren 2012 (2), 38-39.

4. M. Gruber, Valve influence on the power requirement of centralized pumps in hydronic heating systems, Proceedings of 10th REHVA World Congress (Clima 2010), Antalya, Turkey, 2010.

CONTENTS

SYMBOLS AND ABBREVIATIONS

Symbols

Latin letters

A	area	[m^2]
c	CO_2 concentration	[ppm]
c_p	specific heat capacity at constant pressure	[J/(kg K)]
C	thermal capacity	[J/K]
d	thickness	[m]
E	total energy, weighted sum of energy terms	[W]
e	control error	
H	height	[m]
h	hour	
$\dot{M}, \dot{c}$	CO_2 flow rate	[ml/s]
$\dot{m}$	specific CO_2 flow rate	[kg/(s m^2)]
n	number	[-]
Q	thermal energy	[J]
$\dot{Q}$	thermal power	[W]
r	reference / setpoint	
t	celsius temperature	[°C]
u	general input signal	
V	volume	[m^3]
$\dot{V}$	volume flow rate	[m^3/s]
W	electric work	[J]
$\dot{W}$	electric power	[W]
y	general output signal	

Greek letters

α	convective heat transfer coefficient	[W/(m^2 K)]
λ	thermal conductivity	[W/(m K)]
η	efficiency	[-]
ρ	density	[kg/m^3]
τ	time	[s]

Subscripts

a	air
adj	adjacent
c	control
d	derivative
i	integral
inf	infiltration
max	maximum
min	minimum
o	outdoor
r	room
s	supply

sp	setpoint
t	temperature
tot	total
vent	ventilation
w	water

Abbreviations

ACH	Air Changes per Hour $\left(\dot{V}_s / V_r\right)$ [h^{-1}]
AHU	Air-Handling Unit
AMIGO	Approximate M-constrained Integral Gain Optimization
ASHRAE	American Society of heating, Refrigeration and Air-Conditioning Engineers
BAS	Building Automation System
BE	Building Element
D	Derivative term
FCU	Fan-Coil Unit
HRV	Heat Recovery Ventilation
HVAC	Heating, Ventilation and Air-Conditioning
I	Integral term
IAQ	Indoor Air Quality
MPC	Model Predictive Control
OAT	Outdoor Air Temperature
ODE	Ordinary Differential Equation
P	Proportional term
PIR	Passive InfraRed
PMV	Predicted Mean Vote
POF	Principle OF optimality
PPD	Predicted Percentage Dissatisfied
RHC	Receding Horizon Control
SAT	Supply Air Temperature
SFP	Specific Fan Power [$kW/(m^3/s)$]
VAV	Variable Air Volume

1 INTRODUCTION

Approximately 40 % of the final European energy is used in buildings, and in the European energy directive [1], lowering this share is pointed out as a key objective for fulfilling a mutual target of 20 % reduction in total energy use compared to the predicted level in year 2020 [2]. This strategy is supported by previous research publications, in which possible reductions up to 50-60 % [3] of total building energy and 30 % of the electricity have been identified. In the same context, the U.S. Environmental Protection Agency have stated that about 30 % of the corresponding total energy in the United States is used inefficiently or unnecessarily [4]. But even though it is clear that major reductions are possible, it is also important to acknowledge that any efficiency measures on the way for a less energy intensive building stock are unrealistic on a large scale if not economically feasible, relatively easy to implement and applicable in a large variety of objects.

In European countries, 76 % of the building sector energy is used by systems for heating, ventilation and air-conditioning (HVAC) [5]. A key element for reducing this part is to improve the associated building automation system (BAS), and such measures have the possibility of yielding a number of benefits. First, they can coincide with the primary function of achieving a desirable indoor climate. Second, they have the possibility to be overall effective since the control system determines the operation of the entire HVAC system, and therefore has a decisive role when it comes to the associated energy usage. Third, to a certain level, energy savings are possible without any major retrofits of the HVAC system or building.

1.1 Background

A building and its spaces are continuously affected by internal and external indoor climate disturbances in terms of heat, air-emission and humidity sinks/gains. The purpose of the BAS is to adapt the operation of the HVAC system so that a desirable indoor climate is maintained throughout the building for all possible conditions. Hence, the BAS acts as an interface between the building and the HVAC system, and as an HVAC system alone only can be operated either at full capacity or to be completely off, the purpose of the BAS is to manage everything in between - that is, all part load scenarios. For buildings in general, this is the absolutely most common operational mode, which means that the BAS plays a crucial role in providing HVAC services during most of a buildings life-time.

For building automation tasks, specific information is typically gathered by a set of sensors and is transformed into a HVAC system operational routine by a set of controllers. Conventionally (*fig. 1*), the main source of data comes from measurements that are intended to reflect the present state of the indoor climate, and the controllers act upon deviations from predetermined comfort regions. The controller offset is further commonly determined by a single variable in an open-loop manner (such as the outdoor air temperature) but these two sources of information are otherwise completely detached. Hence, this procedure provides no answers to why a measured deviation was detected, how it is best met and for how long it should be acted upon. Furthermore, neither the primary control objective regarding comfort, nor a desirable low energy usage, can be expressed explicitly in the conventional control laws. [6]

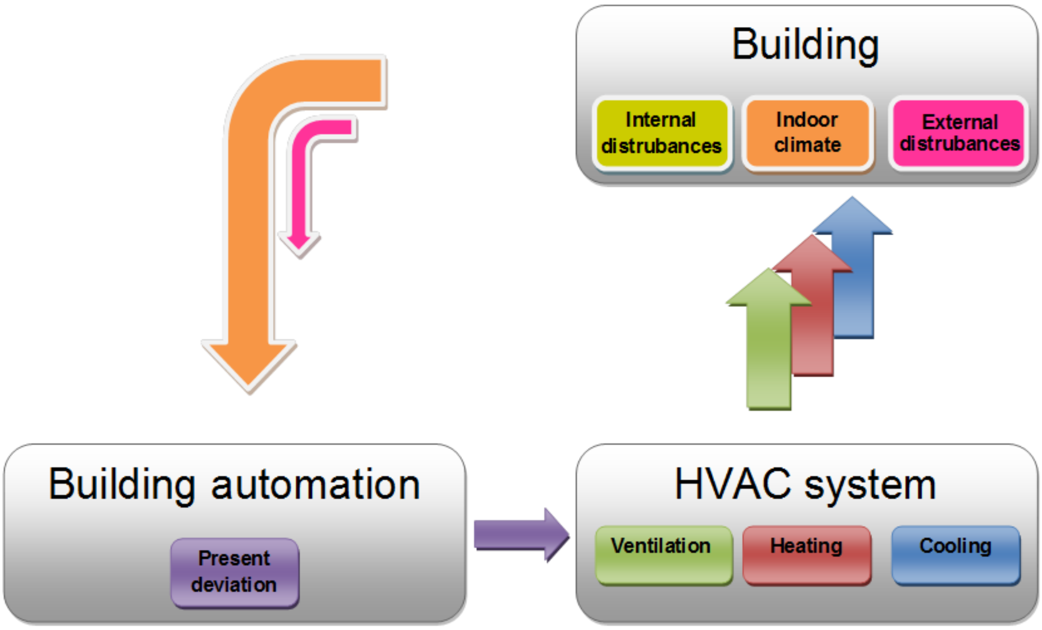

Figure 1. Typical working principle of a conventional building automation system. The main source of information comes from present indoor climate variables and the controller acts upon deviations from predetermined comfort regions. The controller offset is further commonly determined by a single external disturbance such as the outdoor air temperature.

A way of improving the BAS is to increase the adaptation to prevailing conditions by incorporating relevant information about the control task, building and HVAC characteristics, the activities inside the building, the ambient climate etc. That is, to provide a holistic view of the systems, the processes as well as present events and their consequences in time. By doing so, the prerequisites of achieving a desirable indoor climate from a static and dynamical point of view could be estimated in advance - before any deviations from considered comfort regions occur. Also, the control activity could be planned ahead by anticipating future demands, which opens up for the possibility of optimizing the operation by deciding on the most preferable counteractions for changed conditions.

The above described technology is in its broadest sense referred to as model-based control (*fig. 2*), and even though there are several subgroups of different structures and arrangements, mutual design elements are a disturbance sensing system and an internal control model. The sensing system is a network of components that are used to collect data about relevant indoor climate disturbances through measurement, prognosis and/or estimations. The information is passed on to the control model as so called exogenous inputs, and based on some kind of process representation, the associated influences on the controlled variables are predicted or anticipated. In turn, control signals are generated for adapting the operation of the HVAC system to achieve a desired combination of comfort and energy usage - both for the present time and in the future. [7]

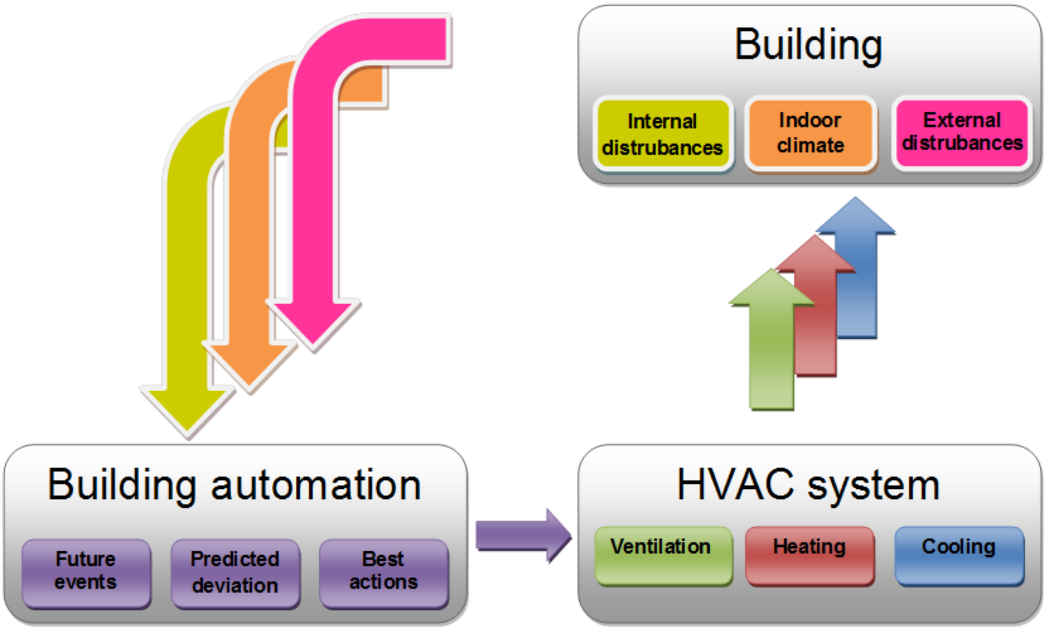

Figure 2. Typical working principle of a model-based building automation system. A relevant set of indoor climate disturbances is used to predict future consequences and to decide on the best actions. Further, several future events such as vacant periods, energy prices, changed operational modes etc. can also be taken into account simultaneously.

1.2 Building Automation Research

Model-based controllers for building automation have recently become a popular research topic. Literature contains plenty of examples that cover a broad range of applications from single tasks up to a system-wide level where the entire building and its systems are taken into account. In this section, a number of relevant publications are selected and reviewed in order to provide a representative and up-to-date overview regarding potential benefits through a broad range of BAS improvements. To facilitate for the reader, these publications are further divided into three classes, dependent on their extensiveness with respect to the number of involved exogenous inputs and the considered control tasks. Note that the associated technology is of less importance at this point and will instead be presented thoroughly in the following parts of this work.

1.2.1 Model-based controllers on room level

The first class involves publications where occupancy (from now on referring to the number of people) was utilized as single exogenous input to local model-based controllers, i.e. controllers that are designed for managing the indoor climate in separate rooms or in a confined part of a building.

Morosan et al. [8] equipped each room of a simulated office building with a controller that utilized future occupancy profiles to adapt the supply of heat. The control model consisted of a complete dynamic energy-balance of the conditioned space, and was used to optimize a trade-off between energy performance and deviating degree-hours from a temperature setpoint. Compared to the mean performance of a number of conventional controllers, it was shown that the energy usage could be reduced with about 13 % at the same time as comfort was increased with 37 % according to the considered metric.

Occupancy information was also considered by Lu et al. [9], but to control the ventilation rate in a sport facility. A mass-balance was used during a training session to calculate and return the amount of fresh air required to maintain a desirable IAQ (Indoor Air Quality), defined as CO_2 concentrations below 1000 ppm. The number of people was presumed to be known through a schedule and it was shown that energy saving up to 26 % were possible compared to a conventional control approach.

Similar studies were further presented by Goyal [10] and Oldewurtel et al. [11], but in these cases, the building was made up of one and two office room zones respectively, while the control tasks primary considered temperature, and involved the whole ventilation system. Moreover, both of these works studied an additional time-aspect of the exogenous input, by comparing benefits of utilizing future or present occupancy information as retrieved from prognosis or measurements, respectively. The results were consistent and showed that measurements were sufficient for achieving energy savings around 50 % in comparison to conventional controllers, while only small additional gains were provided through prognosis.

1.2.2 Model-based controllers on a central building level

The next class refers, like the previous, to publications regarding model-based controllers with single or relatively few exogenous inputs, but the control task is now extended to involve a larger part of the HVAC system.

Prívara et al. [12] used weather prognosis to automate the heating supply water temperature in an office building by optimizing comfort and energy usage. The study was conducted in an office building during heating season, and the results showed that between 17 - 21 % of the energy could be saved compared to a conventional weather-compensated strategy. Similar methodologies and applications were also considered in references [13-16], but in these cases, occupancy schedules were furthermore incorporated to distinguish between periods of stringent and relaxed comfort constraints, which resulted in heating energy savings up to 30 - 40 %.

Kolokotsa et al. [17] extended the application a bit further by considering a controller with information about outdoor air temperature (OAT), occupancy and illumination for temperature and lighting control in an office building. The thermal part was formulated as a trade-off between energy usage and comfort indicated by PMV (Predicted Mean Vote), and the controller was allowed to automate the ventilation rate, lighting as well as the opening of windows and solar shadings. The results showed that the annual total energy usage was reduced with 38 % compared to on/off HVAC control and manual lighting.

The publications in the second class also contain examples where controllers with weather prognosis were used to find an optimum mix among a set of available energy supply technologies. A common approach was to maximize the contribution from renewable parts provided by e.g. solar heating or free-cooling

[18-20], and it was shown that other sources could be reduced with up to 35 % in comparison to simple on/off sequence control.

1.2.3 System-wide model-based controllers

The final class refers to publications regarding extensive controllers. In these examples, most internal and external indoor climate disturbances are typically included in the exogenous inputs, and several vital HVAC energy streams are managed either directly or indirectly.

A common approach involved central supply air temperature (SAT) control in ventilation systems, by employing an optimization algorithm to find a system-wide energy usage minimum while satisfying comfort in the entire building. Nassif et al. [21] used such algorithm in an office environment during two summer weeks by incorporating thermal climate and energy for air-handling in the optimization objectives. A similar investigation was also presented by Mossolly et al. [22], and it was found that up to 30 % of the energy to an educational environment could be saved compared to maintaining a constant SAT setpoint. These findings are moreover consistent with the results of Parameshwaran et al. [23] where an optimal controller was used for climate control in an academic building scale model. Compared to maintaining constant SAT levels between 12 - 14 °C, the strategy yielded energy savings between 54 - 61 % during summer and winter ambient conditions, and this range was furthermore assessed as equivalent to annual savings between 29 - 36 %.

Wang et al. [24] considered instead a multi-zone office building model in which the entire ventilation system operation was optimized. Simplified adaptive control models of the processes were used to estimate responses to various external and internal conditions, while a solver searched for a trade-off between air-handling energy and comfort aspects. Simulations were conducted for four different weather conditions and it was found that up to 40 % of the energy could be saved compared to maintaining constant setpoints.

A bit different approach to the same problem was in turn chosen by F. Engdahl and D. Johansson in [25]. Instead of using numerical tools, expressions for the HVAC energy usage was formulated for a number of conditions, and the optimal SAT was derived analytically. The theory was applied on a ventilation system in an office building and an energy saving potential between 8 - 27 % was indicated compared to constant setpoint approaches.

1.3 Motives

In the light of the previous examples, it is clear that the potential for energy efficiency improvements through alternative BASs are huge, and that model-based control in that sense is a beneficial technology in a vast variety of applications. On the other hand, a mutual feature of the cited works was that the evaluated controllers were associated to high levels of complexity. This is a problem in the general sense, since like any other energy efficiency measure, alternative BASs must be cost effective and relatively easy to implement in a large variety of sites in order to contribute to any significant energy usage reductions in the building sector.

1.3.1 Model-based controller designs

The overall complexity and cost of a model-based controller is primary determined by the design and extensiveness of its two fundamental parts (the disturbances sensing system and the control model), and how these are interconnected. As the complexity of the disturbance sensing system is directly related to the number of registered indoor climate disturbances and their measurability, the complexity of the control model is determined by how the associated exogenous inputs are processed and how unmeasured influences are compensated for. Typically, to achieve predictive and optimal indoor climate control as in the cited works, a complete control model of the process and HVAC system would be required together with accurate and continuously updated information about all relevant internal and external conditions.

When it comes to the control model design, physical models have the potential of describing the process and HVAC system sufficiently accurate, but a large number of parameter values must then be defined, whereof several are hard (or even impossible) to measure without major efforts. Another alternative are black-box models that are constructed from experimental data through an optimization process in which the best description between input and output measurements is derived [26]. But since the accuracy immediately becomes uncertain when operated in a range from where the recorded data lack information, the commissioning phase can be an extensive and time-consuming process. When it comes to gathering information about internal and external conditions, the customary set of exogenous inputs can be divided into a number of disturbances, whereof several can be determined with established sensor technologies (for example OAT, lighting, solar radiation). But for others, this is not an option (considering people and infiltration flow rate for example) without involving models for prognosis and/or estimations, and these are typically afflicted with the same problems as the control model.

1.3.2 Previous approaches

The absolute majority of previous works within the area of model-based BAS for indoor climate control have not addressed the issues as pointed out above. Instead, most approaches involved two assumptions:

- an ideal control model with perfect correspondence to the process and HVAC system.
- an ideal disturbance sensing system with perfect correspondence between actual disturbances and exogenous inputs.

Hence, implementation of the same technologies would be extremely hard (or even impossible) without major efforts put in to the design, commissioning and maintenance of the BAS.

To sum up, even though previous works have indicated substantial energy reduction potentials, the same results would be unreasonable to expect in typical buildings without major costs. In this context, a trade-off technology would probably be more sufficient for achieving a widespread energy efficiency increase in the building stock. That is, BASs that are simple enough for a facilitated implementability, but still has a considerable higher performance than systems of current practice.

1.4 Objectives

This work deals with practical aspects on energy efficient indoor climate control in buildings. The most important aim is to suggest and evaluate BAS technologies that are sufficiently simple and efficient to be realistic alternatives to systems of current practice. Or in other words, to enable significant energy reductions in the building sector, by facilitating a widespread utilization of energy efficient BAS technologies.

Focus is put on thermal comfort and IAQ control in modern office buildings, using room air temperature and CO_2 as indicators, respectively. The investigated time-frame stretches between 1 - 5 working days during which a suggested and common BAS technology were compared. Furthermore, due to the considerable energy savings that were indicated in several of the cited works, all suggested BAS technologies were derived using the principle of model-based controller as inspiration - but while aiming for an enhanced implementability, in accordance to the overall aim.

1.5 Method

In *table 1*, a brief overview of this work is provided. It consists of six appended journal papers that are maintained within the research topic through a number of shared features.

- First, all papers share the same overall goal of reducing the amount of energy for indoor climate control in office buildings while maintaining comfort.
- Second, all papers address the foregoing bullet from a practical point of view, and contribute in the search for realistic solutions that are implementable at typical sites through standard technologies.
- Third, all papers address the two foregoing bullets through the same technological approach of incorporating information about indoor climate disturbances in the BAS for an enhanced adaptation to present conditions.

The work further aims to provide a complete picture of the research topic. On one hand, all relevant details of the technological approach are addressed under non-idealized conditions. This is achieved through a systematic procedure in which results from previous papers are used as starting point for others. On the other hand, the papers are together expanded to account for most relevant conditions such as building structure, type of office site, working activity, HVAC system and ambient climate. The selection of investigated variants was broadly spread so that most real configurations of some practical aspect can be found within the range of results. Moreover, the work addresses different tasks related to indoor climate control as well as technologies for automating different levels of HVAC systems. The emphasis is however on integrated room automation strategies (local level) since more practical issues needed to be resolved for these tasks. In turn, the desired features for central control (building level) could be fulfilled more directly and hence required less attention.

The procedure involves a combination of theoretical computer simulations and experimental studies in a laboratory environment. As the theoretical parts focus on aspects that could not be reproduced in reality or would have been too time-consuming, the experiments are mainly used to expand and validate specific theoretical outcomes. The general methodology in all parts was to re-create internal disturbances connected to typical office-like activities, in single- or multi-zone sites, during periods of 1 to 5 days. The same conditions were repeated with a common and a suggested BAS that were constrained to fulfill a desirable indoor climate within predetermined comfort regions. The two systems were then compared using the associated HVAC system energy usage for space heating, comfort cooling and air-renewal as performance metric.

1.6 Thesis Outline

The thesis is divided into nine chapters while the full versions of the journal papers are included in the appendix. Chapter 2 provides the technological background regarding BASs in general as well as detailed descriptions of the considered control strategies. Chapter 3 presents the available resources and chapter 4 describes how these were used in the work. Chapter 5 describes the general methodology of the appended papers while their contents are provided through short reviews in chapter 6. The combined results are then summarized and discussed in chapter 7 and 8, while further research is suggested in chapter 9.

Table 1. Overview of appended papers.

Characteristic features	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
Approach	Computer simulations	Computer simulations and laboratory experiments	Computer simulations	Laboratory experiments	Laboratory experiments	Laboratory experiments
Addressed controller function	Integrated room automation	Integrated room automation	Central supply air temperature control	Integrated room automation	Integrated room automation	Integrated room automation
Addressed HVAC function	Hygienic ventilation, hydronic heating and cooling	HVAC system independent but with hygienic ventilation as base-line	Air-based heating and cooling, hygienic ventilation	Air-based heating and cooling	Hygienic ventilation, hydronic heating and cooling	Air-based heating and cooling, hygienic ventilation
Overall goal	Partly derive a sufficiently simple controller structure for an increased energy efficiency	Evaluate a sufficiently simple method for gathering occupancy information	Derive a sufficiently simple controller structure for an increased energy efficiency	Evaluate and validate the controller from paper I	Evaluate and validate the controller from paper I	Evaluate the controller from paper I with simplified occupancy information

2 TECHNOLOGY BACKGROUND

In this chapter, a technology background is given. The focus is on systems for indoor climate control in office buildings, but the majority of introduced concepts are also valid from a general point of view. Given the topic of this work, the most essential part is an introduction to model-based control and a review of common types. But before going that far, the appropriate context is first provided through an overview of HVAC systems, regarding building automation on different levels. Furthermore, typical conventional BASs are also introduced to broaden the perspective and to prepare the ground for the appended journal papers in which these systems are considered as benchmarks.

2.1 HVAC Systems

The purpose of an HVAC system is to maintain a desirable climate in a given space, typically through the operation of various equipment and appliances for heating, cooling and/or air-renewal.

In accordance to the principal characterisation in *figure 3*, an HVAC system can be divided into subsystems for generation, distribution and supply. The purpose of the generation parts is to provide the building with cooling and/or heating energy through the operation of one or several units, such as boilers, district heating substations, cooling machines etc. The energy is in turn transported via carriers in the distribution system to various zones of the building, where some kind of service for a maintained indoor climate is provided through terminal units.

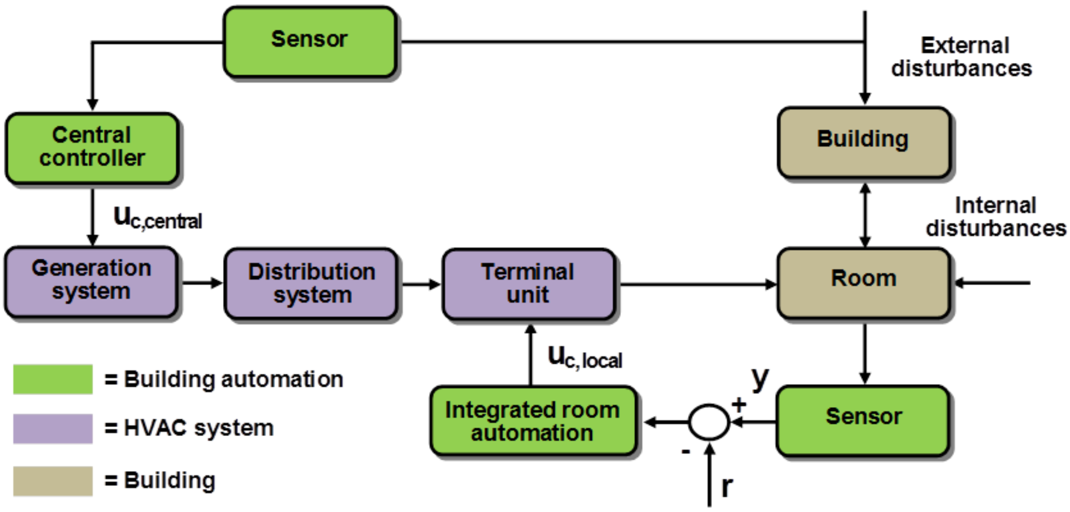

Figure 3. Principal characterisation of a building HVAC system: u_c = control signal(s), r = setpoint(s), y = measured controlled variable(s).

Typical heating and cooling carriers in buildings are air and water, and the associated parts of the HVAC system is referred to ventilation- and hydronic- (or water-based) systems, respectively. Common terminal units in the hydronic part are radiators, chilled beams or fan-coils, and these are used to supply or extract heat in a space for covering heat deficits or to remove heat surpluses. In turn, the primary purpose of the ventilation system can also be to manage heat surpluses/deficits (referred to as an all-air system), or to provide an air-renewal in the room (referred to as hygienic ventilation [27]). These services are commonly associated with diffusers as terminal units but there are also other examples such as inductors or ventilation-connected fan-coils.

The mutual task of all controllers that are involved in the operation of an HVAC system is referred to as building automation. When it comes to indoor climate control, a distinction can be made between controllers that act on a local respectively on a central building level. The generation part of the HVAC system is typically automated centrally, and the associated controllers then determine the temperature levels of heating and cooling carries in the distribution system. In turn, local controllers are involved in a task referred to as integrated room automation and are used to determine the transfer conditions on room level – from the distribution system via the terminal units. This is primary done by changing the flow rate of carriers, but there are also examples of supporting functions for varying the temperature (e.g. re-heaters in ventilation systems).

An overview of these concepts is presented in *figure 4*, and as pointed out, the building automation task is divided between integrated room and central automation. In this example, the supply temperatures of ventilation air and heating carrier are automated on the central level, while the associated flow rates in each conditioned zone of the building are managed through integrated room automation.

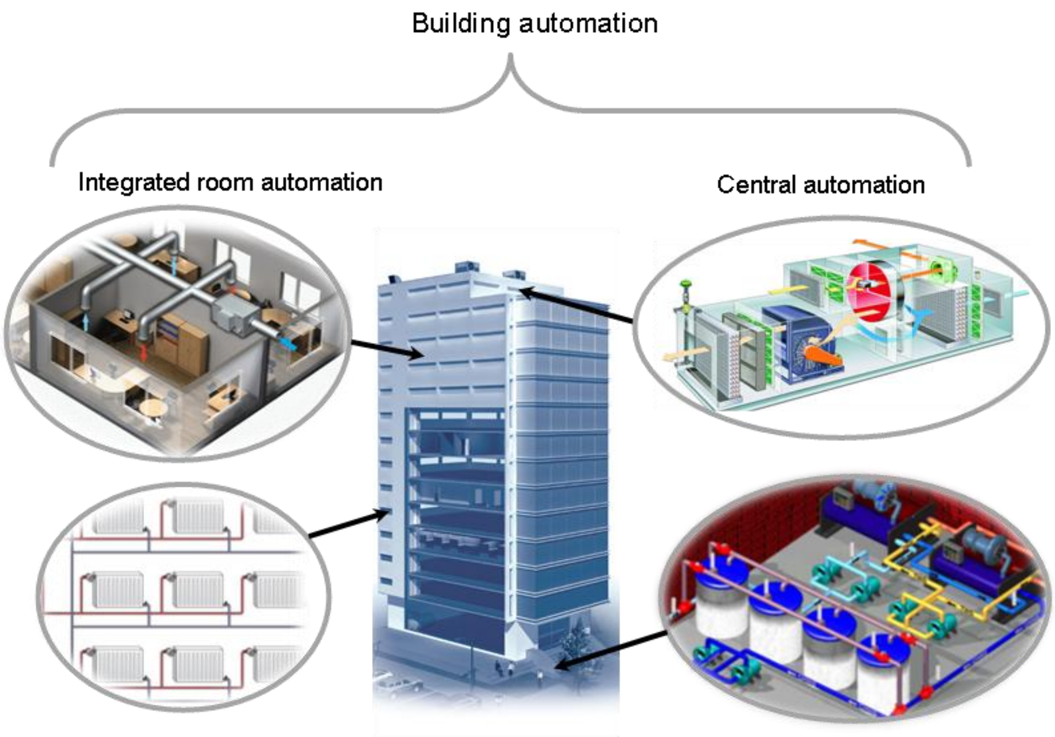

Figure 4. Examples of integrated room and central automation tasks; together referred to as building automation (figures from various internet sources).

2.2 Controllers and Control Systems

A general control system typically consists of the three following components, while translations into building automation terms are provided in parenthesis;

- A system of sensors for gathering relevant information (indoor climate disturbances, state of controlled variables) from within and around the controlled process (conditioned space).
- A controller for transforming the sensor outputs (measurements) into control signals.
- An actuator (HVAC system component) for transforming control signals into physical actions (heating, cooling or ventilation) on the controlled variables (indoor climate indicators).

2.2.1 Conventional central controllers

Central controllers are commonly used to provide the generation system with setpoints for supply temperature levels of heating and/or cooling carriers (see *fig. 3*). Since the associated distribution system stretches out to the entire building, these temperatures should preferable suite the whole range of demands within the conditioned zones simultaneously. A common conventional approach is to use an open-loop structure where the output explicitly is determined as a function of the OAT, such that a decreased input is met by an increased output and vice versa. Even though an understandable choice, because the entire building is affected by OAT variations, there might be several more or less influential disturbances that are not accounted for using this approach.

A relatively common way of improving the performance of the controller type described above is to incorporate additional features and/or more process information - without changing the overall principle. For example, measuring representative room temperatures means that the supply can be adjusted accordingly, in order to fit local needs more precisely via feed-back. Another method is to employ time-scheduled control that varies according to a predetermined pattern. In this way, distinctions can be made between e.g. day and night in office buildings to employ relaxed comfort constraints during commonly vacant periods. It is furthermore possible to utilize information about other disturbances with a presumed or known impact on the indoor climate (such as solar radiation, wind etc), along with the OAT in the open-loop.

2.2.2 Conventional controllers for integrated room automation

Controllers for integrated room automation are employed to adjust the supply of heating, cooling and/or ventilation in a certain space of a building. The absolutely most common type is feed-back, whose main task is indirect compensation of indoor climate disturbances by maintaining a constant (or periodically constant) setpoint.

In *figure 5*, a principle block-scheme of a typical feed-back is illustrated. Control signals (u_c) are generated by processing a control error (e), which is formed by comparing measured (or actual) values of the controlled variable to a setpoint (y respectively r in *fig. 3*). Different controller variants are enabled through a selection of three basic control error processing modules, referred to as

Proportional- (P), Integrating- (I) and Derivative- (D) actions. The following text focuses on the three most common combinations: P, PI and PID, whereof the PI primary was considered in this work. As all three modules are included in *figure 5*, the illustrated example is a PID while other variants could be formed by simply removing either the D- or/and the I-action without changing the overall structure.

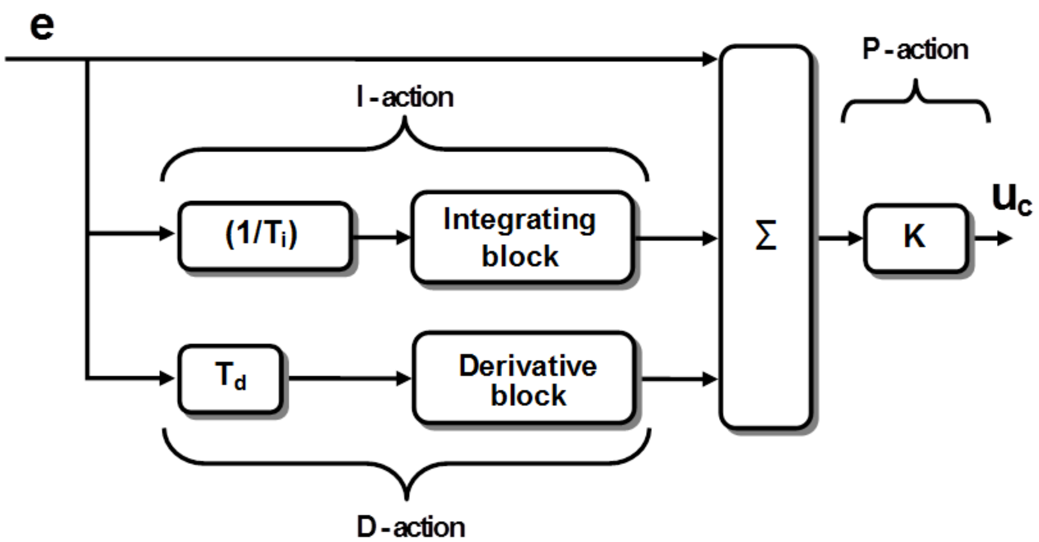

Figure 5. Schematics of a feed-back controller.

The corresponding mathematical interpretation to *figure 5* is given in *equation 1*, where the final control signal (u_c) is expressed as the sum of the three module outputs. Each individual contribution is in turn weighted by a parameter denoted as static gain (K), I-time (T_i) and D-time (T_d) for the P, I and D-module respectively.

$$u_c(\tau) = K \times e(\tau) + \frac{K}{T_i} \times \int_0^{\tau} e(\tau)\, d\tau + K \times T_d \times \frac{de(\tau)}{d\tau} \qquad (1)$$

When designing a feed-back, the module- (or controller-) parameters are tuned together. This can be done in different ways but the main goal is to maximize the overall performance by finding combinations for an optimal trade-off between speed (the time for reaching a sufficiently small control error) and stability [28]. A low control signal activity as a response to a certain error results in a stable but slow control. In turn, a large response results in a fast control but might also lead to instabilities; that is, the system does not settle since any control signal is larger than required to retain the setpoint.

Feed-back actions

In the remaining part of this section, the three most common feed-back variants are presented according to a step-wise approach, in which a new module is added to an already existing set. The individual response of the latest module is then illustrated for an arbitrary control error step of quantity *a*, and its contribution is discussed from a holistic point of view. These responses should be interpreted as the resulting behaviour if the error is registered, but the generated actions do not reach the process. [29]

The (P) in a **P-controller** is short for "proportional" and corresponds to the first term on the right hand side of *equation 1*. As illustrated in *figure 6*, P-action is simply generated by multiplying the control error with the static gain (K), and while a fast response is provided, only the present error is accounted for. In practise, this means that the setpoint cannot be completely retained, and a controller with a sole P-module is therefore always associated to a remaining error.

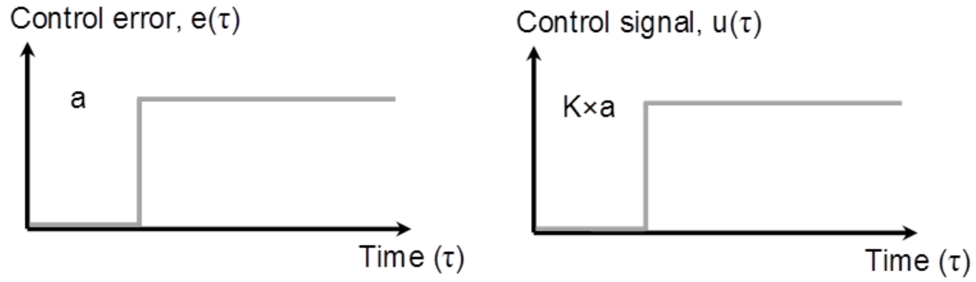

Figure 6. The response of a P-module (right) to a control error step of quantity a (left).

The (I) in a **PI-controller** is short for "integral" and corresponds to the second term on the right hand side of *equation 1*. I-action is generated by accumulating past control errors (i.e. through integration over time) and the weight parameter (T_i) corresponds to the elapsed time until the contributions of the I- and P-module are equal for a given static error. As illustrated in *figure 7*, the I-action grows continuously for non-zero errors which mean that the setpoint eventually can be retained, and that the resulting control signal moreover is kept. That is, the remaining errors associated to the P-module can now be removed, but to avoid instabilities, the static gain must also be decreased which typically results in an overall slower control.

Remark: If the outputs from an I-module do not reach the process over a certain period of time, errors that were accumulated must be reversed before the controller has retained its complete function. The majority of such events can be avoided by adding an anti-windup function, which holds the output if the actuator becomes saturated in one of its end-positions. This function also provides the controller with some memory, since once the anti-windup is deactivated, the I-module starts to accumulate control errors from its previous level.

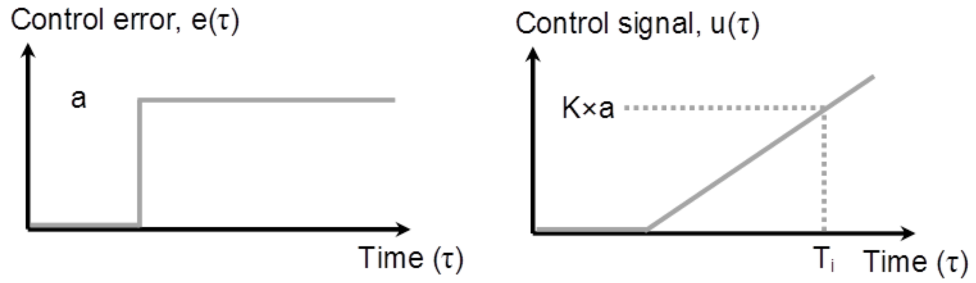

Figure 7. The response of an I-module (right) to a control error step of quantity a (left).

The (D) in a **PID-controller** is short for “derivative” and corresponds to the third term on the right hand side of *equation 1*. As illustrated in *figure 8*, the D-module compensates for future errors by acting on the rate-of-change, and as the response to a step is infinite, the output rapidly declines as the error has settled. The interpretation of the parameter T_d is not as straight forward as in the previous cases, and in the context of this work, it is sufficient to note that it scales the output. To avoid instabilities, the static gain is normally decreased when D-action is added, but due to its fast response, the speed of the controller is typically increased.

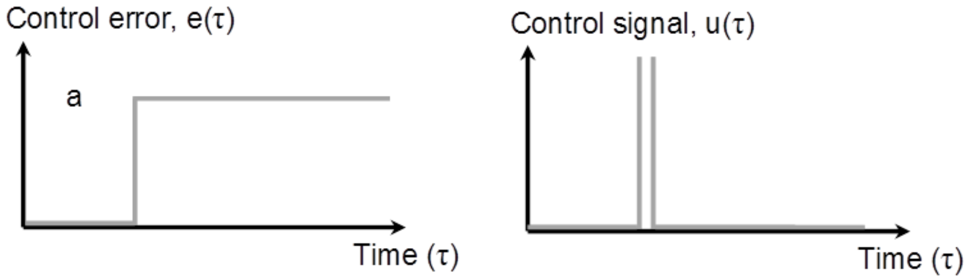

Figure 8. The response of a D-module (right) to a control error step of quantity a (left).

2.2.3 Model-based controllers in general

Any building is constantly affected by intermittent disturbances of external and/or internal origins which together determine the required amount of heating, cooling and ventilation for maintaining a desirable indoor climate. The variety and impacts are primary dependent on the type of building, the activities within and on the ambient conditions. For example, in modern offices with tight and well insulated envelopes, people, lighting and equipment are dominating during office hours, while the ambience then is of minor importance. Vice versa, the OAT will be decisive for the annual heating demand in residential buildings that are located in regions of cold and temperate climates.

In contrast to conventional BASs that primary act on setpoint deviations, model-based controllers can be used for an increased adaptation to prevailing conditions. For example, conventional BAS are commonly associated to considerable lags, and are primary capable of maintaining a desirable indoor climate during fairly constant conditions. In turn, mismatches between supply and demand typically occur for more varying disturbances, with a decreased indoor climate quality and/or an increased energy usage as a consequence. On the other hand, model-based controllers can in theory achieve a lag-free routine, with instantaneous and perfect responses to every registered change. Moreover, while conventional BASs are divided into a large number of individual controllers that are locked to restricted tasks, the entire system and every possibility can be taken into account by model-based. For example, the HVAC operation can be optimized to minimize the usage of energy at the same time as free or low-cost sources are prioritized by incorporating information about spot-prizes.

2.2.4 Model predictive controllers (MPC)

In chapter *1*, several works that had identified model-based controllers as a promising technology for building automation were cited. The absolute majority considered a type called MPC (Model Predictive Controller), whose most characteristic features is that the control procedure is formulated as an optimization problem. Typically, information about indoor climate disturbances and present state of the controlled variables is provided to a detailed and accurate dynamic control model. From these sets, the future behaviour of the process is predicted over a predetermined time-horizon, while an algorithm searches for future control signals that fulfil some given criteria; such as minimizing energy usage while maintaining comfort. [15]

Given the extensive control model, the optimization algorithm and the prediction features, MPC is obviously a complex technology and not realistic for considering in typical buildings without major retrofits. Further, the design is more or less locked by its characteristic features and the margin for a reduced complexity is therefore limited. On the other hand, the benefits of MPCs are enormous, and were considered as a main motivation to this work, while acknowledging the need for simpler and more standardized solutions. MPCs have therefore been used as reference cases in several of the appended papers and the following section provides an extensive review about the general concept.

Principle of optimality

A typical automation problem is to control a process from an initial state to a final state in the best possible way while the process is subjected to various disturbances. If the associated controller is used for indoor climate control, the two states can for example be located outside respective inside a comfort region, and the best possible way can be “while using as little energy as possible”.

There are different ways of addressing the optimization problem above, but one of the most transparent is to apply the principle of optimality (POF). The POF states that “An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.” [30]. When applied to model-based controllers, the optimization procedure is initiated at the end of the time-horizon (*N*) - in the final state where the process should settle. According to the POF, the optimal trajectory between the final state at time *N* and the state at time *N-1* is optimal independent on how the state at time *N-1* was reached. Hence, the overall control task can be divided into a number of individual steps, and by going backwards to time *0*, a sequence of optimal control actions can be solved by initiating each calculation in the state where the previous ended up in. [31]

Objective function

Equation 2 illustrates an objective function commonly used for MPC controllers; primary because the quadratic form is suitable for optimization purposes since the so called least-squares criterion can be used for its solution [32]. In accordance to the previously presented designations: the variable y is used to denote the controlled variables of the process, r denotes the associated setpoint that should be maintained and u denotes control signals that are generated for this task. The designation *U* is furthermore introduced to denote a set of future optimal control signals; one for each time-step between the present time (*0*) to the end of the predetermined time-horizon (*N*) over which the problem should be solved.

$$J = \min_{U} \left(P \times (r_N - y_N)^2 + \sum_{k=0}^{N-1} Q \times (r_k - y_k)^2 + \sum_{k=0}^{N-1} R \times u_k{}^2 \right) \qquad (2)$$
$$U = [u_0, ..., u_{N-1}]$$

By considering the objective function *J* in *equation 2*, the essence of the control task can be illustrated. The aim is to minimize the sum of terms on the right hand side by finding the optimal future control signals (*U*) from time *0* to *N-1*. Each term is furthermore multiplied with weight factors (*P*, *Q* and *R*) that serve as design parameters. By adjusting the weights, the user can decide on the most important features of the controller and hence the primary goal of the control task. The first term in the objective function penalizes the final state by the weight *P*. Hence, if the controlled variables at time *N* (y_N) ends up in a state which differs from the desired one (r_N), this term will grow. The second term includes all other state values from time *0* to time *N-1*, and in each time-step, deviations from an optimal trajectory (r_k , as determined by the POF for example) is penalizes by the weight *Q*. The third and last term penalizes the control signals by the weight *R*. The purpose of this term is to avoid overall large control signal activities but also to enable the ability of favouring some actions while suppressing others.

Remark 1: Another possibility of MPCs is to add constraints along with the objective function in order to restrict the solution regarding both controlled variable values (allowed states), as well as control signal values. The constraints can for example be used to include the operational interval of actuators (hard) or floating setpoints such as a temperature dead-band (soft).

Remark 2: The weights *P*, *Q* and *R* are commonly tuned to assure stability and persistent feasibility (i.e. that the control task can be fulfilled without violating any constraints, cf. remark 1), whereof stability can be guaranteed by designing the objective function as a Lyapunov function [32]. But in practice, this property is generally relaxed for stable systems with slow dynamics, such as buildings, which means that the objective function then can be designed by focusing on performance criterions [33].

Receding horizon controller

An MPC controller can both be designed with an open- or feed-back structure. The only input to an open-loop MPC is the initial state (information about where the process starts from) and the solution is a complete sequence of control signals over the considered time-horizon. Since the solution isn't updated along the way, the control model has to describe the process perfectly within the current range of operation in order to avoid a non-optimal process trajectory.

In the area of indoor climate control, most previous publications considered a type of feed-back MPC referred to as a receding horizon controller (RHC). By measuring the present state, the optimization problem is solved over a long but finite time-horizon. However, only the first step of the resulting control signal sequence is implemented. The time-horizon is then moved forward and the procedure is repeated until the system has converged to the final state at time *N*. Thus, the solution of a RHC is an open-loop control signal sequence, but since the calculation is performed in each time-step for the present state, the overall behaviour corresponds to an MPC with feed-back function [32].

An RHC has some benefits which make is especially suitable in building automation applications, but one aspect must also be considered as potentially problematic. These are briefly reviewed in the final part of this section and more details can for example be found in reference [32].

Since the present state is measured at each time-step, an RHC is robust to disturbances and modelling errors, and both stability and persistent feasibility can furthermore be explicitly guaranteed. On the other hand, one of the main issue of the RHC design process is to determine *N* so that these desirable features are inherited. For computational reasons, *N* should be kept small, but must at the same time be sufficiently large for the process to be able to converge to the final state. [12]

3 RESOURCES

This work was conducted through a combination of theoretical simulations in MATLAB® Simulink®, and experiments in a laboratory environment. Each individual study has its own purpose in the whole, and together, most important aspects of the research topic are covered. In this chapter, the resources that were available during the procedure of the work are presented and described; mostly to prepare the grounds for chapter 4, in which the overall methodology is presented.

3.1 Experimental Framework

In accordance to the late *table 1*, experimental studies are presented in paper II, IV – VI whereof the first took place in the spring of 2011 and the remaining during the calendar year of 2013. All experiments were conducted in a detached University laboratory building, located in the mild tempered coastal city of Gothenburg, Sweden which has a normal mean annual temperature of 7.9 °C. In the following text, the facility is first presented which is followed by a description of the technological systems that were considered during the experiments.

3.1.1 Site

In accordance to the schematic layout in *figure 9*, the laboratory building consists of two levels with an approximate total floor area of 300 m^2. Besides of a few office and hygienical spaces, most of the facility is made up of a large open hall that contains various technological equipments and appliances for research and education within the field of building services engineering. As the majority of installations are allocated on the entrance floor, the second level is made up of an entresol that covers part of the total surface.

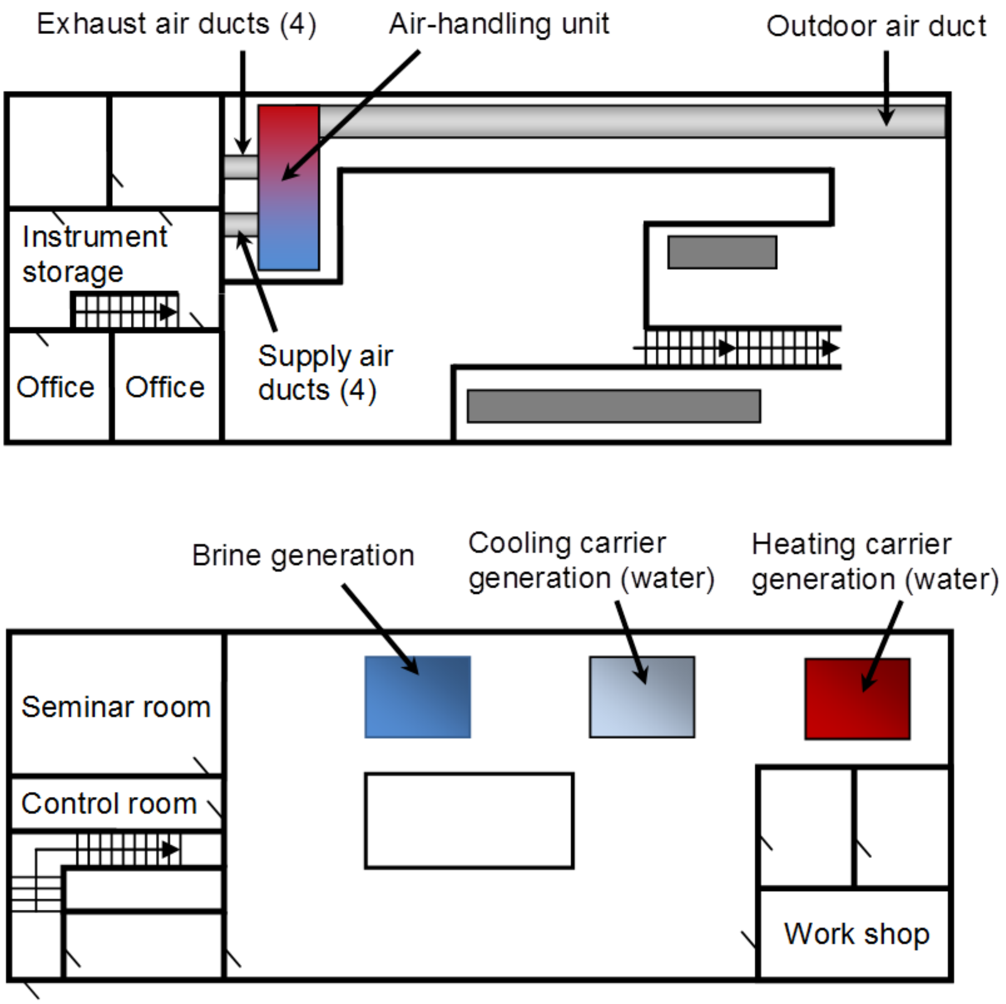

Figure 9. Schematic layout of the laboratory building. Bottom: entrance floor, top: 2nd level and entresol.

The experiments were conducted in a seminar room which is located on the entrance floor in the north-west corner of the facility. It is designed for studying indoor climate control and effects and has a large variety of technical systems installed for managing thermal climate and IAQ. The room itself has floor area of 5.6 × 6.2 m in accordance to *figure 10*, as well as a height of 2.4 m. As the floor and ceiling are made of concrete and the frame is of steel, the envelope consists of mineral wool, wood and gypsum with an exterior of metal sheet. The walls represented as left and up in *figure 10* are external, whereof the left has a section of outside solar shaded windows over most of its length. The remaining walls are adjacent to other parts of the building, whereof the lower in *figure 10* is equipped with a set of windows to facilitate observation from a control room.

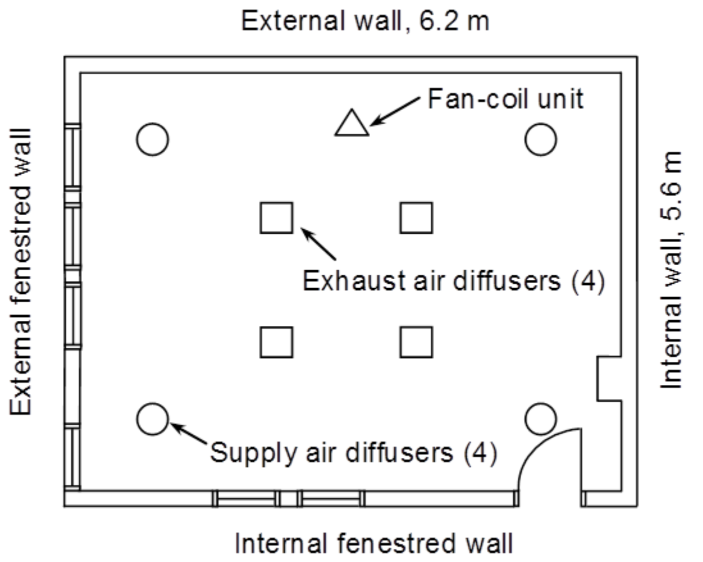

Figure 10. Schematic layout of the seminar room and some of the associated technical installations.

3.1.2 HVAC system

A wide range of systems and components associated to HVAC are installed in the facility, whereof most can be characterized as either used for ventilation or hydronic heating and cooling. A shared feature throughout is a high level of flexibility, both when it comes to automation possibilities and to altered properties. In the following section, a detailed description of the overall system is presented and to facilitate for the reader, a three level division was applied in accordance to the functions and services that were provided during the experiments (*fig. 11).*

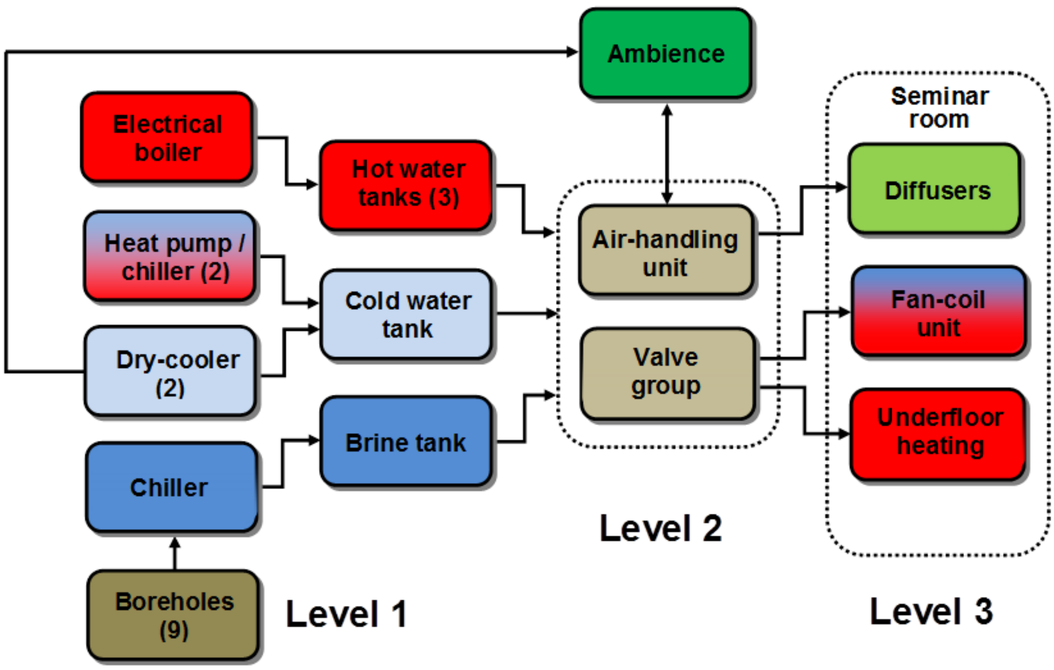

Figure 11. Flow sheet of technical installation in the experimental site. The level division is associated to functions that were provided during the experiments.

First system level

The first level in *figure 11* is characterized by generation and storage of heating/cooling carriers, for which there are several available units in the open hall on the entrance floor. All together, there are two combined heat pump/chillers for simultaneous heating and cooling, two roof-top mounted dry-coolers, one ground source heat pump connected to nine boreholes and one electrical boiler. Furthermore, the system includes five tanks, divided in three temperature levels of about -10 °C, 5 °C and 50 °C.

Second system level

The second level in *figure 11* is characterized by heat transfer and transportation of mediums for heating, cooling and ventilation in the seminar room, and the previous mentioned division between components for ventilation or hydronic heating/cooling now becomes clear.

The hydronic part consists of the valve group presented in *figures 12* and *13* by a simplified sketch and a photograph, respectively. The primary component is an automated by-pass, three-way valve (CV) connected between the carriers from the first level and a water-circuit belonging to a set of terminal units in the seminar room. The valve has two synchronized inlets whereof one makes up the return from the terminal units and the other the primary supply of either heating or cooling carrier; which, is decided manually by a series of on/off valves.

The two CV inlets are mixed at the outlet to generate an intermediate temperature stream that further is diverted to the terminal units by a series of manual valves (MV). The CV opening is automated by a linear step-motor and the group is also equipped with speed-controlled pumps (P). Finally, a number of balancing valves (BV) can be used to achieve equal rates through the terminal units at the end-positions of the CV.

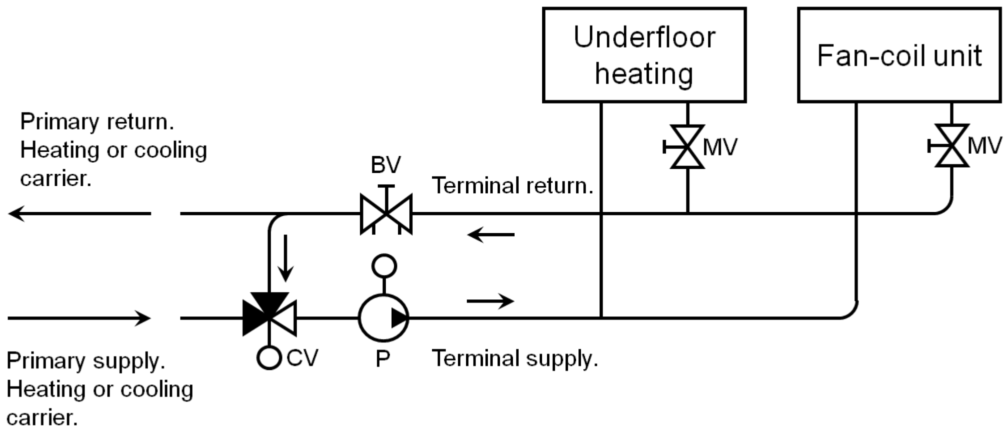

Figure 12. A simplified sketch of the valve group that was used to automate the hydronic terminal units for heating/cooling in the seminar room.

Figure 13. Photograph of the valve group from figure 12.

The ventilation part of the second HVAC level consists in turn of the air-handling unit (AHU) in *figure 14* which is located on the entresol in the open hall. Its schematics are further presented in *figure 15* and involve two integrated speed-controlled fans for transporting air to and from the seminar room via four ducts in each direction. Moreover, the carriers from the first HVAC level are used for conditioning supply air via two air-coils for heating and cooling/dehumidification. The coil capacities can either be controlled by bypass, three-way valves in the same manner as previously described for the hydronic terminal units, or through a variable water flow rate via speed-controlled pumps.

Primary, there are two features of the AHU that are important to highlight. First, the supply air can be circulated in the AHU with a larger flow than supplied to the room. This means that several passes through the air-coils are possible for facilitating an accurate temperature and humidity control. Second, the only option for recovering heat is to re-circulate exhaust air to the supply air stream. However, this principle is conflicting with the common ventilation practice in Sweden called heat recovery ventilation (HRV), which implies that a closed heat exchanger instead is utilized [34]. This problem was solved by disregarding heat recovery during experiments and instead selecting air-conditioning independent energy performance indicators (which is further discusses in section 5.2.2). As the exhaust air thus was discharged to the ambience, the supply air was entirely made up of conditioned outdoor air that had been transported through a long duct and passed three filter bags on the way.

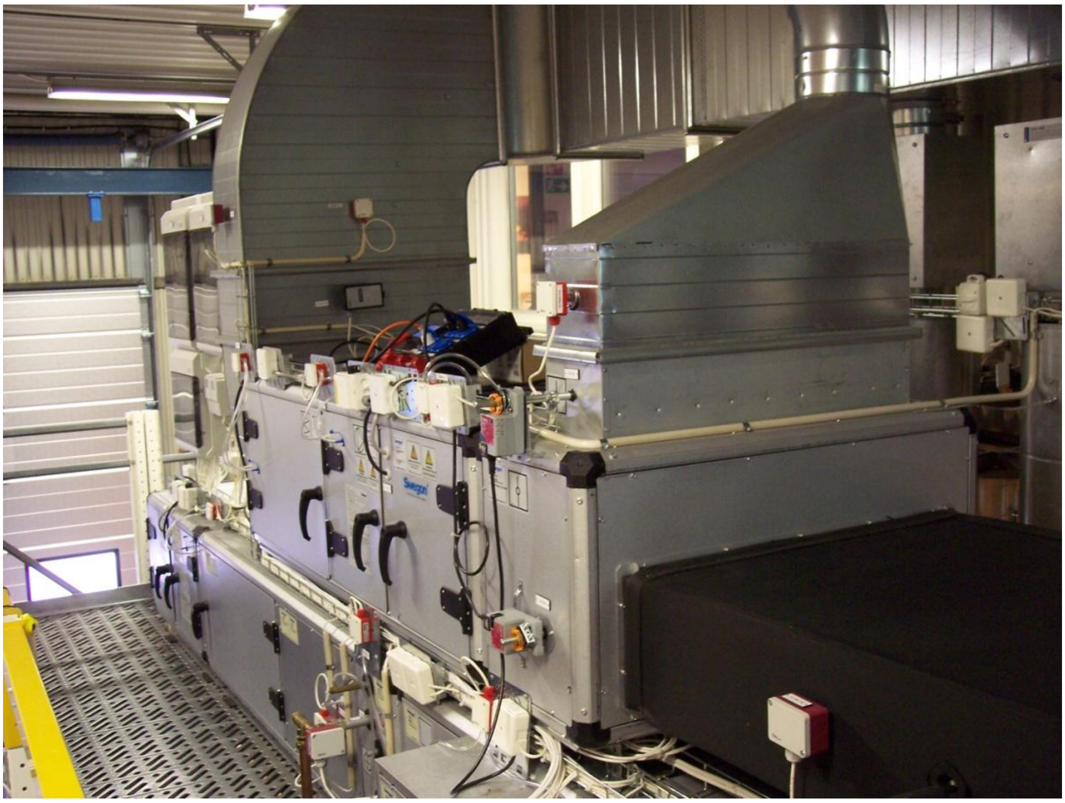

Figure 14. Photograph of the experimental air-handling unit which is located on the entresol in the facility.

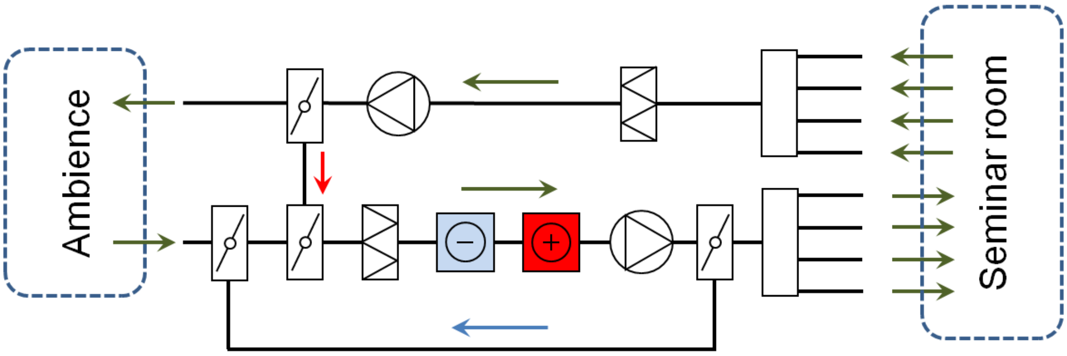

Figure 15. Schematics of the experimental air-handling unit. Green arrows indicate the normal pathways; the blue arrow indicates the auxiliary circulation pathway for an accurate control; the red arrow indicates the available but ignored re-circulation pathway.

Third system level

The third level in *figure 11* is characterized by the final stage of heat transfer and fresh air supply in the seminar room.

As already indicated in *figure 12*, there are mainly two available hydronic terminal units inside the seminar room:

- The entire surface of the floor can be used for underfloor heating or cooling.
- A re-circulating fan-coil unit (FCU) with a speed-controlled fan is installed in the ceiling near the long external wall (marked as a triangle in

figure 10). During operation, room air is taken in from below and is passed over a stack of tubes with an internal carrier flow, before discharged back through outlets on each side.

In turn, the ventilation system on this level consists of eight symmetrically distributed ceiling-mounted diffusers for mixing ventilation, equally divided between supply and exhaust air in accordance to *figure 10*. The flow through each diffuser can be shut off or balanced by manual dampers, and as the supply side furthermore has automated openings for variable air volume (VAV), the exhaust side is fixed during operation.

3.1.3 Building automation system

The entire facility, including generation units, distribution system and terminal units, can be automated and observed from the control room in which a computerized building automation system is installed. Data is collected from a large number of distributed sensors for flow rate, temperature and gaseous emissions in various locations. The system is very flexible and each control function can be entirely customized by first selecting the desired inputs and outputs from the entire set of available options, and then to individually design each controller.

In *tables 2a* and *2b*, the sensors involved in the experiments are specified, and each one was calibrated within a period of maximum two months before the experiments were initialized. In a few cases, the manufacturer was involved in this process, but the common approach was to compare readings to a high performance reference, which in turn had been calibrated by a certified agency within the considered time-span. This procedure was throughout performed under conditions that were expected to occur during the experiments.

- For temperature, a reference sensor with an uncertainty of 0.03 °C was used by comparing readings in a stirred ice bath, in water at room temperature and in free room air. Based on observed deviations, the sensors were corrected in the building automation software using a piece-wise linear error regression between the measured points.
- The considered flow rate sensors for air had fixed locations in the ventilation system and were calibrated by comparing readings to a reference sensor with an accuracy of about 2 l/s. During this procedure, deviations were returned over the entire admissible flow range while varying the speed of the central fans incrementally. Error regressions were then calculated and implemented in the building automation software.
- The accuracy of the flow rate sensor for water was sufficiently high to disclaim the need of a reference (a maximal error of 1 % of the reading) but to ensure the absence of calibration drift, a differential pressure sensor over a known resistant was employed in series throughout the study.
- As for the remaining, all CO_2 sensors were calibrated and adjusted by the manufacturer to an uncertainty of ± 50 ppm, while the power sensor was adjusted against a known load.

Table 2a. Summary of temperature sensors involved during the experimental studies.

Measured quantity	Placing	Range	Purpose	Label	Principle
Temperature	Spatial independent	-50 to +150 °C	Reference	Dostman P650	PT100
Temperature	**Conditioned space - Free air**	**-50 to +50 °C**	**For control**	**Schneider Electric STD400**	**Immersed transmitters**
Temperature	Outside conditioned space - Free air	+5 to +45 °C	For repeatability	Schneider Electric STR100	Thermistor
Temperature	**Ventilation system - Inlet to air-handling unit**	**-50 to +50 °C**	**For repeatability**	**Schneider Electric STD300**	**Immersed transmitter**
Temperature	Ventilation system - Outlet of air-cooler	-50 to +50 °C	For control	Schneider Electric STD300	Immersed transmitter
Temperature	**Ventilation system - Outlet of air-heater**	**-50 to +50 °C**	**For control**	**Schneider Electric STD300**	**Immersed transmitter**
Temperature	Ventilation system - Supply air duct	-50 to +50 °C	For control	Schneider Electric STD300	Immersed transmitter
Temperature	**FCU - Shunt outlet**	**-50 to +50 °C**	**For control**	**Schneider Electric STP100**	**Immersed NTC thermistor**
Temperature	FCU - Inlet water-side	-50 to +50 °C	Energy calc.	Schneider Electric STP100	Immersed NTC thermistor
Temperature	**FCU - Outlet water-side**	**-50 to +50 °C**	**Energy calc.**	**Schneider Electric STP100**	**Immersed NTC thermistor**

Table 2b. Summary of other sensor types involved during the experimental studies.

Measured quantity	Placing	Range	Purpose	Label	Principle
Air flow	Spatial independent	2 to 125 l/s	Reference	SwemaAir300, SWA31	Hot-wire anemometer
Air flow	**Ventilation system - Supply air duct (low flow)**	**3 to 65 l/s**	**For control, Energy calc.**	**LindInvent TTD160**	**Orifice pressure drop**
Air flow	Ventilation system - Supply air duct (high flow)	-50 to +50 Pa	For control, Energy calc.	Klimatbyrån ZMC160, Honeywell DPTE	Orifice pressure drop
Air flow	**Ventilation system - Exhaust air duct**	**-50 to +50 Pa**	**For control**	**Klimatbyrån ZMC160, Honeywell DPTE**	**Orifice pressure drop**
Air flow	FCU - Inlet air-side	5 to 125 l/s	For control	SwemaAir 300, Flow 650	Hood, hot-wire anemometer
Water flow	**FCU - Water-side, first sensor**	**0.4 to 200 l/min**	**Energy calc.**	**Sharky FS473**	**Ultrasonic**
Water flow	FCU - Water-side, second sensor	0 to 40 kPa	Energy calc.	TA STAD, TA Link	Orifice pressure drop
CO_2 level	**Conditioned space - Free air**	**0 to 2000 ppm**	**For control**	**Schneider Electric SCR100**	**Infrared spectrometer**
CO_2 level	Outside conditioned space - Free air	0 to 2000 ppm	For control	Schneider Electric SCR100	Infrared spectrometer
CO_2 level	**Ventilation system - Supply air duct**	**0 to 2000 ppm**	**For control, repeatability**	**Schneider Electric SCD100**	**Infrared spectrometer**
CO_2 level	Ventilation system - Exhaust air duct	0 to 2000 ppm	For paper II	Schneider Electric SCD100	Infrared spectrometer
Electrical power	**Conditioned space - Variable electrical heater**	**0 to 600 V AC**	**For control, repeatability**	**Schneider Electric PM810**	**Pulse counter**

3.2 Theoretical Framework

The theoretical studies in paper I-III were conducted through network simulations performed in MATLAB® Simulink® with a fixed step-size of 0.6 seconds using standard finite difference first order Euler-Forward method. In this section, only a brief introduction to the models are given, while a more detailed description can be found in the licentiate thesis [35].

In general, the previously described experimental site was used as a reference in the modeling procedure, and even though several more variants were considered during the simulations, the most fundamental features coincide. The simulation platform consists of an HVAC system part and a building part that in turn are made up of a large number of subsystems and components. One-dimensional equations from various previous publications [36-39] were used to describe how the modeled variables varied over the platform, and validated sources were prioritized throughout. The change of CO_2 and temperature over HVAC components or in the building were calculated by physical balance equations while the relations between pressure and flow in the distribution system were based on empirical data.

3.2.1 Building model

The temperature of building elements (BE) such as walls, floor and ceiling were calculated in two nodes located on the inside and outside surfaces. The heat exchange between a certain building element (*i*) and its surroundings was described by two coupled ODEs (Ordinary Differential Equation) on the form presented in *equation 3a*. Temperatures of different building elements were in turn coupled via the room air (*r*) temperature, which was calculated in one node using the ODE in *3b*. The right hand side of this equation consists of terms describing the heat exchange between the room air and the building elements ($\dot{Q}_{BE,i\to r} - \dot{Q}_{r\to BE,i}$), and terms describing the heat emitted by internal disturbances ($\dot{Q}_{D,i\to r}$). Also the CO_2 concentration of the room air was calculated in one node using the mass balance in *equation 3c*. The terms on the right hand side describes the CO_2 exchange between the room and the ambience ($\dot{c}_{\to r} - \dot{c}_{r\to}$) as well as the CO_2 emitted within the room by internal disturbances ($\dot{M}_{D,i\to r}$). A less general form of this equation will be of importance further on in this work and is therefore given in *3d*.

$$\frac{dt_{BE,i}}{d\tau} \times C_{BE,i} = \dot{Q}_{\to BE,i} - \dot{Q}_{BE,i\to} \tag{3a}$$

$$\frac{dt_r}{d\tau} \times C_r = \dot{Q}_{BE,i\to r} - \dot{Q}_{r\to BE,i} + \dot{Q}_{D,i\to r} \tag{3b}$$

$$\frac{dc_r}{d\tau} \times V_r = \dot{c}_{\to r} - \dot{c}_{r\to} + \dot{M}_{D,i\to r} \tag{3c}$$

$$\frac{dc_r}{d\tau} \times V_r = \dot{V}_s \times (c_s - c_r) + \dot{V}_{door} \times (c_{adj} - c_r) + \dot{M}_{CO_2} \tag{3d}$$

3.2.2 HVAC models

As the first level of the experimental site in *figure 11* was replaced by a Dirichlet condition (isothermal boundary) in the computer model, both the second and third level was modeled for full resemblance with a few exceptions.

- First, the second level of the ventilation system was complemented with the missing heat recovery function through a non-hygroscopic thermal wheel between the supply and exhaust air streams. In accordance to common practice in Nordic countries, heat transfer was only allowed from the exhaust to the supply.
- Second, the by-pass, three-way valves for capacity control of air-coils and hydronic terminal units were replaced by two-way valves for a variable flow rate. This choice was made as a simplification, and has no direct influence on the correspondence between experimental and theoretical results.
- Third, in rare cases, the supply air diffusers were complemented with small hot-water connected air-heaters with the ability to increase the temperature above the central AHU setpoint. These were modeled in the same way as the central air heating coil but with lower capacities and sizes.
- Fourth, the fan-coil unit was considered as the only available terminal unit for hydronic heating and cooling, which means that underfloor system was not incorporated as an option in the theoretical studies. This choice was made as a model simplification since the heat transfer between room air and the FCU requires fewer assumptions: since the air flow is forced by the fan, the complete thermal contribution to the room can be allocated to convection at the same time as the capacity flow is proportional to the fan speed.

Remark: The presented, and the simulation framework previously used in the licentiate thesis [35], are identical with a few exceptions regarding changes that were made during the present work. First, latent contributions to the air-conditioning energy were accounted for by increasing the sensible cooling part with 18 %, which according to reference [40] is representative for the considered ambient climate. Second, the maximum efficiency of the heat recovery unit was limited to 80 % with flow dependence up to -20 %, both according to manufacturing data (IV-produkt in Växjö, Sweden). Third, the efficiencies of central fans were set as speed-dependent according to the model provided in reference [36]. Fourth, erroneous transport delays of pressure waves in ducts were removed.

4 GENERAL APPROACH

All appended papers except number II were conducted using the same methodology, in which sequences of office-like activities were applied to office-like environments during 1 to 5 working days. This procedure was repeated as the indoor climate was controlled by a suggested strategy and an equivalent conventional system as benchmark. In some case, an advanced controller alternative was also included to represent the upper boundary of performance with respect to energy savings and maintained comfort.

The appended papers were furthermore expanded to consider the various conditions in *table 3*, and the investigated variants were selected as end-points of a region involving most relevant options of some concerned aspect. Using this approach, the aim was to spread the investigation so that most real scenarios can be found within the range of results.

Table 3. Investigated conditions along with the concerned aspect and its spread.

Conditions	Concerned aspect	Selected end-points
Office site regarding activity and layout	Origin of indoor climate disturbances	Dominating influence from external / internal disturbances
Building structure	Thermal mass	Concrete and steel frame / wooden frame
HVAC system	Extensiveness of ventilation system operation	All-air / hygienic ventilation
Ambient climate	HVAC operation	Heating mode / cooling mode

[shaded] = theoretical studies only

In this chapter, the features of the mutual methodology are presented together with the broadness of the work regarding conditions for which results were produced. The purpose is to provide a general overview, as well as supplementary information to the descriptions that can be found within the respective appended paper. The chapter is structured as follows; each section begins with a general description of a shared element in the methodology. Then, the approach for incorporating this element into the theoretical as well as experimental studies is presented and analyzed.

4.1 Investigated Building Type

Throughout the work, the investigated office environment is represented as of modern type with outside solar shadings and with tight and well insulated envelope. These choices were made for two reasons:

- First, to limit the number of variants included in the study.
- Second, to focus the study on the more problematic internal indoor climate disturbances, by suppressing the influence of external. That is, even though all office sites aren't equipped with the considered technology for mitigating the influence of the ambient climate, common practice provides

the possibility, while internal variations only can be compensated for by the HVAC system.

On the other hand, it is regarded that these aspects does not imply a definite limitation on the validity of the work and that the results also in general can be transferred to other types of office buildings.

4.1.1 Office sites

In both theoretical and experimental studies, the office environment was commonly made up of the two single-zones in *figure 16*. As a height of 2.4 m was considered in both cases, the remaining dimensions and the layouts were chosen to represent a meeting room and an office cell as parts of a bigger building. The larger meeting room and the smaller office cell have floor areas of 18 and 10 m^2, which corresponds to an activity-based design occupancy of 9 and 1 people, respectively [41]. The two sites were also differentiated by their envelopes: while all surfaces in the meeting room were interior; one external wall with a large proportion of windows was considered in the office cell design.

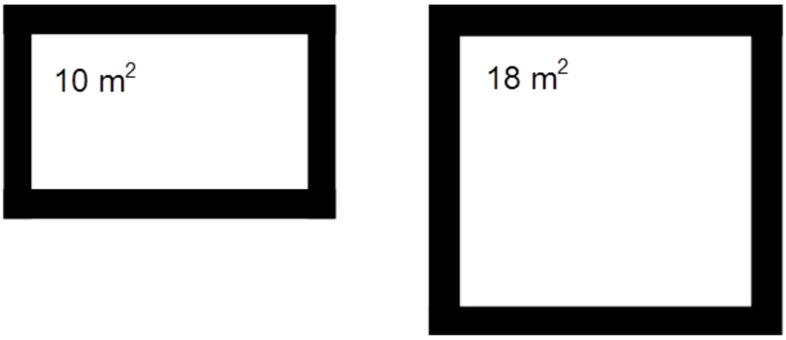

Figure 16. Schematics of the sites that were considered in the mutual methodology; office cell to the left and meeting room to the right.

4.1.2 Theoretical studies

As indicated in *table 3*, the two office environments in *figure 16* were during theoretical studies furthermore considered with a heavy and a light structure, and the overall designs were chosen to fit two criterions. First, to fulfill the condition of modern office building spaces with tight and well insulated envelopes. Second, so that each structure represented an extreme from a thermal characteristic point of view in order to span the work over most real configurations.

All building variants regarding combinations of sites and structures were modeled according to the following four-step procedure:

- In the first step, the mass-balance in *equation 3d* was formulated by plugging in the associated room air volume.
- Second, *equation 3a* was defined for each individual building element (such as walls, floor and ceiling) by assigning material layers of types and dimensions according to *table 4* or *5*. The overall thermal properties (such as internal heat storage and transfer) were then characterized by plugging in the associated material data.

- Third, the entire structure was thermally connected through dynamic heat balances (*eq. 3b*) that were set up between each element and the room air. The dynamic properties of the air were further enhanced by a wooden interior furnishing of 20 kg per m^2 of floor area, whereof 10 % was assumed to be thermally active [36].
- In the final step, thermal boundary conditions were implemented in each direction.
  - The ceilings and floors were set as symmetrical through adiabatic outer layers (zero thermal conductivity).
  - Adjacent internal spaces were represented by constant temperatures, while the external ambience was described by climate data including OAT and solar radiation in different cardinal directions.

Both rooms were also modelled with a 1.25 m^2 door on the right interior wall in *figure 16* by assuming identical materials as the associated building structure. As air could be directly transferred through a door opening, the remaining infiltration flow rate to each room was assigned as insignificant. Moreover, the window part of the office cell was modeled as two-pane with external solar shadings; leading to an overall heat transfer coefficients of 2 W/K and solar reduction factor of 0.12 [42].

Building structures

The two considered building structures in *tables 4* and *5* are based on the archetypes presented by P-E Nilsson [43] as well as some additional manufacturers data [44]. The heavy structure in *table 4* was entirely made of concrete, with additional layers of mineral wool and brick on the external wall of the office cell space. The load-bearing elements of the light structure in *table 5* were in turn made of wood, while the envelope consisted of mineral wool and gypsum with an additional layer of metal sheet on the exterior.

Table 4. Design of heavy building structure. Material layers are listed from inside to out.

Building element	Layer	Material	d [m]	λ [W/(m K)]	ρ [kg/m^3]	c_p [J/(kg K)]
Interior wall	First	Concrete	0.15	1.5	2300	880
Exterior wall	First	Concrete	0.15	1.5	2300	880
	Second	Mineral wool	0.2	0.04	20	750
	Third	Brick	0.15	0.12	1500	800
Ceiling/floor	First	Concrete	0.15	0	2300	880

Table 5. Design of light building structure. Material layers are ordered from inside to out.

Building element	Layer	Material	d [m]	λ [W/(m K)]	ρ [kg/m^3]	c_p [J/(kg K)]
Interior wall	First	Gypsum	0.013	0.22	970	1090
	Second	Mineral wool	0.07	0.04	20	750
	Third	Gypsum	0.013	0.22	970	1090
Exterior wall	First	Gypsum	0.013	0.22	970	1090
	Second	Mineral wool	0.2	0.04	20	750
	Third	Metal sheet	0.002	272	2700	890
Ceiling/floor	First	Gypsum	0.013	0.22	970	1090
	Second	Mineral wool	0.07	0.04	20	750
	Third	Wood	0.044	0	500	2300

Model validation

All considered Simulink® office site models were validated against IDA ICE® which in turn has been tested in the Building Energy Simulation Tests (BESTEST) developed under IEA SHC Tasks 8, 12 and 22.

The procedure is thoroughly described in the licentiate thesis [35], but to summarize, the considered combinations of structures and sites were also modeled in IDA ICE® and indoor air temperature responses were returned for alternating and step-shaped changes of internal heating power. Using these results, the corresponding Simulink® models were trimmed by adjusting the penetration depth (the active thermal mass of the building) and the internal convection coefficient in order to achieve the dynamic and static correspondence presented in *figures 17* and *18*. As a simplification, these two parameters were maintained constant during the investigations while dependency on advection and load intermittency can be expected in reality.

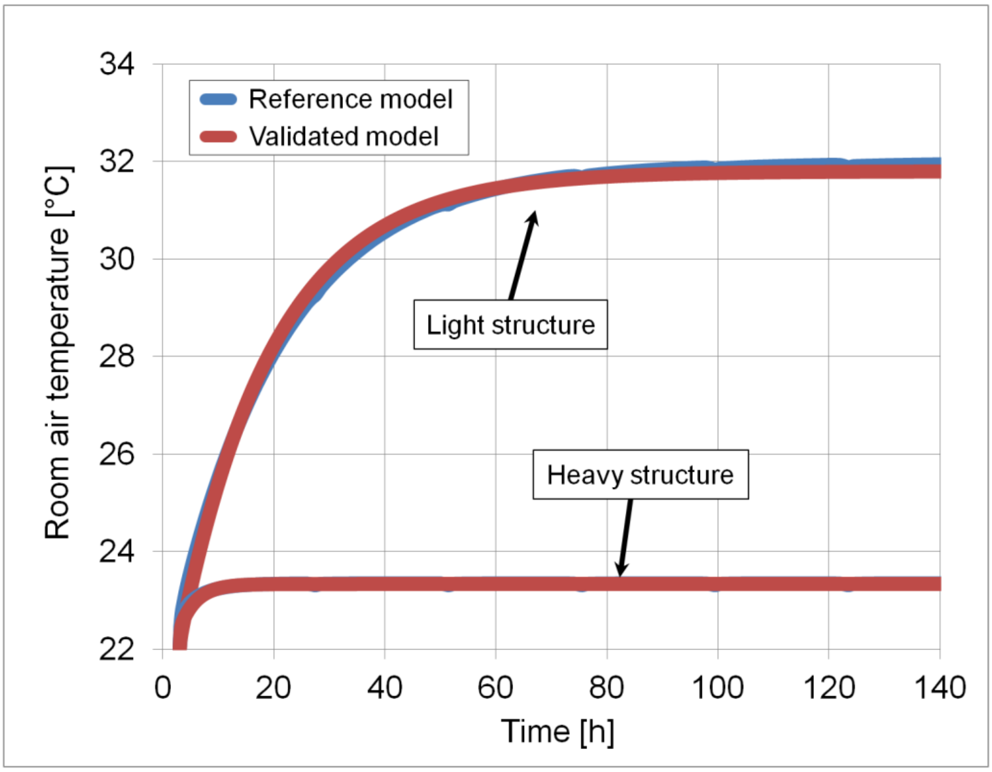

Figure 17. Room air temperature responses to a step in internal heat gain (0-280 W).

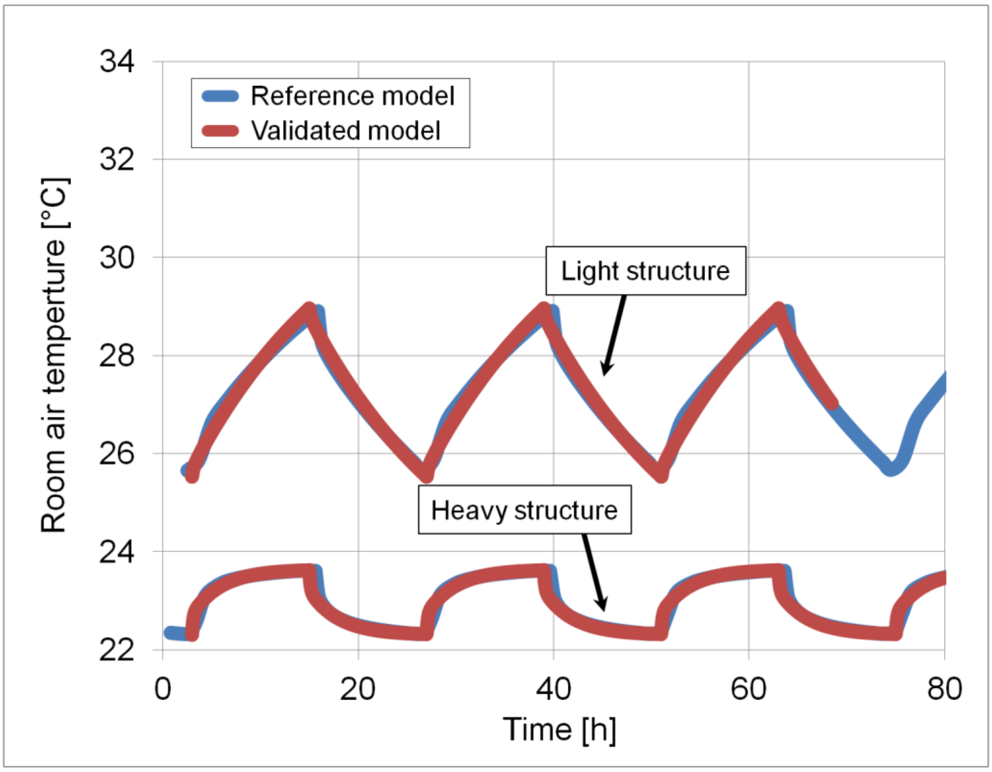

Figure 18. Room air temperature responses to internal heat gain pulses (shifting between 0 and 280 W every 12th hour).

Additional building model parameters

In each space, the ODEs for room air temperature and CO_2 (*eq. 3b* and *3d*) were furthermore afflicted with sensor models that provided two additional functions. First, to account for the inertia of real sensor elements (time-constant), and these were modeled as state-of-the-art using manufacturers data. Second, to account for all types of transport delays due to finite air movement in the spaces, i.e. not only the part associated to the sensors. Total delays of 3 and 5 minutes were assumed in the office cell and meeting room, respectively, and since these were allocated to the sensors, they applied for all convective terms in the balance equations. These assumptions could moreover be confirmed as very accurate in the subsequent experimental studies.

Additional building sites in theoretical studies

In addition to the previously described office room pair, two other building sites were considered in the theoretical parts of the work.

- In paper II, the CO_2 part of the entire seminar room (*see fig. 10*) was modeled by plugging in the total room air volume in the mass-balance of *equation 3d*.
- In paper III, a multi-zone model was used to represent parts of an office building floor consisting of 11 thermally connected rooms. Nine of these were of the same type as the previously described office cell, whereof five were modeled with the external fenestrate wall in a southern direction and the remaining in a northern. While the tenth room was identical to the previously described meeting room, the eleventh was represented by a corridor without external walls and a floor area of 140 m^2. All rooms except the corridor had individual supply and extraction of ventilation air via a duct system, and air could also be directly exchanged between the rooms through open doors via the corridor.

4.1.3 Experimental studies

In accordance to *figure 19*, both the meeting room and the office cell were built inside the seminar room using its ceiling, floor and one of the walls, while the remaining parts of the envelopes were constructed from glued sheets of 10 cm thick Styrofoam. Each space could also be accessed through a door (*fig. 20*) that was added to the right Styrofoam wall in *figure 19*.

The main reason for selecting Styrofoam as material was to represent equivalent thermal resistances as internal walls in office environments. In, turn disparities to other properties of common building materials were regarded as of insignificant influence on the results. In this context, there are primary two aspects that are closely connected to the considered control tasks and therefore need further justification. First, the resemblance to custom material surfaces properties was regarded as of less importance since the operative temperature in the space (and the associated heat radiation contribution) was not considered in the investigation. Second, as the heat storage capacity of Styrofoam is low, the seminar room is partly of concrete and steel. The total thermal mass of the experimental sites is therefore regarded as realistic and somewhere in between the two extremes that were considered during theoretical studies.

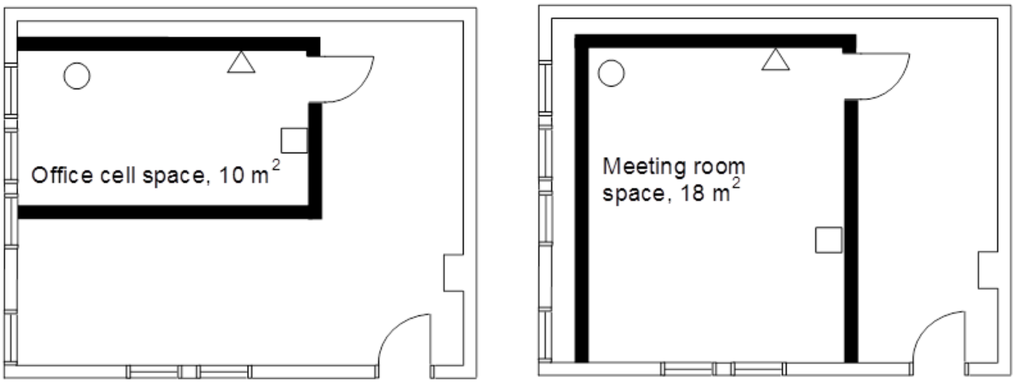

Figure 19. Alignment of the office cell and the meeting room in the seminar room during the experimental studies, respectively.

Figure 20. Photograph illustrating the right temporary Styrofoam wall in figure 19, which was shared by the two considered spaces and had a built-in door.

Preparation

The experimental environments were prepared by shielding the fenestrated wall in the office cell from the outside, and surrounding the meeting room with interior air through sufficient air-gaps next to exterior surfaces.

Each space was also aligned to contain the necessary HVAC equipment including the FCU and a pair of diffusers that were activated by closing the remaining ones using manual dampers. The diffuser pairs were chosen so that most of the conditioned spaces were covered between them, and smoke-gas tests were furthermore conducted to ensure that adequate ventilation was achieved. As smoke was injected close to the supply air part, observations could confirm that the proper mixing and flow directions were achieved in the meeting room as well as in the office cell during both low and high ventilation rates.

Infiltration

To fulfill the condition of modern office sites with tight envelopes, each space was sealed from the ambience using duct tape and strips along all seams, windows and the door. The air leakages were in turn quantified through trace-gas tests in which the ventilation was shut off, CO_2 was momentarily injected to a space and the transient decrease in *figure 21* was observed. In the next step, the duration of the test (τ_n), the ambient concentration (c_s), the volume of the space (V) and the CO_2 decline ($c_r(\tau_n) - c_r(\tau)$) were plugged into *equation 4b*, which is a rewritten version of *equation 4a* (*equation 3d* on analytical form). From these calculations, it was found that the infiltration rate to meeting room and office cell corresponded to approximately 2.5 (0.2 ACH) and 3 l/s (0.5 ACH), respectively.

$$c_r(\tau_n) = c_s + \frac{\dot{M}}{\dot{V}} - \left(c_s + \frac{\dot{M}}{\dot{V}} - c_r(\tau)\right) \times e^{-\frac{\dot{V}(\tau)}{V}\cdot\tau_n} \qquad \text{[ppm]} \qquad (4a)$$

$$\dot{V}(\tau) = \frac{V}{\tau_n} \times \left(ln\left(c_r(\tau) - c_s\right) - ln\left(c_r(\tau_n) - c_s\right)\right) \qquad [\mathrm{m^3/s}] \qquad (4b)$$

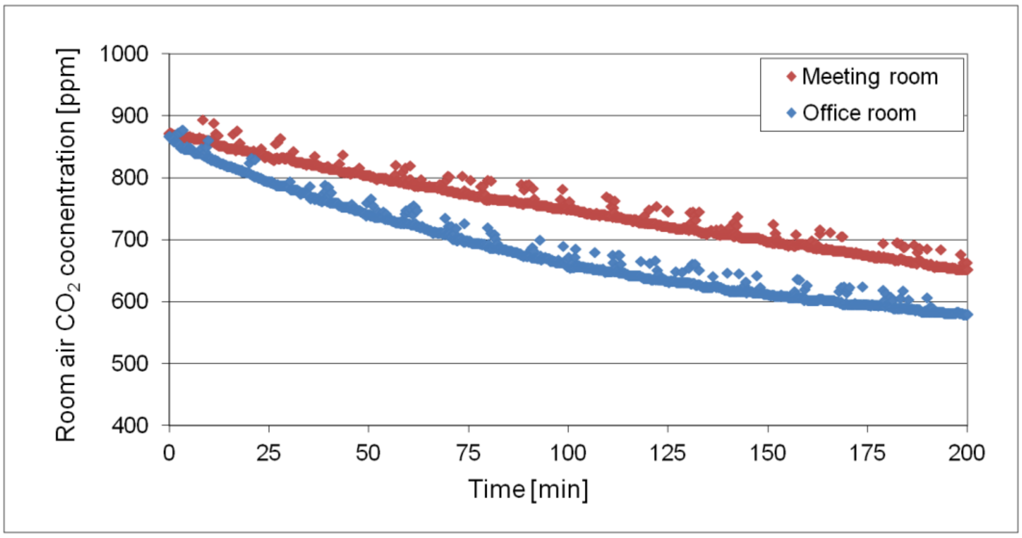

Figure 21. Transient CO_2 decrease in the respective site during periods without any sources or ventilation.

4.2 Office Activities

In the mutual approach, internal disturbances connected to office-like activities were re-created in sequences with durations between 1 and 5 working days. These were applied to the considered office environments and the same conditions were repeated with a conventional and a suggested system for indoor climate control. In several studies, also an advanced alternative was included to represent the upper boundary of performance with respect to energy savings combined with a maintained comfort.

Most of the re-created office activities are based on the work by M.Maripuu [27], in which motion sensors were used to indicate occupancy in 58 cellular office rooms of a Swedish administrative University building. Annual measurements were then statistically condensed into the maximum, minimum and mean occupancy factors of the entire building as functions of clock time. In turn, these results were used in two ways to formulate the occupancy patterns that were considered during both experimental and theoretical studies.

- First, to divide the working days in the office cell and the meeting room between nominally occupied and vacant periods.
- Second, to allocate a number of people to each occupied session in the meeting room (leading to occupancy factors between 30 and 70 % in the resulting sequence).

Close to identical occupancy sequences were used for theoretical and experimental studies, with the exception that the working day was scaled down during **experiments** for practical reasons. Separate sequences were further formulated for lighting and equipment, and both were assumed to be dependent on occupancy. According to SS-EN 12464-1 [45], lighting was represented as a heat emission of 10 W per m^2 of floor area that was ON during occupied periods and OFF during vacancy. The equipment part in the meeting room was consistently represented with 50 W of heat per occupant, and as a computer of 100 W in the office cell that runs all day but is turned off outside office hours. Finally, the door to the meeting room was consistently closed, while open for approximately one hour during the afternoon in the office cell.

4.2.1 Theoretical studies

The modeling procedure for implementing office activities during simulations was focused on describing the interconnection between disturbances and controlled variables (room air temperature and CO_2).

The heat emissions in *table 6* concerned occupants of 70 W each, lighting, equipment as well as air infiltration through an open door, and were divided into parts transferred via radiation and convection, respectively [46]. The convective part was then modeled with a direct affect on the room air while the radiative part first was transferred to the building structure. In turn, CO_2 emissions solely concerned occupants of 18 l/h each, while an open door both could act as a sink or a gain depended on the associated temperature and CO_2 gradients. Both of these disturbances were further described as evenly distributed and perfectly mixed with the room air, which means that a CO_2 event occurred everywhere at the same time while engaging the entire inertia of the space.

Table 6. Modelled office activities with respect to heat transferred to the room via convection and radiation, respectively.

	Convective part [-]	Radiative part [-]
Lighting	0.67	0.33
Equipment	0.85	0.15
Occupants	0.52	0.48
Open door	1	0

4.2.2 Experimental studies

During the experiments, both lighting and equipment were imitated with an electrical panel radiator inside the conditioned space as illustrated in *figure 22*. Its thermostatic control was deactivated and the electrical supply was passed through the variable resistance in the foreground. The heating power output was measured for a number of resistance settings from which the regression in *figure 23* was formulated, and later used during each trial to set the combined heat emission level of lighting and equipment as provided by their associated sequences.

Figure 22. Disturbance sources during experimental studies. Additionally, a temporary wall of Styrofoam can be seen in the background.

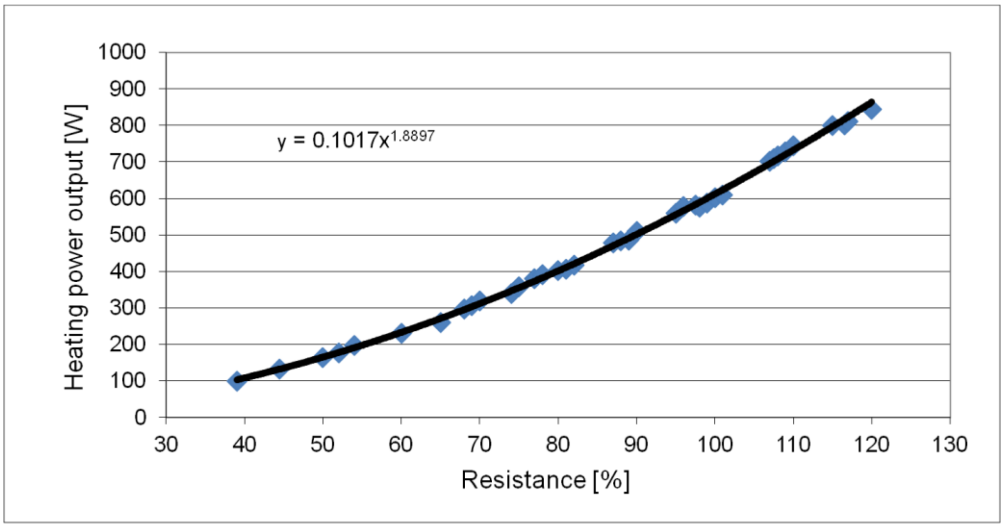

Figure 23. Measured relation between variable resistance setting and heating power output from the electrical panel radiator.

The occupancy sequences were in turn imitated by burning candles that were lit and blown out manually during occupied and vacant periods, respectively. The selected type was confirmed to have close simultaneous correspondences to the heat and CO_2 emissions of an office worker as presented in *figures 24* and *25*, respectively. These results were produced in a confined space of Styrofoam, by measuring and comparing temperature and CO_2 responses for one burning candle and one person[1] performing light office activities, such as reading and writing on a computer. Both scenarios were repeated for similar ambient conditions and with balanced ventilation of 30 l/s and 21 °C while only considering conditioned outdoor air in the supply.

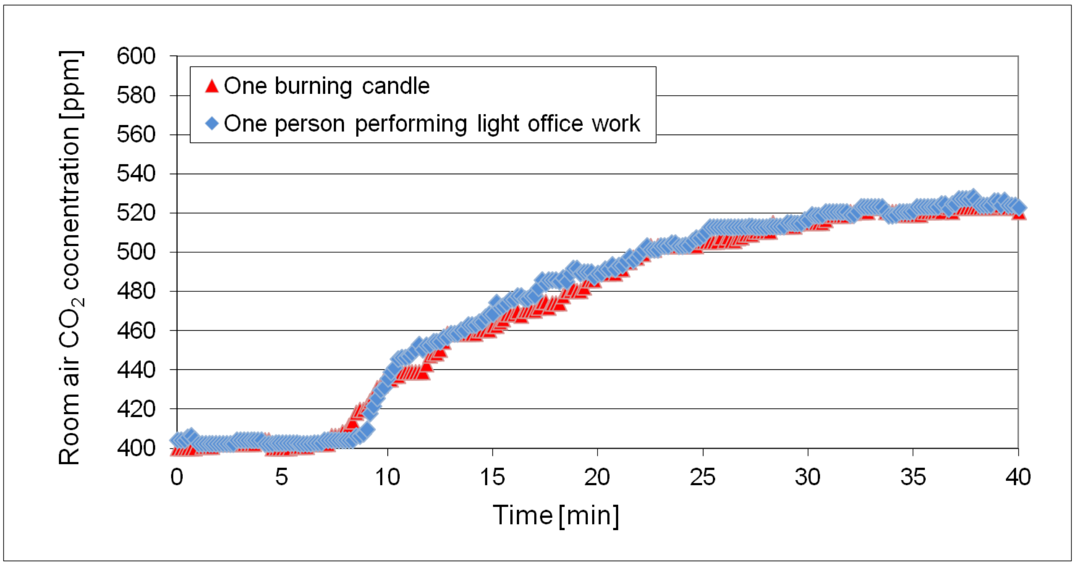

Figure 25. Correspondence between heat emission from one burning candle and one office worker indicated by comparing measurements of the respective temperature rise in a confined space.

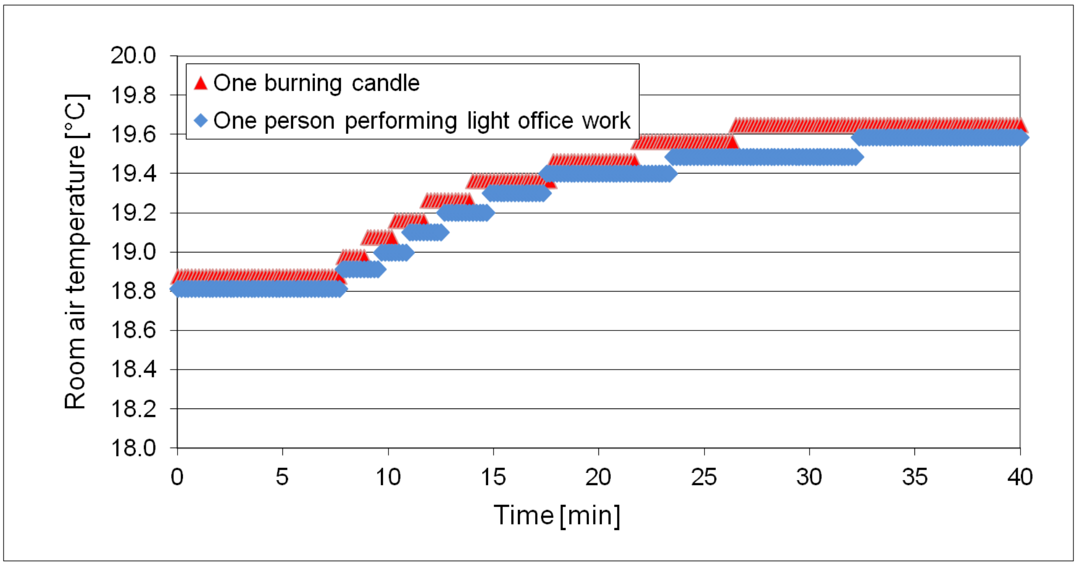

Figure 24. Correspondence between CO_2 emission from one burning candle and one office worker indicated by comparing measurements of the respective concentration rise in a confined space.

[1] The author himself: male, age of 33, approximate weight of 70 kg, approximate height of 170 cm.

Placing of test equipment

In each space, the experimental equipment including candles, electrical heater and room air sensors for CO_2 and temperature, was equivalently placed along a straight hypothetical line between the active pair of supply and exhaust air diffuser (see *fig. 26*).

The disturbance sources were placed in the centre of the line (with equal distance to the diffusers) to maximize their propagation in the space. In turn, the sensors were installed without protective cover in the free air on tripods. In accordance to the nation standard AFS 2009:2 [47], these were placed at least 2 m from the disturbances on their exhaust-diffuser-side to avoid the measurements to be directly influenced by walls, the supply air stream or the disturbances. The vertical sensor positions were in turn selected using the BBR19 comfort zone in which indoor climate constraints are valid and regions close to floor, ceiling and walls are excluded [41]. The temperature sensor was placed in the middle of the zone (1.05 m from the floor), to avoid regions with higher or lower temperatures than the average, and the CO_2 sensor at the maximum height (2 m from the floor) where the highest concentrations were expected.

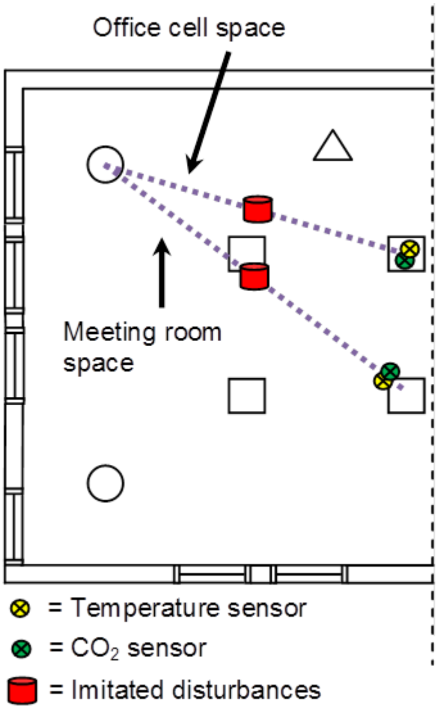

Figure 26. Outline of experimental setup. In each space, the sensors and equipment for imitating disturbances were equivalently placed along a straight hypothetical line between the active pair of air diffuser.

4.3 External Climate Variants and Duration

The individual parts of the work stretched over time-periods between 1 and 5 office working days and were, whenever relevant, repeated for ambient conditions of Swedish summer and winter seasons.

In the **theoretical studies**, both seasons were modeled using climate data from the coastal city of Helsingborg which has a mild tempered climate and an annual average OAT of 8.2 °C. The considered data involved hourly values of OAT as well as diffusive and direct solar radiation on south- and north-facing vertical surfaces from a reference year between 1961 and 1990.

The **experimental studies** were conducted during one calendar year, and while the meeting room trials were carried out without taking the ambient conditions into account (due to its minimal impact on the indoor climate), the parts involving the office cell were repeated during the summer and winter months (June to August, respectively December to February). The combined effect of relatively small internal heat gains, and OATs between -10 and +20 °C, enabled the experiments to span over scenarios when the HVAC system operated in heating as well as cooling modes.

4.4 Overall Conditions

To summarize, the meeting room was designed without any external walls which means that the ambient conditions had no direct influence on the indoor climate. On the other hand, the internal disturbances were occasionally large since the respective occupancy sequence exclusively contained more than one person at the time. In the office cell, the proportions were the complete opposite due to the external fenestrated wall in combination with a design-occupancy of one person. Hence, each space represents its own extreme regarding the dominating origin of indoor climate disturbances, and these choices were made to span the results from the investigation so that most relevant configurations of the same aspect can be found within the range.

4.5 HVAC System Variants

Both experimental and theoretical studies were repeated with two HVAC systems variants for temperature and CO_2 control in the considered office sites. The systems are based on the general structure that was described in the resource chapter 3, and in this section, the same terminology is used to review their active components, their purposes and how they were operated during the investigations.

The schematics of the considered HVAC systems are presented in *figure 27*, and both were configured and operated according to state-of-the-art practice regarding performance and automation possibilities. In this part of the work, they are referred to type A as an all-air variant, and to type B, with hygienic ventilation as well as hydronic heating and cooling. In other words, as the ventilation system was used to manage all functions related to indoor climate control in system A, only the CO_2 part was air-based in system B. Hence, each system represents its own extreme, with an extensive and minimal use of the ventilation system respectively, and these choices were made to span the results from the investigation so that most relevant configurations of the same aspect can be found within the range.

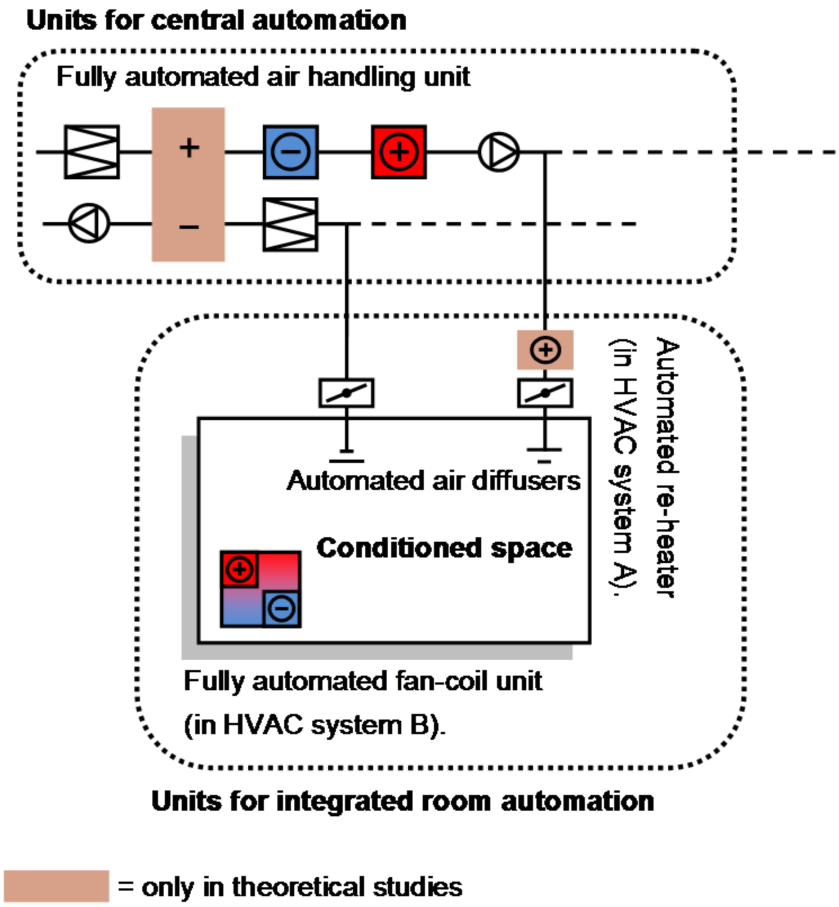

Figure 27. Schematics of the two HVAC systems A and B that were considered in the investigation.

First system level

The first generation level from *figure 11* in chapter 3 was not system specific and identical variants were considered for HVAC system A and B. During **simulations**, this level was represented by isothermal boundary conditions, which means that heating and cooling carriers of constant temperatures were available at any rate.

During **experiments**, on the other hand, three scenarios were possible depending on the resulting indoor climate disturbances that were acting on the seminar room.

- During cooling mode, a combined heat pump/chiller was used to lower the temperature in a water-tank to about 10 °C at the same time as the condenser heat was rejected by a dry-cooler.
- If both heating and cooling were involved (e.g. comfort cooling together with heating of supply air), the condenser heat was instead stored in a second tank and the temperature was increased to about 50 °C by the electrical boiler.
- During heating mode, hot water of about 50 °C was generated by the electrical boiler.

Second system level

Remember from chapter 3 that the distinction between HVAC components for ventilation and hydronic heating/cooling became evident in the second system level from *figure 11*. When applied to the two considered HVAC systems, hydronic heating/cooling was only considered in system B, while their second level ventilation parts were close to identical while slightly different variants were considered during experimental and theoretical studies.

The considered air-handling unit arrangements are presented in *table 7* (cf. *figure 15)*, and as HVAC system A and B shared the same components and associated control routines, the total flow resistance was adapted (with model parameters during **simulations** and dampers during **experiments**) to fulfill a national requirement of a maximum SFP (Specific Fan Power) of 2 during maximum ventilation rate [41]. Moreover, differences between experimental and theoretical studies refer to the additional heat recovery option during simulations as well as to the considered type of air-coil actuators.

Table 7. Summary of components for central air-handling. Both HVAC systems in the investigation used the same kinds but the flow resistances were adjusted to achieve a maximum SFP of 2.

Central components	Description	Control arrangement	
		Theoretical studies	Experimental studies
Heat recovery unit	Rotating non-hygroscopic wheel between supply and exhaust air. Maximum temperature efficiency of 0.8. First actuator in sequence for supply air temperature control.	Variable speed drive of wheel motor.	N.A.
Air-heater	**Air-coil with supply air on one side and hot water on the other. Second actuator in sequence for supply air temperature control.**	**Two-way control valve for variable water flow rate.**	**By-pass, three-way valve for variable water inlet temperature.**
Air-cooler	Air-coil with supply air on one side and cold water on the other. Third actuator in sequence for supply air temperature control.	Two-way control valve for variable water flow rate.	By-pass, three-way valve for variable water inlet temperature.
Supply air fan	**Axial fan for transportation of supply air. Flow controlled, tracks the control signals to the supply air diffusers.**	**Variable speed drive.**	**Variable speed drive.**
Exhaust air fan	Axial fan for transportation of exhaust air. Flow controlled, tracks the control signals to the supply air diffusers.	Variable speed drive.	Variable speed drive.

The air-conditioning components were throughout used for supply air temperature control and were operated according to the sequence in *figure 28* for a reduced energy usage. The general order was: heat recovery unit, air-heater and air-cooler, whereof the heat recovery unit only was included in theoretical studies. As the same setpoint were used for all components, the one(s) of higher order could only be actuated if the one(s) of lower order were deactivated.

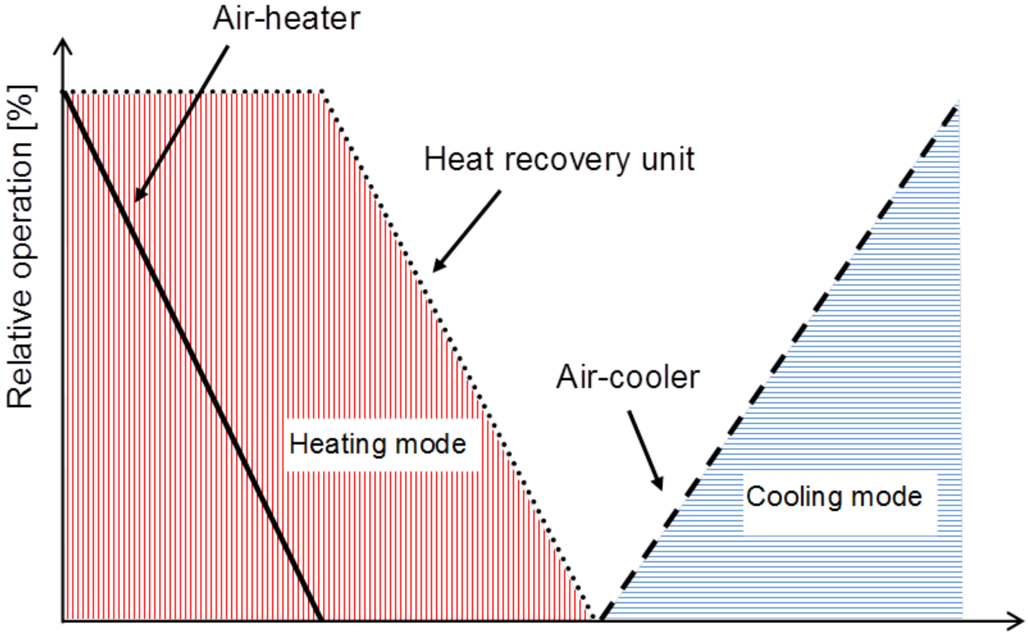

Figure 28. Considered control sequence for central air-conditioning. The heat recovery unit was only considered in theoretical studies.

The ventilation air was furthermore entirely made up of conditioned outdoor air, with a constant CO_2 level of 400 ppm in the **theoretical** studies, and with **experimental** variations similar to the example presented in *figure 29*. Finally, the central fans were operated to supply the amount requested for integrated room automation, and to extract the same for a maintained balance.

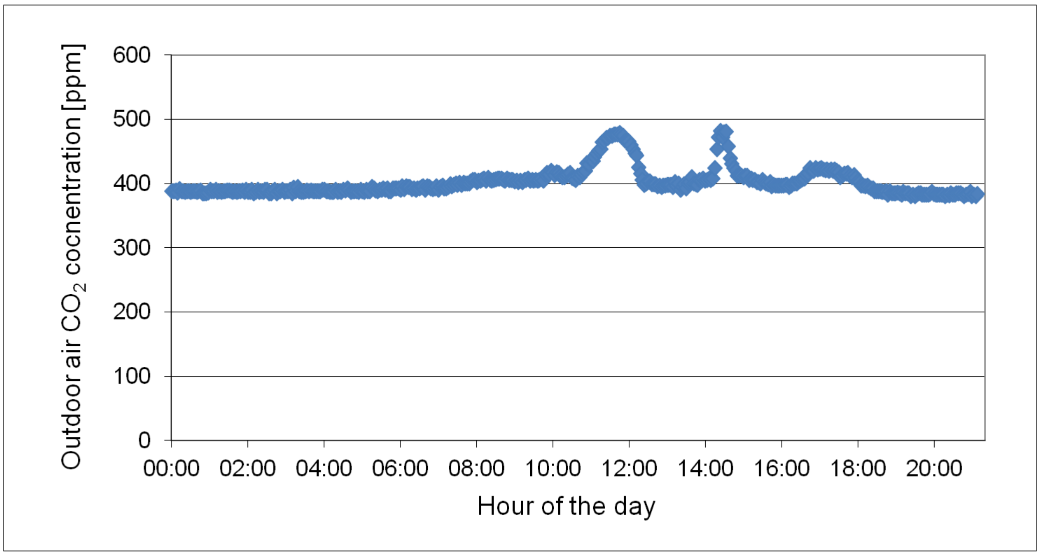

Figure 29. Typical variations in outdoor air CO_2 concentration as observed during the experiments: fairly constant levels during night and evening, but momentary traffic induced rises during morning and afternoon.

Third system level

HVAC system A and B were mainly differentiated by their third level components for integrated room automation as presented in *table 8* for theoretical and experimental studies. In system A, ventilation rate automation was employed for room air temperature control, while a desirable CO_2 level was ensured by assigning minimum levels depending on the design-occupancy of the conditioned space in question. The supply air temperature was primary determined on a central level, but in the **theoretically** considered multi-zone site (see section 4.1.2) each room was further equipped with a re-heater to cover local heat deficits. In this configuration, the control routine "dual maximum" which is thoroughly described in paper III was selected for sequential operation.

In type B, ventilation rate automation was instead employed for CO_2 control, and the admissible range was set in compliance to national recommendations [41] between zero and (7 l/s × design number of people) + (0.35 l/s × floor area). The SAT was entirely determined centrally, while temperature control was managed by a hydronic (water-based) system with a fan-coil as terminal unit (FCU). Thus, heating or cooling was provided by circulating room air on one side and hot or cold water on the other, while slightly different operational routines were chosen in the experimental and simulation parts:

- In order for the heated or cooled air to propagate sufficiently during **experiments** while avoiding direct influence on room sensors, the FCU air-outlets were in accordance to *figure 26* restricted to the left and bottom sides.
- Second, since the exact same conditions could be re-created during the **simulations**, the most intuitive approach of automating the thermal power by modulating the fan-speed was chosen. At the same time, the temperature of the circulated air was maintained constant by a valve control on the water side. However, due to different ambient conditions during **experiments**, such strategy would lead to inconsistent fan operation. In turn, each experiment would be associated to unique and unknown transport-delay variations in the conditioned space, which mean that the investigation would be non-repeatable. This was solved by instead maintaining a constant fan operation to promote a continuous dissipation in the room, while the thermal power was automated by modulating the water inlet temperature by the bypass, three-way valve (see CV in *figure 12*).

Table 8. Summary of terminal (on room level) HVAC components considered in the investigation for integrated room automation.

Local component	HVAC system	Simulated office building floor (paper III)	Simulated office rooms (paper I, II)	Experimental office environments (paper II, IV, V, VI)
Ceiling-mounted fan-coil unit (FCU) for heating and cooling of recirculated room air.	A	N.A.	N.A.	N.A.
	B	Actuator for room air temperature. Air-side: variable speed drive of fan. Water-side: automatic on/off valves for hot or cold water. Control valve for constant outlet air temperature.	Actuator for room air temperature. Air-side: variable speed drive of fan. Water-side: manual on/off valves for hot or cold water. Control valve for constant outlet air temperature.	Actuator for room air temperature. Air-side: constant fan speed. Water-side: manual on/off valves for hot or cold water. By-pass, three-way valve for inlet temperature control.
Re-heater (RH) for heating of supply air above the central air-handling setpoint.	A	Actuator for room air temperature. Valve control for variable flow on water-side. Controlled in sequence with supply air diffuser.	N.A.	N.A.
	B	N.A.	N.A.	N.A.
Ceiling mounted supply air diffuser for mixing ventilation with automated opening.	A	Actuator for room air temperature. Controlled in sequence with the re-heater.	Actuator for room air temperature.	Actuator for room air temperature.
	B	Actuator for room air CO_2 concentration.	Actuator for room air CO_2 concentration.	Actuator for room air CO_2 concentration.
Ceiling mounted exhaust air diffuser for mixing ventilation.	A	Actuator for balanced ventilation. Automated opening.	Actuator for balanced ventilation. Automated opening.	Not controllable (balanced ventilation via the central fan).
	B	Actuator for balanced ventilation. Automated opening.	Actuator for balanced ventilation. Automated opening.	Not controllable (balanced ventilation via the central fan).

5 EVALUATION METHOD

All appended papers focused on evaluating suggested control strategies during periods when a desirable indoor climate is of utmost importance. For that reason, the individual studies primary addressed office hours, and the indoor climate aspects was taken into account by applying fixed comfort constraints. Furthermore, whenever night-time periods are included, no additional control related energy efficiency measures were applied (such as temperature setback or recirculation of exhaust air).

5.1 Evaluated Control Functions

Considered the cascade-arranged controller structure in *figure 30*, with an external input (from the left) consisting of process information regarding states of controlled variables, internal/external disturbances etc. The purpose of the first controller is to transform these inputs to internal setpoints, representing HVAC system counteractions such as increased/decreased heating, cooling and/or ventilation. In turn, the final realization into physical actions is managed by the second controller by comparing actuator outputs to the setpoints from the first controller.

In this work, all addressed control functions are allocated to the first controller. That is, the purpose of the suggested control strategies and the benchmarks is to indirectly determine the operation of central and local HVAC components by generating their setpoint. This procedure was chosen since while the second controller manages the actuator and the associated sensor, the remaining aspects of the control task is accounted for by the first controller; including properties of the process from where information is gathered. Hence, the first controller stands for the unique and dominating contributions on all imaginable scales, and represents the part for which improvements with an overall impact are possible.

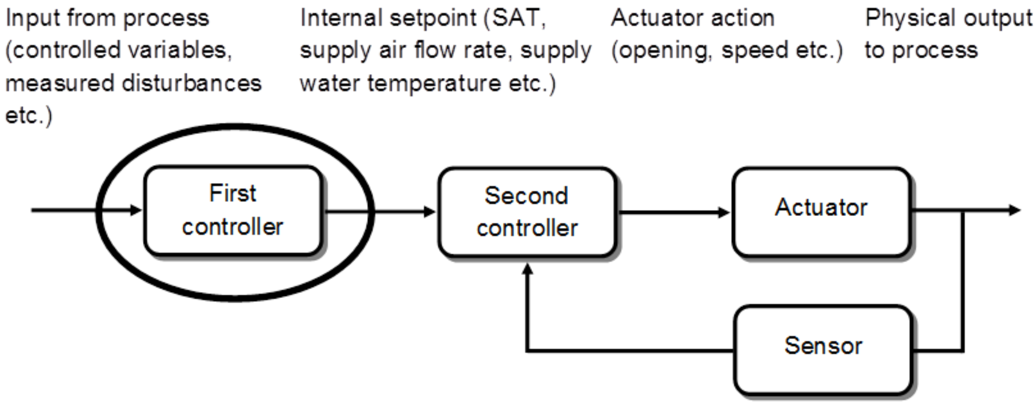

Figure 30. Schematic picture of the addressed control function. All suggested and benchmark strategies were applied to the first controller in a cascade alignment. The second controller was throughout made up of conventional feed-back controller.

5.1.1 Feed-back controller design

Common feed-back controllers are throughout considered for various tasks in this work.

- First, independent on if the first controller in *figure 30* is made up a benchmark or a suggested strategy, the second is a feed-back.
- Second, also the first controller is of feed-back type when considered as benchmark for an integrated room automation task.
- Third, most of the suggested strategies are complemented by a supporting feed-back function, either in parallel with some type of control model with additional process information, or by integrating these two functions.

Tuning procedure

Throughout the work, the considered feed-back controllers are of PI-type with parameter settings according to the AMIGO [48] tuning method. This is not the most common method in practice, but was chosen as a step in achieving state-of-the-art benchmarks and to provide supporting functions that does not hinder suggested strategies.

AMIGO has been derived through a large number of optimization processes and approximately return control parameter combinations for a minimized setpoint deviation. It is based on a step-response approach, which means that the tuning procedure began by manually applying an instantaneous control signal change. From the response of the controlled variable, a number of characteristic values were identified and inserted into an empirical function from which the static gain and integral-time were calculated.

The procedure provides a linearization of the process between the initial and final level of the applied control signal. The commonly non-linear characteristics of HVAC and building systems were addressed by dividing the considered control signal range into incremental steps of 10 % for which the procedure was carried out individually. Among the resulting set of parameters, the combination with the smallest static gain was selected in order to avoid instabilities in the whole operational region.

Feed-back sensors

State-of-the-art feed-back controllers are also facilitated through desirable properties of sensors in the loops. The **theoretical studies** involve sensors that were modeled without any measurement uncertainties, and the transport-delay between process inputs and sensor outputs was set as the lowest values provided through experiments or previous studies [27].

During the setup for **experimental studies**, the placing of stationary sensors in the HVAC system (e.g. in the distribution systems, air-handling unit, hot and cold water generation units, terminal units etc.) was inspected and multiple available options allowed for deciding on the most preferable locations with respect to fast responses and low influences from ambient factors. The sensors in the office sites are instead mobile, and fast responses were promoted by installing uncovered elements in the free air. Smoke-gas tests were moreover used to visualize the general air-movement to ensure that regions of stratification or low ventilation efficiencies were avoided as far as possible.

5.1.2 Realization of suggested strategies

Based on measured thermal disturbances, some of the proposed control strategies for integrated room automation anticipated a heat surplus or deficit in the conditioned space. This information was in turn sent as a setpoint to the second controller (*fig. 30*) to be realized in a terminal unit through the actuator. Hence, the second controller required the ability to affect the actual heating/cooling power through a single controlled variable in a closed-loop fashion. This was achieved by adding an additional model along with the sensor in *figure 30*, and since all internal variables were known during **simulations,** simple energy balance could then be employed.

During **experiments**, supply and room air temperature measurements were used to specify *equation 5a* over the supply air diffuser in HVAC system A (air-based heating and cooling), and the anticipated heat surplus or deficit was realized by assigning the corresponding supply air flow rate.

A similar approach during **experiments** with HVAC system B (hydronic heating and cooling) was prevented by less available measurement points and the selected control arrangement. Instead, a series of pre-processing steps were applied to formulate an expression between the FCU power output and the water-inlet temperature (t_{w1}). The procedure began by setting up the correspondence to *equation 5a* over the FCU air-side (*equation 5b*), by assuming an identical temperature at the air-inlet (t_{a1}) as measured in the room (t_r). In the remaining steps, a relationship between the temperatures at the water-inlet and the air-outlet was formulated through the temperature efficiencies on each side.

- First, a certain opening of the three-way valve was assigned and the temperature efficiency on the water-side (*equation 5c*) was determined under stationary conditions. Since this metric is flow depend and the valve caused some variations, a number of values over the opening range was returned.
- Second, the corresponding temperature efficiency on the air-side (*equation 5d*) was determined by plugging in data from the previous step.
- Third, the relation to the outlet air-temperature was stated with *equation 5e,* which completed the FCU power to be predicted through the water-inlet temperature through *equation 5b*.

$$\dot{Q}_{vent} = \dot{V}_s \times \rho_a \times c_{p,a} \times (t_s - t_r) \quad [W] \quad (5a)$$

$$\dot{Q}_{FCU} = \dot{V}_{a,FCU} \times \rho_a \times c_{p,a} \times (t_{a2} - t_r) \quad [W] \quad (5b)$$

$$\eta_{t,w} = \frac{t_{w2} - t_{w1}}{t_{a1} - t_{w1}} \quad [-] \quad (5c)$$

$$\eta_{t,a} = \frac{\eta_{t,w} \times \rho_w \times c_{p,w} \times \dot{V}_w}{\rho_a \times c_{p,a} \times \dot{V}_a} \quad [-] \quad (5d)$$

$$\eta_{t,a} = \frac{t_{a2} - t_{a1}}{t_{w1} - t_{a1}} \quad [-] \quad (5e)$$

5.2 Performance Metrics

This chapter ends by describing the general methodology for comparing controllers, and while already covered in several of the appended papers, the feature of being one of the most important elements in this work justifies repetition. Remember that the research objective is focused on control strategies that are sufficiently simple and efficient to be realistic alternatives to commonly-used BAS technologies. For that reason, suggested control strategies are first and foremost evaluated against conventional methods as benchmarks, i.e.

- PI feed-back controllers for integrated room automation (see sections 2.2.2 and 5.1.1),
- OAT-compensation for central SAT control (see section 2.2.1).

The evaluation method is based on the two most important aspects of an HVAC system and the associated BAS: indoor climate is to be kept within given comfort ranges, by preferably using as little energy as possible. Conversion into a method was achieved by formulating two comfort criterions (one each for IAQ and thermal climate), and constraining their fulfillment within feasible limits through setpoint adjustments of compared controllers. At the same time, the associated HVAC energy usages were introduced as performance metrics, which means that controllers are compared on equal grounds: i.e. what energy usage can be expected if the primary function of a desirable indoor climate already has been fulfilled. Moreover, any differences in comfort that could be expected in real situation are thereby translated into energy quantities.

In the following text, the two comfort constraints are first presented together with the indoor climate standards and guidelines from which they derive, and the chapter then ends with a description of the associated performance metrics.

5.2.1 Indoor climate constraints

Indoor air quality constraint

IAQ was indicated by the room air CO_2 concentration (c_r) and the associated comfort constraint is presented in *equation 6*. It states that the level was not allowed to cross an absolute boundary of 1000 ppm, either when a suggested strategy or the associated benchmark was employed. This constraint is based on several national recommendations such as AFS 2009:2 [47] and SOSFS 1999:25 [49] as well as the ASHRAE standard 62-1989 [50] (similar in 62-2007 [51]).

$$\hat{c}_{r,suggested} = \hat{c}_{r,benchmark} = 1000 \qquad \text{[ppm]} \qquad (6)$$

An important remark in this context is that CO_2 itself is not considered as harmful until in concentrations way above 1000 ppm (5000 in Sweden). On the other hand, the CO_2 level in buildings correlates to human metabolic activity and is therefore commonly used to indicate the perceived IAQ. The purpose of the metric is hence to maintain acceptable concentrations of other emissions that derive from occupancy (such as bio affluences and body odor) and 1000 ppm has shown to be an appropriate level for this purpose [52].

Thermal climate constraint

In accordance to the European standard EN-15251 [53], thermal comfort was indicated by the deviating degree hours above and below a thermally neutral room air temperature region in which variations have no negative influence on the perceived climate. In turn, similar comfort associated to a suggested strategy and its benchmark was proclaimed by constraining equality of this metric during occupied periods in accordance to *equation 7*, while drifts were allowed during vacancy without any penalties.

The neutral room air temperature (t_r) region was set between 21 and 22 °C in accordance to current standards and recommendations. The first end-point is equivalent to the lowest allowed temperature in occupied office rooms according to a national guideline [54]. The second end-point addresses in turn transients, and in this case, associated standards typically distinguish between different kinds of room air temperature changes. In ISO 7730:2005 [55], drifts or ramps are restricted by a maximum rate of 2 K/h until thermal comfort is decreased, and similar recommendations are also given in ASHRAE standard 55-2004 [56]. But due to the time-dependence, the outcome of this metric is hard to fore-cast which means that control related implementation is more or less unrealistic. Instead, a peak-to-peak temperature cycle restriction was employed, and in accordance to ISO 7730:2005, the second end-point was set 1 K above the first since smaller amplitudes do not have a negative influence on the thermal comfort. This choice is further supported by the finding of a comprehensive literature review presented by Hensen [57], which states that there is no evidence to why the restrictions on cyclic variations should not apply to drifts and ramps as well. Hence, all types of room air temperature changes are according to this statement accounted for by the selected criterion.

$$\begin{cases} \left(\sum \Delta t_{high}\big|_{\infty,0} \times time\right)_{Suggested} \approx \left(\sum \Delta t_{high}\big|_{\infty,0} \times time\right)_{Benchmark} \\ \left(\sum \Delta t_{low}\big|_{\infty,0} \times time\right)_{Suggested} \approx \left(\sum \Delta t_{low}\big|_{\infty,0} \times time\right)_{Benchmark} \end{cases} \quad [°Ch] \qquad (7)$$

Provided that the space is occupied

Where

$$\begin{cases} \Delta t_{high} = t_r - 22 \\ \Delta t_{low} = 21 - t_r \end{cases}$$

Remark 1: The temperature comfort region was implemented as a theoretical tool for enabling similar thermal climate in the comparison between suggested and benchmark control strategies. Several practical aspects were not in accordance with this scope and were therefore omitted in the methodology.

- First, it can be assumed that thermal comfort most definitely is preserved within the selected room air temperature region since it was formed from stringent requirements. But, it is important to acknowledge that the associated end-points are narrower than typically applies in most real situations.
- Second, the neutral comfort region was maintained within fixed temperatures throughout the investigation, while seasonal dependent shifts usually are implemented in reality; i.e. the entire comfort region is

commonly moved upwards during summer and downwards during winter. In practice however, such shift applies first and foremost to the upper boundary, regarding that higher temperatures are allowed before cooling is actuated during summer (due to adaptation of occupants). The lower boundary is at the same time fixed, which means that heating is not actuated until the temperature has dropped below a minimum level which is similar during summer and winter. Thus, since the upper boundary in this work was set based on transient conditions, such approach was hence not applicable.

- Third, seasonal dependent comfort regions were moreover omitted to increase the investigation transparency. That is, to be able to state definite conclusions regarding different scenarios, the influence of each condition (e.g. summer/winter, HVAC system A/B etc.) was isolated by minimizing uncertainties regarding other underlying effects.

Remark 2: It is worth pointing out that a more common metric in this context is the PMV-PPD [58], on which several thermal climate categorization schemes are based, e.g. classes A-C in ISO 7730:2005. It was formulated using principles of heat balance and experimental data under steady-state conditions, such as constant temperatures of air and surfaces. However, due to time-lag associated to thermal adaptation of occupants, even small temperature changes during transient conditions can lead to discomfort, which means that PMV-PPD then no longer apply.

5.2.2 HVAC energy indicators

Throughout the investigation, different control strategies are compared using the associated HVAC system energy usage as performance metric. However, due to the available amount of data, different indicators are employed for experimental and theoretical studies.

Theoretical studies

In the theoretical studies, the simulated energy usages associated to central and local HVAC components were determined by calculating the instantaneous heating, cooling and electrical power for every time-step, and integrating these variables over time. The individual terms were then combined using *equation 8* which is weighted according to the European Energy Efficiency Directive 2006/32/EG [59].

$$E_{total} = \left|Q_{total,thermal}\right| + \left(W_{total,electrical} \times 2.5\right) \qquad \text{[kWh]} \qquad (8)$$

Experimental studies

In the experimental studies, working days with a suggested strategy and the associated benchmark for indoor climate control were re-created during separate occasions. Hence, identical conditions could not be guaranteed, even though the exact same procedure was followed every time, and a maximum mean OAT difference of 2 °C was allowed between trials. For that reason, the energy associated to ventilation and to the FCU (HVAC system type B) were indicated by the supply air flow rate and the calculated heat change on the water-side (*equation 9*), respectively.

These two indicators were chosen due to their small dependence on potential variations between trials, at the same time as the main bulk of energy records were accounted for. In the FCU indicator, only site dependent parts, such as distribution losses and efficiencies regarding the generation of heating and cooling carriers, were neglected. Further, since equal and constant SAT setpoints were used during all experiments with compared outcomes, the ventilation indicator is directly proportional to the air-handling energy. At the same time, the indicators prevented the results to be influenced by outdoor climate dependent air-handling energy and by operational dependent efficiencies due to unequal controller setpoints (for fulfilling the comfort constraints).

$$\dot{Q}_{FCU} = \left| \dot{V}_w \times \rho_w \times c_{p,w} \times (t_{in} - t_{out}) \right| \quad \text{[W]} \qquad (9)$$

6 APPENDED PAPERS IN SHORT

In this chapter, the six journal papers that constitute the foundation of this work are briefly described while their full versions are included in the appendix. Remember that the papers deal with seemingly diverse aspects of the research topic, such as standard sensor technologies for an increased measurability of exogenous inputs, simplified control models for automating local and central parts of HVAC systems, as well as systematic analysis to reduce the overall amount of parameters, inputs and outputs. But, the overall procedure follows a holistic approach in which each paper has its own specific purpose in the whole, and where the next part takes on where previous left off. Altogether, most important aspects regarding realistic energy efficient indoor climate control are covered, and the work is spread over most relevant conditions and system variants.

Further remember that the work was conducted through theoretical simulations and experiments in a laboratory facility. In accordance to the previously presented *table 1*, paper I and III are solely based on simulated results, papers IV-VI on experiments and paper II on a combination of both. Finally, as paper III deals with central SAT control for VAV ventilation systems, the rest are focused on integrated room automation tasks due to many more practical issues that needed to be resolved.

Paper I: Model-based controllers for indoor climate control in office buildings – complexity and performance evaluation

In paper I, a model-based controller for integrated room automation was considered as base-line for deriving a simplified strategy. A large number of measures for a reduced complexity, and with a limited impact on control performance, were evaluated through simulations of the meeting room and office cell.

The investigation is spread over a variety of internal and external conditions, and was conducted through the three-step procedure illustrated in *figure 31* (for a detailed description, turn to reference [35]). First, a total number of four simplified control models were proposed and evaluated against two complex versions. Second, the number of exogenous inputs was systematically reduced by identifying the disturbances with the largest contribution to control performance. Third, the most promising outcomes from step one and two were combined to constitute a final controller design.

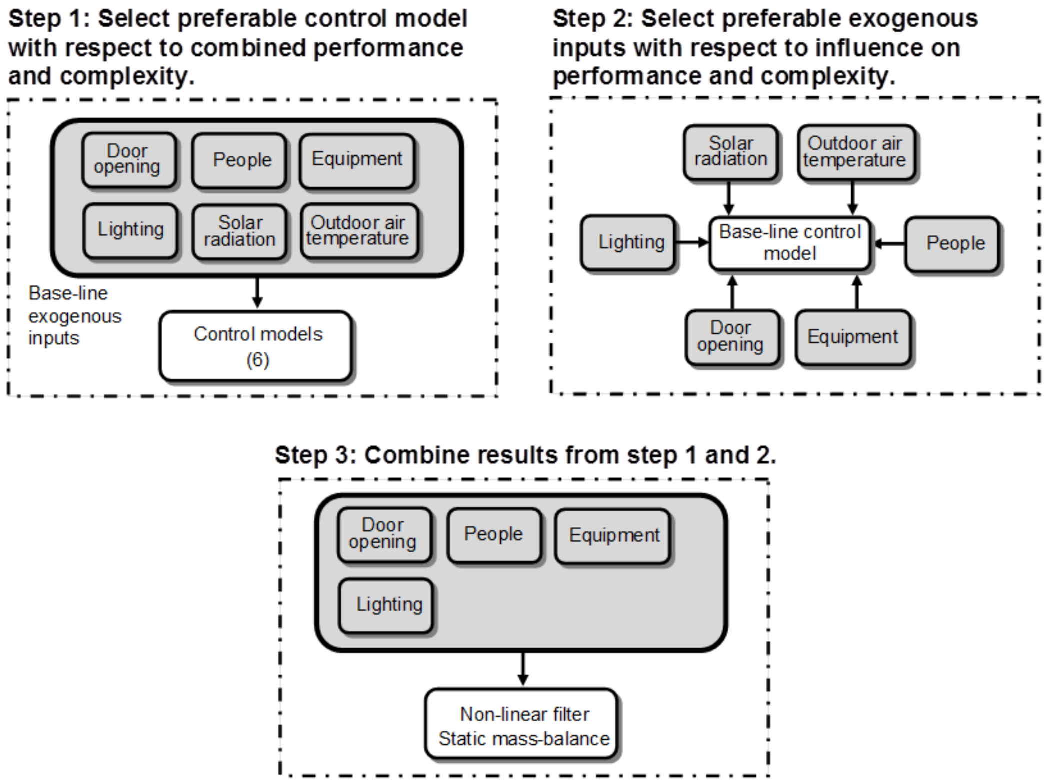

Figure 31. Illustrated procedure of paper I.

Resulting controller design

Compared to the base-line, the final outcome was a drastically simplified strategy which has figured in all other appended papers except number III. In the process of reducing the number of exogenous inputs, the individual and combinatorial gain among the available options were studied and a clear distinction was found between disturbances of external and internal origins. Conclusively, information about ambient conditions was omitted since the associated performance contribution was too small to justify the required number of exogenous inputs and control model parameters. Instead, the exogenous inputs were limited to internal disturbances made up of equipment, lighting, door opening and occupancy.

The control model of the suggested strategy was divided in two parts with only one parameter in total; a non-linear filter for temperature control and a static mass-balance for CO_2 control. Moreover, each part was also supported by its own feed-back controller to compensate for unmeasured disturbances etc. When it comes to the non-linear filter, the exogenous inputs were formed as the sum of measured thermal disturbances expressed in heat emission units (W). This signal was in turn scaled to the output (control signals) using the present room air temperature as an indicator for the required heating/cooling in order to remain inside the comfort region. Hence, instead of involving a process representation in the control model, the present state was used to determine the transformation of exogenous inputs into control signals. The static mass-balance for CO_2 control consisted of *equation 3d* in which the right hand side was set as equal to zero. The CO_2 gains and sinks associate to occupancy and an open door were used as inputs while the equation returned the required flow rate to remain below 1000 ppm.

Altogether, the controller was designed to suite the previously stated control problem (together with the implied condition of a low complexity): i.e. to maintain a desirable indoor climate according to the considered comfort constraints while using as little energy as possible (see section 5.2). For this task, present control was prioritized through generation of short-term actions for maintaining the comfort boundaries even under heavily shifting internal disturbances. Thus, the possibility of performing predictions over a time-horizon was omitted, together with the associate possibility of optimal control.

Paper II: CO_2 sensors for occupancy estimations: potential in building automation applications

According to paper I, it is sufficient to only account for the most common internal disturbances for indoor climate control in modern office buildings. This rationalization alone simplified the design of both disturbance sensing system and control model considerably (since less information needed to be processed), and paper II deals with the consecutive step of achieving an overall low complexity by suggesting simple ways of retrieving this information.

While detailed information about lighting and equipment can be gathered using standard sensor technology (e.g. wire-less power meters in the electricity outlets), the main source of complexity derives from returning information about the number of occupants. In this case, there are no accurate and simple methods available, but given the frames of this work, the information is important to account for since the occupancy density in office buildings is high, and its influence on the thermal climate and IAQ is large. In single-person office spaces, PIR (passive infrared) motion sensors are typically cheap and sufficient, but the expected error grows in rooms with a higher design-number of occupants.

Suggested occupancy estimation method

The problem of retrieving occupancy for integrated room automation in multi-person office spaces was addressed in this paper by evaluating an estimation method based on CO_2 responses. Basically, as people enters a confined space, the CO_2 level start to rise. The rate-of-change is furthermore dependent on the source strength which means that the gradient can be used to return an estimation of the occupant increase. The obvious advantage of the method is that both the associated sensor and the required signal processing are simple and easy to implement. CO_2 is furthermore an appropriate indicator for the number of people in office building since there are no other disturbances that affect the level to the same extent. However, the feasibility of the method may be limited by response delays of CO_2 sensors, and potential uncertainties in the relationship between sensor responses and the number of people (i.e. estimation errors are possible).

The aim of paper II was to determine the influences of potential limitations by combining experiments and simulations in two consecutive steps. In the first step, the estimation method was tested in the seminar room to determine the expected time-delay and error under various conditions. In the second step, an equivalent site was simulated and two types of model-based controllers with information about occupancy were considered for a CO_2 control task. One was a robust but complex MPC with a receding prediction horizon (see section 2.2.4) and the other was the simplified model-based controller from paper I. Each controller was individually evaluated by documenting the loss of performance with respect to setpoint deviation as the exogenous input was subjected to various time-delays or estimation errors. The results are presented in *figures 32-33*, and conclusively, both controllers had similar or equal performances for small errors and delays. But for the experimentally derived quantities and above, a high level of performance could only be maintained by the robust controller (MPC).

So, the initial problem was not resolved in this paper. It was concluded that a high control performance could either be maintained by accurate and fast occupancy estimations, or by a complex controller. But the overall complexity was neither way reduced to a satisfying level. This issue was once again addressed in paper number VI by turning to an alternative signal processing method for motion sensor responses.

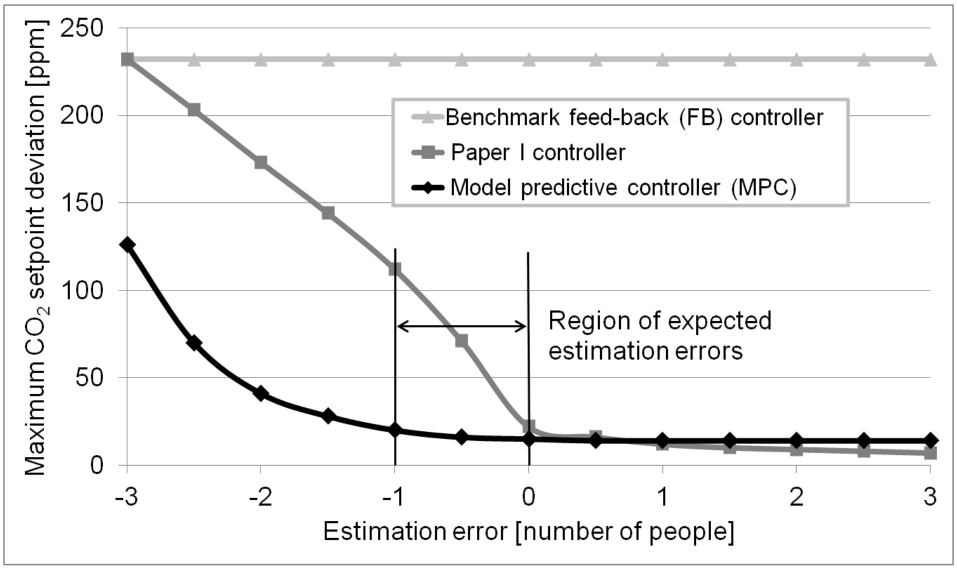

Figure 32. Influence of occupancy estimation error when the information is used by various model-based controllers for CO_2 control. The expected quantity which was derived in the experimental part is marked out.

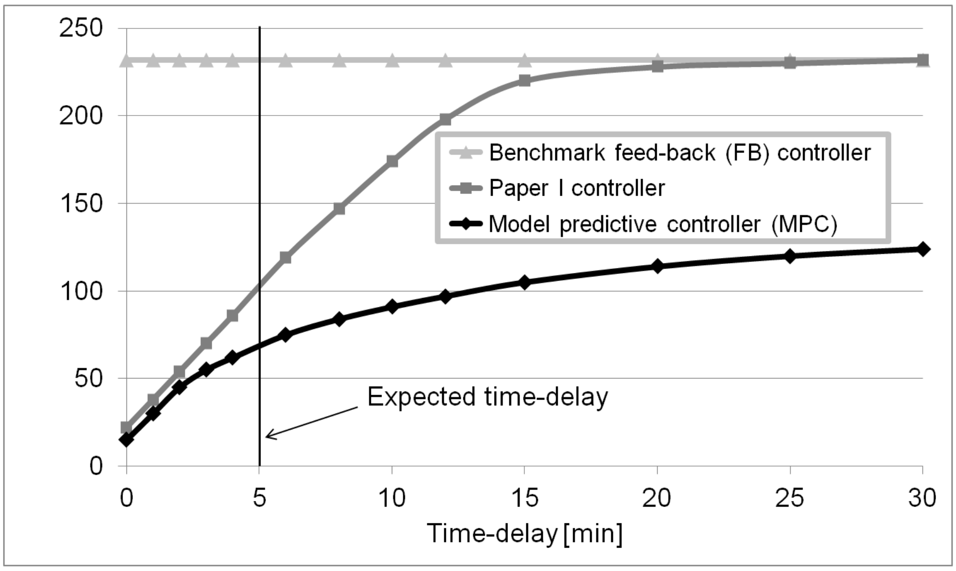

Figure 33. Influence of time-delay associated to occupancy estimations when the information is used by various model-based controllers for CO_2 control. The expected quantity which was derived in the experimental part is marked out.

Paper III: Alternative strategies for supply air temperature control in office buildings

This paper deals with central supply air temperature (SAT) control in office buildings, and four strategies were compared to a conventional OAT-compensation with a linear structure according to *equation 10* (k_1 and k_2 are constants). The investigation was conducted by simulating light and heavy structured multi-zone sites (floor plane with 11 rooms, see section 4.1.2) for two working weeks of Swedish summer and winter respectively. All evaluated strategies have an open-loop structure and were individually considered for generating SAT setpoints for central air-handling. The indoor climate was in turn directly controlled by terminal units in each zone and the study was repeated for both of the considered HVAC system variants (previously referred to as type A and B). In this paper, the indoor climate constrains for overall similar comfort at zone level were relaxed since an energy penalty explicitly follows from a central SAT control that does not synchronies with the integrated room automation system. Instead, identical room air temperature and CO_2 setpoints were maintained throughout the study, and these were chosen with respect to the comfort considerations described in section 5.2.1.

The core of the investigation consists of three suggested low-complexity strategies that are structured in the same way as the OAT-compensation in *equation 10*. That is, the SAT setpoints (y_{ts}) were generated through some single input (u) in a linear manner. But instead of considering the ambient climate, the inputs to the suggested strategies intended to reflect the activities inside the building through the number of occupied rooms, the amount of heating supplied by terminal units or the average room air temperatures. Furthermore, these inputs were chosen so that the associated information could be gathered using standard sensor technology in HVAC applications.

$$y_{t_s} = k_1 \times u + k_2 \qquad [°C] \qquad (10)$$

The final strategy out of the four was optimal with respect to a low energy usage and a maintained indoor climate. The heuristic solver Genetic algorithm was used to find optimal SAT setpoints for all considered variants of weather season, building structures, HVAC systems and activity levels. Its purpose in the investigation was twofold. First, to serve as an upper boundary of possible energy savings. Second, the solutions (see *fig. 34*) were examined for patterns that could be used to formulate simplified strategies with less input data. In HVAC system B, this task was succeeded, and the outcome was a strategy as simple as the OAT-compensated but way more effective for achieving a desirable indoor climate using less energy.

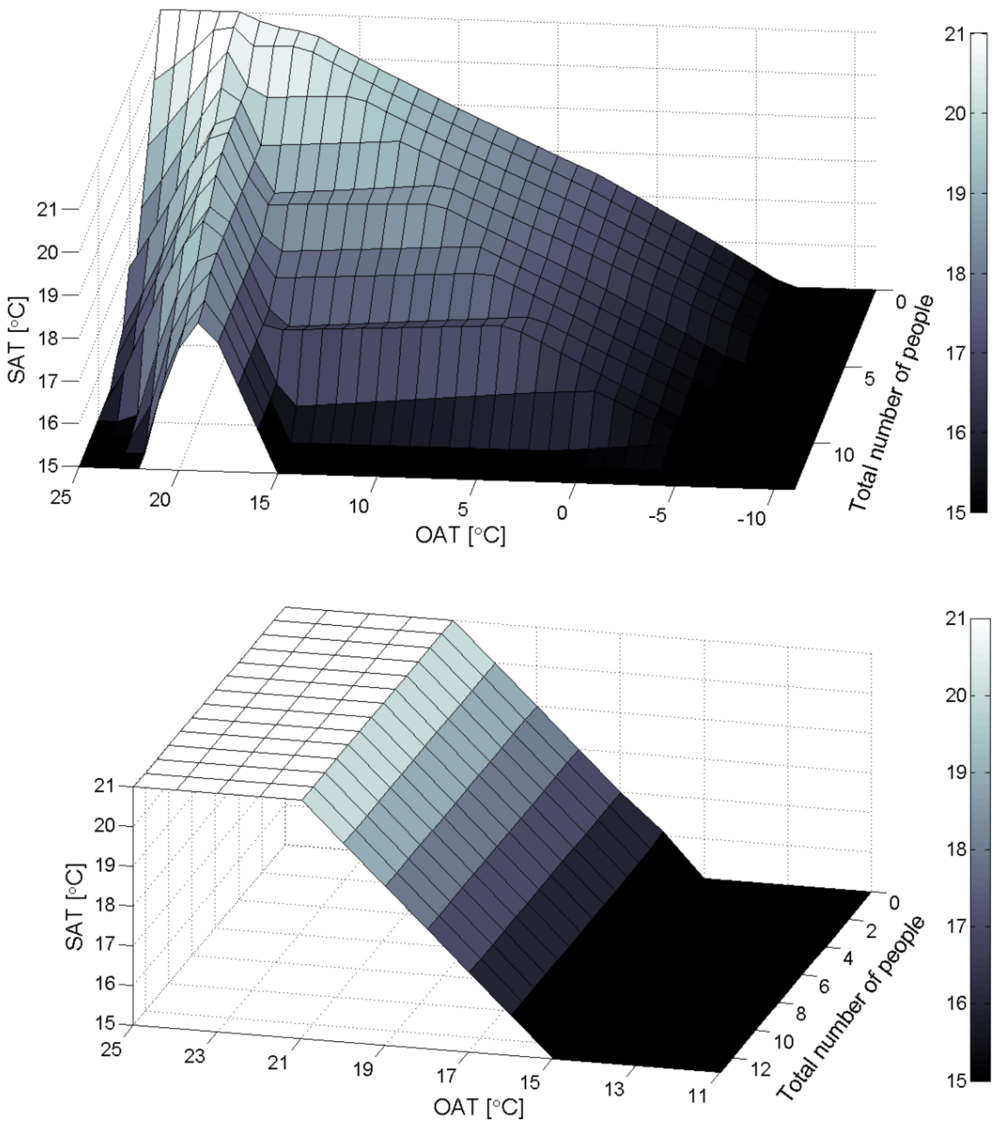

Figure 34. Optimal supply air temperature (SAT) setpoint as a function of external and internal disturbances. The upper part is for HVAC system A (all-air), and the lower is for HVAC system B (hydronic heating/cooling and hygienic ventilation).

Paper IV and V: Energy efficient climate control in office buildings without giving up implementability, and, Combining performance and implementability of model-based controllers for indoor climate control in office environments

These two papers are of common nature since both present experimental studies that aimed to answer the intermediate and hypothetical question: what is the value of providing perfect information about occupancy, lighting and equipment to the controller for integrated room automation that was derived in paper I?

The experiments stretched over one calendar year and were conducted in both the meeting room and office cell spaces, whereof the latter were repeated during both winter and summer ambient conditions. The controller was evaluated for indoor climate control with respect to temperature and CO_2 during the re-created working days while feed-back controllers were used as benchmarks. As paper IV focused on HVAC system A, paper V focused on B, and examples of associated results are presented in *figures 35* and *36*, respectively. In both papers, the controller was used for automating the terminal units, i.e. the supply air diffuser and the FCU, while the central conditions, i.e. the supply temperatures of air and water, were operated on constant levels set to meet the conditions at room level.

In accordance to the scope of these two papers, the imitated sequences of internal disturbances were directly provided as information to the paper I controller and no time-delay or errors associated to a hypothetical disturbance sensing system were accounted for. Considering such ideal conditions, the results were intended to represent the upper performance boundary of the controller and thereby reflect its theoretical potential.

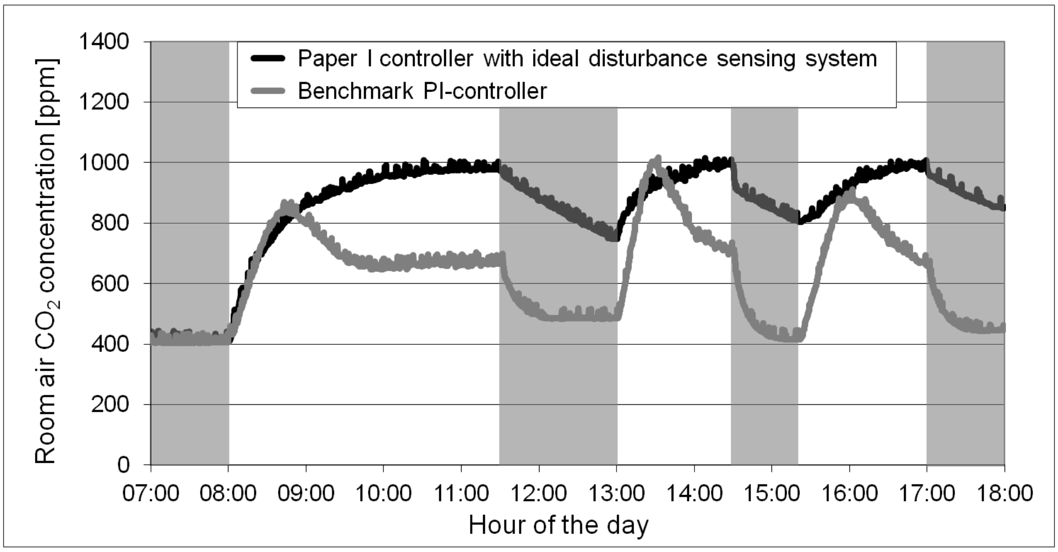

Figure 35. Example of the CO_2 control task during the re-created working day in the meeting room space (comfort constraint of concentration below 1000 ppm). The controller from paper I has perfect information about internal disturbances and the benchmark is a feed-back. Vacant periods are marked in grey.

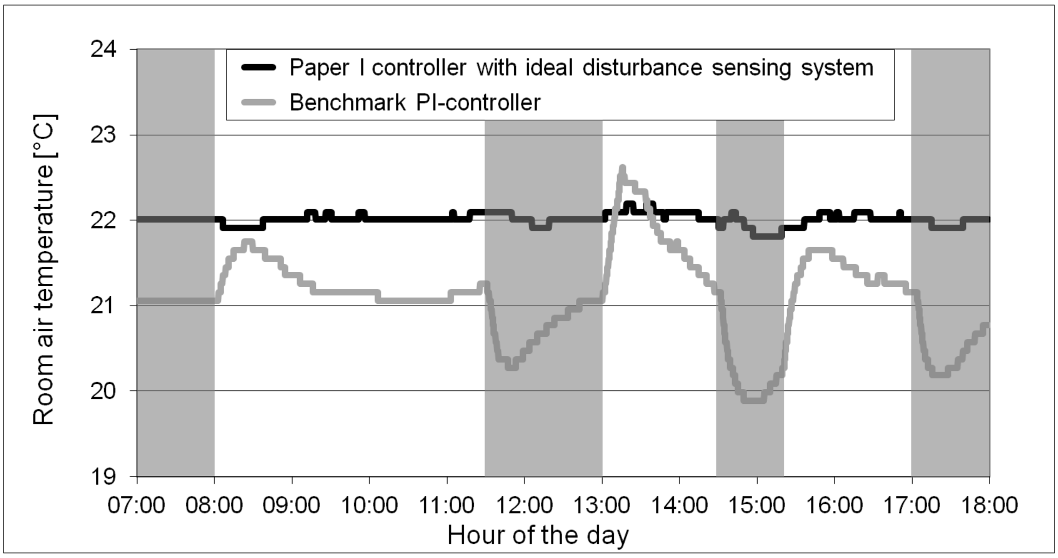

Figure 36. Example of the temperature control task during the re-created working day in the meeting room space (comfort constraint of equal degree hours outside a neutral region between 21-22 °C). The controller from paper I has perfect information about internal disturbances and the benchmark is a feed-back. Vacant periods are marked in grey.

Paper VI: Motion sensors for ventilation system control in office buildings

As paper IV and V presents intermediate experimental investigations of the controller from paper I, the progress is continued in paper VI by taking the implementability aspect even further and virtually removing all complexity inducing elements of its design. This was done by considering the disturbance sensing system entirely with standard HVAC sensors for gathering information about equipment, lighting and occupancy. The most problematic aspect of this arrangement is the lack of simple and accurate methods for accounting the occupancy part in spaces where the number of present people varies (as in the meeting room site in this work). As paper II previously investigated the possibility estimating the number of people from CO_2 responses without finding any definite solution, paper VI focuses instead on a method for processing motion sensor responses so that a large share of counteractions for occupancy induced disturbances are allocated to the control model.

Procedure

The experiments of paper VI were as previously conducted by re-creating a typical working day, but the exogenous inputs were now further divided in two sets regarding signal processing approach.

- Since equipment and lighting (electrical power) can be measured both accurately and fast using standard sensor technologies, these sequences were provided directly to the non-linear filter from paper I.
- The motion sensor responses (i.e. occupied or vacant space) were in turn processed by an additional control model part denoted as a memory function. The main idea was to save and transfer the control signal residues that derived from unmeasured disturbances, (i.e. the part that eventually is quantified and compensated for by the supporting feed-back) from one occupied period to another. In this way, the supporting feed-back only had to compensate for the difference in number of people between consecutive occupied periods while the remaining part was managed by the memory function.

The experiments were limited to the meeting room since multi-person sites are most problematical in this context and a motion sensor can return fairly accurate information in a single-person space. Further, the extended controller structure was solely evaluated for ventilation rate automation, but both for CO_2 and temperature control.

Remark: Since only the meeting room site was considered in this paper, an open door was not involved. In other situations though, the static mass-balance from paper I could furthermore be included to only manage this disturbance.

Examples of results are presented in *figures 37* and *38* for the CO_2 and temperature control tasks, respectively. Compared to providing ideal disturbance information as in paper IV and V (see *figures 35* respectively *36*), the performance regarding accurate and fast control actions was slightly reduced due to an increased share of unmeasured disturbances. But, the overall complexity became significantly lower.

The final idealized element of the suggested strategy for integrated room automation that was not removed in paper VI is motion sensor responses without time-delay. However, this aspect was studied separately in paper II, and by further incorporating these results, all practical aspects regarding energy efficient indoor climate control are hence taken into account.

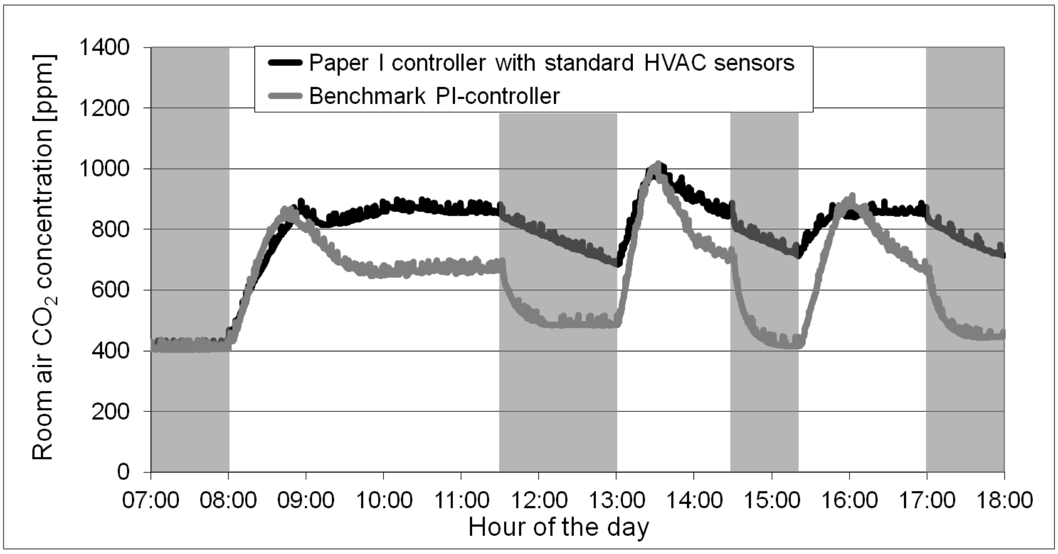

Figure 37. Example of the CO_2 control task during the re-created working day in the meeting room space (comfort constraint of concentration below 1000 ppm). The controller from paper I rely on information from standard HVAC sensors and the benchmark is a feed-back. Vacant periods are marked in grey.

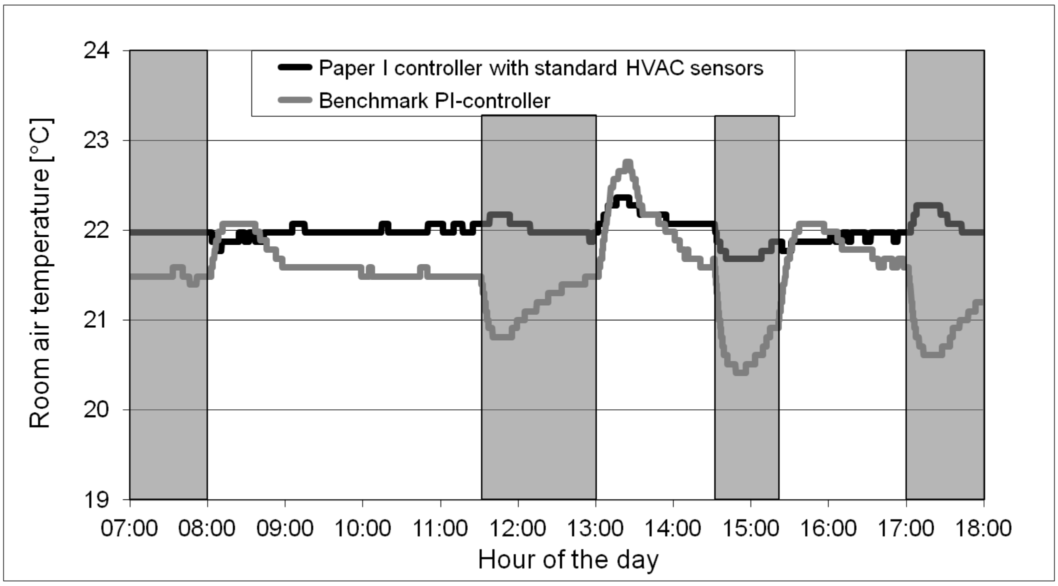

Figure 38. Example of the temperature control task during the re-created working day in the meeting room space (comfort constraint of equal degree hours outside a neutral region between 21-22 °C). The controller from paper I rely on information from standard HVAC sensors and the benchmark is a feed-back. Vacant periods are marked in grey.

7 RESULTS

In this chapter, the results from the appended papers are summarized with respect to their overall aim of achieving energy efficient indoor climate control in office buildings without giving up implementability.

- In the first two sections, the design of the suggested strategy for integrated room automation is reviewed by comparing to the type of model-based controller that constituted the main inspiration to its development process.
- The subsequent section is also devoted to integrated room automation, and here, the potential of the suggested strategy to save energy and improve the indoor climate is presented. This is done by prioritizing comparisons to BAS of common practice (i.e. benchmark feed-back controllers) since benefits over these technologies are regarded as the most important feature next to the implementability aspect.
- In the final part, the attention is instead turned to strategies for central SAT control, where the suggested designs and their energy savings potentials are reviewed.

7.1 Model-based Controller Designs

Although the concept of model-based controllers is quite broad and can include a large variety of different features and designs, the majority of previous publications in the area of building automation considered an MPC type with the general structure presented at the top of *figure 39*, and with signal designations according to *table 9*.

As illustrated, the inputs enter from the left and are mainly of three types: exogenous (*v*), controlled variables (*y*) as well as relevant control signals that derive from other sources than the MPC (*u*). In the most extensive case, the exogenous inputs are made up of the complete set of present and/or prognosticated indoor climate disturbances, and the control model predicts their short- and long-term influences by taking the present states (*y*) and the operation routines of external controllers (*u*) into account. In many cases, control signals are in turn generated by solving a system-wide optimization problem with the objective to fulfill future indoor climate demands while minimizing energy usage (or control signal activity). As illustrated *figure 39*, the result is a total of four outputs that can involve future and present control signals for both local and central parts of the HVAC system.

Besides of an extremely elaborate and extensive disturbance sensing system, this type of controller requires accurate, complete and dynamic models of the controlled spaces and the HVAC system to function properly. In *figure 39*, this aspect is illustrated as additional inputs (*x*) of a large but finite number of model parameter.

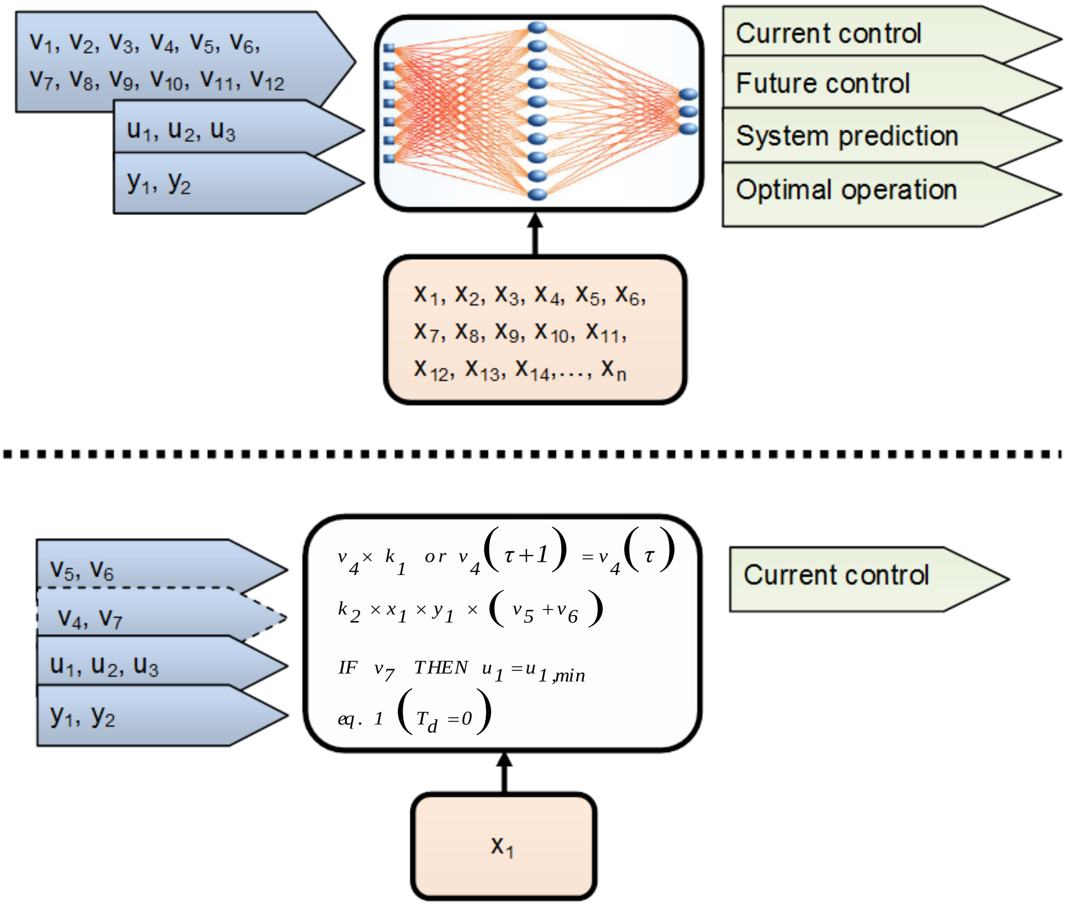

Figure 39. General structures of a typical MPC for building automation (top) and the suggested controller for integrated room automation (bottom). Signal designations according to table 9. k_1 and k_2 are constants.

Table 9. List of common inputs to model-based controllers.

Inputs	Designation	Type	Unit
Infiltration	v_1	External disturbance	l/s
Outdoor air temperature	v_2	External disturbance	°C
Solar radiation	v_3	External disturbance	W/m^2
Occupancy	v_4	Internal disturbance	Number of people
Equipment	v_5	Internal disturbance	W
Lighting	v_6	Internal disturbance	W
Door opening	v_7	Internal disturbance	l/s
Adjacent temperature 1	v_8	Internal disturbance	°C
Adjacent temperature 2	v_9	Internal disturbance	°C
Adjacent temperature 3	v_{10}	Internal disturbance	°C
Adjacent temperature 4	v_{11}	Internal disturbance	°C
Adjacent temperature 5	v_{12}	Internal disturbance	°C
Ventilation flow rate	u_1	HVAC supply	l/s
Heating supply	u_2	HVAC supply	W
Cooling supply	u_3	HVAC supply	W
Room air temperature	y_1	Controlled variable	°C
Room air CO_2 level	y_2	Controlled variable	ppm

7.2 Strategy for Integrated Room Automation

The approach in this work involved a division between local and central control tasks, and in the lower part of *figure 39*, the main structure that was suggested and evaluated for integrated room automation is presented. The design derives from the principle of the model-based controller in the same figure, but both extensiveness and function has been reduced drastically. Furthermore, as the configuration of the model-based controller is highly site-dependent, the suggested control model is universal and similar parameter settings applies to different HVAC systems and building types, which means that commissioning is facilitated.

7.2.1 Control model and number of exogenous inputs

The largest contribution to the development of the suggested strategy in *figure 39* was presented in paper I. Through simulations, three major simplifications of a model-based controller were achieved without any significant reductions in performance.

- First, it was shown that a complete set of exogenous inputs could be reduced to the most common internal disturbances.
- Second, two simplified control models (one each for temperature and CO_2 control) with only one parameter in total (x_1) were proposed together with supporting feed-backs.
- Third, control model extensiveness was further reduced by omitting information about the HVAC system and only considering setpoint generation for terminal units. In turn, a second set of cascade connected feed-back controllers and an additional sensor model were incorporated for a final transformation into actuator compatible signals (as presented in section 5.1).

During the design process in paper I, the function of the suggested strategy was focused on achieving a desirable present indoor climate. As a result, the influences of exogenous inputs are more anticipated than predicted by the control model, which means that the control signals do not stretch further than the present time - even though parts of the controller (CO_2) considered steady-state process conditions as the terminal state.

7.2.2 Disturbance sensing system

The concept from paper I was further developed in paper II and VI with the objective to represent the selected exogenous inputs with signals that in practice are associated to low sensor complexities. Most of the focus was on finding simple ways for estimating or indicating the number of people in the controlled space, and methods based on responses from CO_2 sensors respectively motions sensors were suggested and evaluated. It was found that both methods were sufficient, as long as CO_2 measurements could be retrieved with short time-delays, or if an additional control model was incorporated, respectively.

A simple method for processing the door opening was further proposed in paper I after it was found that the flow of fresh air through an open door was enough to cover the entire ventilation demand; as long as there was a sufficient temperature difference between the controlled space and the other side. The same thing was also observed in the office cell trials during the experimental studies in paper IV and V, and hence, the door opening could in practice be indicated in an equivalent way as occupancy by a motion sensor (open/closed). Instead of calculating the actual influence when open, the ventilation flow could be reduce to a minimum if the requirement of sufficient temperature and CO_2 gradients is fulfilled.

In *figure 39,* these two contributions are illustrated by broken lines around the occupancy and door opening inputs to indicate that simple estimation methods were considered. Finally, only the heat emitted by equipment and lighting remains as directly measured exogenous inputs, and in both cases, standard sensor technologies for a facilitated installation and commissioning are available, e.g. wire-less power meters that can be plugged into the outlet or in the central fuse-box.

7.3 Energy Savings for Integrated Room Automation

In this section, the collective results for integrated room automation are presented. Recall that all of the associated papers (i.e. I, IV-VI) considered the same suggested strategy - but in different configurations, for different HVAC systems and under different conditions. Further recall that the same methodology was applied throughout, in which a typical working day was re-created in office environments and PI feed-back controllers were used as benchmarks. As compared controllers were constrained to fulfill equal comfort according to the metrics in section 5.2.1, their performances were measured by the HVAC energy indicators in section 5.2.2. However, while different indicators were considered in papers associated to experimental and theoretical studies, this section consistently presents the energy savings potential of the suggested strategy in relative ventilation rate and FCU water-side heat transfer.

In *tables 10* and *11*, the results from papers I, IV-VI are summarized for the various conditions and systems that were considered during one working day in the meeting room and office cell sites, respectively. These tables also provide the complete coverage of the investigations, and the delimitation of individual scopes are marked with x:es. **Remark:** the “almost equal” sign in the tables refers to variations associated to building structure variants considered during the theoretical study in paper I.

Table 10. Results associated to the suggested controller for integrated room automation compared to the benchmark. The numeric values are associated to relative savings of ventilation flow and FCU energy during one re-created working day in the office cell site.

HVAC system	Indicated savings [%]	Ambient climate	Paper I (simulations)	Paper IV (experiments)	Paper V (experiments)
A (all-air)	Ventilation flow	Summer	x	14	x
		Winter	x	12	x
B	Hygienic ventilation flow	Summer and winter	13	x	35
	FCU energy	Summer	≈ 1	x	2
		Winter	≈ 2	x	1

Table 11. Results associated to the suggested controller for integrated room automating compared to the benchmark. The numeric values are associated to relative savings of ventilation flow and FCU energy during one re-created working day in the meeting room site.

HVAC system	Indicated savings [%]	Paper I (simulations)	Paper IV (experiments)	Paper V (experiments)	Paper VI (experiments)
A (all-air)	Ventilation flow	x	19	x	15
B	Hygienic ventilation flow	50	x	55	45
	FCU energy	≈ 6	x	7	x

In summary, the largest energy savings potential of the suggested strategy were associated to ventilation system control in the meeting room site; with total flow reductions of 19 % in HVAC system A and approximately 50 % in HVAC system B. It is important to remember that HVAC system A is an all-air system which means that any flow rate savings are directly proportional to the total energy usage, while HVAC system B combines hydronic heating/cooling and hygienic ventilation. But in both cases, these results are associated to substantial reduction of both electricity to central fans and energy for air-conditioning.

Considerable energy savings were also associated to ventilation system control in the office cell, with indicated flow rate reductions of 14 % in HVAC system A and between 13 - 35 % in HVAC system B. On the other hand, when it comes to the hydronic part with respect to temperature control via the FCU, the indicated benefits were relatively small in the meeting room and diminishable in the office cell.

7.4 Strategies for Central SAT Control

Paper III investigated central SAT control through simulations of the 11 room office floor plane. The outcome consisted of two suggested strategies, one each HVAC system A and B, with the shared features of being linear, having single inputs and to be realizable through very simple programming and standard HVAC sensor technologies.

For HVAC system A, a suggested strategy with information about the total number of occupied rooms as provided by motion sensors turned out to be most favourable, while a general version of the optimal solution with only OAT as input could be formulated for HVAC system B. The associated results are presented in *table 12* as the HVAC energy savings potential when compared to conventional OAT-compensation. Remember that the energy usage in this study refers to the total amount for heating, cooling and air-conditioning during the simulated period of two working weeks of summer and winter climate.

Table 12. Results associated to the suggested SAT control strategies compared to conventional OAT-compensation. The numerical values are associated to relative savings of heating, cooling and electricity during two simulated working weeks of Swedish summer and winter, respectively.

Scenarios		Indicated savings [%]			
HVAC system	Building	Heating energy	Cooling energy	Electricity	Total energy (equation 8)
A	Heavy	25	50	-14	27
	Light	31	42	1	31
B	Heavy	10	22	-4	12
	Light	17	22	-0.5	18

8 CONCLUSIONS AND DISCUSSION

Based on the overall results, it can be concluded that BAS improvements for a more energy efficient indoor climate control are possible without losing HVAC function or implementability. More specifically, substantial energy savings can be achieved together with a desirable indoor climate, at the same time as a sufficiently low complexity for facilitating implementation in most office building sites is maintained. The first part of this conclusion is based on consistent results from comparisons between suggested strategies and benchmarks while equal comfort was constrained. The substance for the second part comes from the coverage of most relevant office sites, HVAC systems and conditions, over which it was shown that the performances of the suggested strategies could be maintained even when standard sensor technologies and programming were used throughout their designs.

In the following text, several secondary conclusions are presented. These derive from the results in the previous chapter, primary through analysis of the various tables. In the first section 8.1, the overall potential of the suggested strategy for integrated room automation is reviewed by identifying the most favorable conditions in comparison to common BAS technologies. In section 8.2, the influence of the suggested method of indicating occupancy with a motion sensor is reviewed, while the accordance between simulations and experiments is addressed in 8.3. In 8.4, the suggested strategies are compared to model-based controllers, and the chapter then ends with a reflection regarding the considered comfort constraints.

Remark: remember that most of this work was dedicated to the integrated room automation. This aspect is naturally also reflected in this chapter and central SAT control is only addressed sporadically in section 8.1 and 8.4.

8.1 Benchmarking

Compared to the considered benchmarks, it is clear that the suggested strategies have a large potential of reducing energy usage while maintaining or improving indoor climate quality. But as the suggested central SAT control yielded desirable results for all HVAC, building and ambient climate variants included in paper III, the benefits associated to integrated room automation were highly dependent on the application as illustrated in *tables 10* and *11*. This aspect is addressed in the following section by identifying the most favorable conditions for the suggested strategy, in order to provide information of how revenues can be maximized in order to achieve cost effective BAS improvements in practice.

The section is structured as follows. First, *table 13* summarizes the underlying effects that followed from the considered conditions, together with their influences on the relative performance of the suggested strategy for integrated room automation. Then, the substances for the statements in *table 13* are further discussed and analyzed in the following subsections.

Table 13. The interconnection between each considered condition and the performance of the suggested controller for integrated room automation compared to the associated benchmark.

	Conditions			
	Increased internal disturbances	Increased transport delay of HVAC system and/or process	Increased building thermal mass	Decreased outdoor air temperature
Influence on the performance of the benchmark (system of common practise)	↘	↘	↗	→
Influence on the performance of the suggested controller	↗	→	↗	↘
Influence on the relative performance of the suggested controller	↗	↗	↘	↘

8.1.1 Increased internal disturbances

The aspect of different indoor climate disturbance was evaluated through the two sites, whereof the meeting room environment was dominated by internal sources and the office cell by external.

Both experimental and theoretical studies showed that the benefits of the suggested strategy increased with the variation and magnitude of the internal disturbances used as exogenous inputs. Even though this conclusion is self-evident, its importance cannot be underestimated. From the most fundamental perspective, the aim of the suggested strategy is to act fast and accurate to changes in the exogenous inputs, and as more disturbances with a decisive role on the indoor climate are included, the benefit over a conventional controller without this type of information will increase.

8.1.2 Increased transport delay of HVAC system and/or process

While an increased transport delay of the process and/or HVAC system is an extremely limiting factor to the performance of conventional feed-back controllers (i.e. the benchmark), both simulations and experiments showed that the suggested strategy was close to unaffected by this condition and was hence favored in comparison.

In systems with large transport delays, feed-back controllers are adapted by lowering the static gain, which means that the overall control error response is decreased. This aspect is captured by all tuning methods and is necessary to avoid instabilities. But in turn, control errors are then enabled to grow larger until the sufficient actions come through, meaning that a narrower temperature dead-band and/or a lower CO_2 setpoint is required in order to fulfill comfort constraints of the kind presented in section 5.2.1.

When it comes to the suggested strategy, the performance of the control model is more or less independent on transport delays associated to exogenous inputs for two reasons. In turn, an overall low influence on the control task can be achieved if most relevant disturbances are incorporated.

- First, the response of the process (i.e. conditioned space) is of secondary importance, and is mainly used for minor control action corrections via the supporting feed-back.
- Second, the control model acts in advance and behind the visible scene (i.e. not seen by measuring controlled variables), which means that each action reaches the process before the effect of disturbances in the exogenous input or previous HVAC counteractions have come through, i.e. independently on their associated transport delays.

Illustrative results

The entitled conclusion regarding influence of transport delay on the potential of the suggested strategy will now be illustrated. First, the variants of office site and HVAC system that were considered during experiments regarding integrated room automation will be sorted according to their underlying transport delay. Second, the resulting order will be compared to the relative performance of the suggested strategy to highlight the strong connection.

During experiments, the site was studied in two variants, whereof the delays of both disturbances and control actions in general were longer in the meeting room due to a larger volume. When it comes to the HVAC components, the FCU was operated with constant and relatively high speed on both air- and water-side, which means that short delays between control actions and process applied throughout. The second HVAC component in this context is the air-diffuser, and due to the variable ventilation rate, long transport delays that in turn were decisive for the parameter settings of the PI benchmark, occurred in some parts of the operational range (see tuning procedure in section 5.1.1).

By taking all aspects above into account, the considered conditions can be ordered from overall long to short transport delays as follows:

1. ventilation system in meeting room
2. ventilation system in office cell
3. FCU in meeting room
4. FCU in office cell

Conclusively, this order is according to *tables 10* and *11* more or less equivalent to the relative performance of the suggested strategy, which means that the combined time delays of HVAC system and process is a crucial aspect in this context.

8.1.3 Increased building thermal mass

Since all experimental studies were conducted in the same site, the influence of building variants was solely evaluated theoretically. The simulations in paper I and III were thus repeated for two structures made of concrete and bricks as well as of gypsum, mineral wool and wood. These two variants were otherwise identical in both size and volume which means that only the temperature part of the control task was affected by this condition.

The properties of the respective building materials resulted in smaller thermal resistance and higher thermal capacity of the heavy structure than of the light. A higher capacity means that more energy can be stored in the structure and that the space becomes more robust to sudden thermal changes. Further, a lower resistance means that heat transfer between the conditioned space and the ambience is facilitated, and that temperature differences are evened out more efficiently.

As a result, individual thermal disturbances had a larger effect on the indoor climate in the light structure and a higher control signal activity was required for a maintained comfort. Hence, this condition has the same but opposite influence as the condition of increased internal disturbances, which already has been discussed in section 8.1.1. But to summarize, it was shown that an increased thermal mass promoted the performance of both controller types, but as the benchmark was favored more than the suggested, the relative energy savings were hence decreased.

8.1.4 Decreased outdoor air temperature

The influence of OAT on the temperature control task was investigated in the office cell site through both simulations and experiments. The condition of a decreased OAT was crystallized as two separates scenarios consisting of the HVAC system operating in heating mode during winter and in cooling mode during summer.

The results showed that the performance of the suggested strategy dropped during heating mode with respect to an increased room air temperature variation compared to the cooling mode scenario. In turn, as the benchmark was more or less unaffected, the thermal comfort constraint could be fulfilled without any major setpoint adjustments, which means that the savings potential was decreased.

These results are directly related to the design of the suggested strategy which makes is less appropriate for heating modes. The first aspect in this context is that the exogenous inputs for temperature control solely were made up of internal heat generation. The majority of these disturbances did not have a negative influence on the thermal comfort during heating mode since the associated temperature rises were smaller than 1 K (see section 5.2.1). Hence, the possibility of the suggested strategy to further improve the indoor climate was very limited. The second aspect follows from that the exogenous inputs only could be counteracted by an increased cooling or decreased heating. During heating mode, the non-linear filter was hence limited to performing heat supply reductions by counteracting the output from the supporting feed-back. These two controller parts were then operated against each other, and in order to avoid instabilities, the contribution from the non-linear filter had to be relaxed which means that a larger proportion of the control was allocated to the supporting feed-back.

8.2 Occupancy Information

A main conclusion regarding integrated room automation was that occupancy information can be gathered without involving any complex elements, at the same time as a sufficiently high control performance is achieved. This section provides the associated justifications, and since the results from paper II indicated that a complex controller might be required when CO_2 sensor responses were utilized, the focus is on motions sensors and the suggested signal processing methods.

8.2.1 Office cell site

During the experiments in the office cell, ideal occupancy information was throughout provided to the suggested strategy, and the results indicted energy savings between 12 - 14 % when applied to HVAC system A, and 35 % when applied to HVAC system B.

Such an idealized procedure is actually not far from reality during these circumstances. Since the office cell was designed for one person, the same information could be acquired by a motion sensor. Estimation errors would then be a minor issue since each response is associated to the normal number of people in the controlled space. In practice, on the other hand, a time-delay needs to be applied to adapt the sensor for real office work with occupied periods without movements. The influence of this aspect can be estimated from the results of paper II (see *fig. 33*) where it was shown that a maintained control performance is possible for delays up to about 5 minutes. When increased further, the performance of the suggested strategy dropped rapidly but it took a delay of about 20 minutes until the benefits over the benchmark were completely diminished and their performances coincided (since only the supporting feed-back then was involved in the control).

8.2.2 Meeting room

The experiments in the meeting room were instead divided between two phases. The first phase was presented in paper IV and V and the suggested strategy was then provided with perfect occupancy information. The exact same conditions were also studied during the second phase (paper VI), but with the exception that motions sensor responses instead were considered together with an additional control model for signal processing.

As the results from the second phase indicated savings of 15 and 45 % when applied to the ventilation system of HVAC system A and B respectively, only an addition of 4 respective 10 %-units were indicated in the first phase. From these results, it can be concluded that a sufficiently high performance of the suggested strategy can be achieved even though occupancy is represented with standard HVAC sensors in the disturbance sensing system. The main finding is that motion sensors can be used in both single- and multi-person spaces, and the additional benefits of providing ideal information regarding the number of people are small – at least when put in relation to the extensive efforts that would be required in reality.

8.3 Measurements Versus Simulations

The suggested strategy for integrated room automation was evaluated on HVAC system B through simulations in paper I and through experiments in paper V. Hence, these two papers involved the same conditions and can be compared to determine the correspondence between theory and reality.

8.3.1 Setpoint agreement

The ventilation system was in this case used for CO_2 control and recall that the setpoint of the benchmark was tuned to avoid concentrations above 1000 ppm. In this perspective, simulations and experiments agreed very well with a maximum deviation of 20 ppm (about 3 % error) as presented in *table 14*. One important remark in this context is that the maximum ventilation rate in the office cell throughout was smaller than required to attain these setpoints. Hence, the ventilation rate was eventually saturated during occupied periods, and the actual CO_2 level then settled somewhere between 1000 ppm and the setpoint.

Table 14. Resulting benchmark setpoint for fulfilling the IAQ constraint of avoiding CO_2 concentrations above 1000 ppm. Observed for HVAC system B.

Site	Experiments	Simulations
Office cell	740	750
Meeting room	680	700

8.3.2 Energy savings agreement

Theory and experiments can also be compared through the respective indicated energy savings presented in *tables 10* and *11*.

Throughout, the correspondence of the FCU parts (i.e. hydronic heating/cooling for temperature control) was regarded as sufficient and only minor inconsistencies of a few percents were reported. The same applies furthermore to the ventilation part (i.e. for room air CO_2 control) in the meeting room site: simulations and experiments corresponded in this case to 50 and 55 % of flow savings respectively, and this difference can easily be explained by various simplifications in the computer model.

A less satisfying result was on the other hand observed in the office cell scenario, with indicated savings of 10 respectively 35 % during simulations and experiments (see *table 10*). Before going in to this matter any further, it is important to remember that the scenario of concern deals with hygienic ventilation in a small space. Hence, the overall ventilation rate is low, which means that even minor difference on an absolute scale has a large influence on the relative measure.

Having that said, the larger savings potential during experiments is due to benchmark inconsistencies, and has very little to do with the suggested strategy. In order to discuss the underlying causes, a simulation of the shorter experimental working day was conducted explicitly for this section (as mentioned in section 4.2, the simulated working day from paper I was scaled down for the experiments in paper V). These results are presented in *figure 40* as a comparison between the simulated and experimental benchmarks for CO_2 control in the office cell.

From the figure, it is clear that the simulated benchmark can reside closer to the limit value which means that less supply air is needed – hence the decreased relative savings associated to the suggested strategy. This disagreement depends on the two aspects presented below, that together afflicted the experimental benchmark in the office cell with an overall increased ventilation rate, while leaving the remaining scenarios close to unaffected.

Remark: it is important to highlight that the simulations were conducted before the experiments in *figure 40*. Hence, the model was not trimmed in any way to agree to the experimental results.

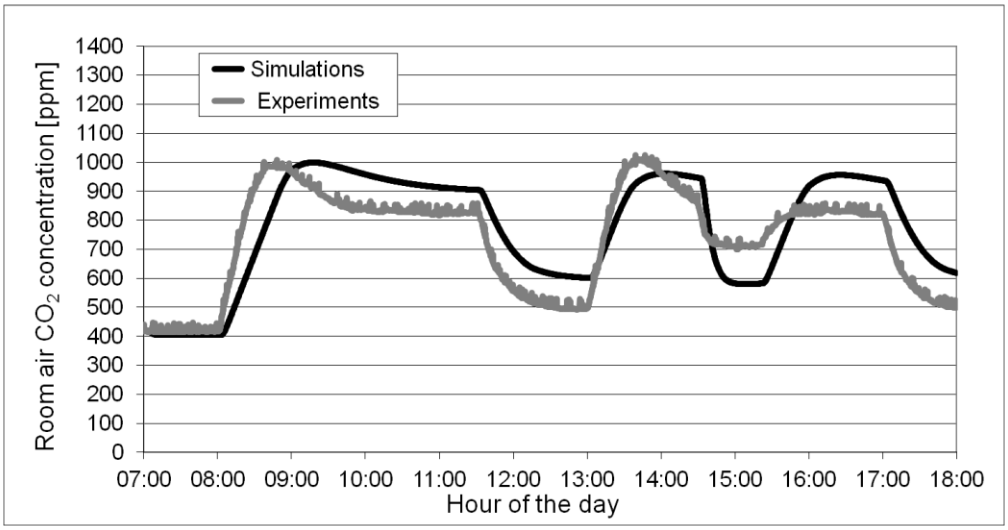

Figure 40. Experimental and simulated results of the benchmark for CO_2 control via HVAC system B in the office cell. Note that the duration of the simulated working day was adjusted to agree with the experimental.

Differences in process dynamics

The **first aspect** as pointed out above refers to inconsistencies between simulated and experimental process dynamics. As the assumed transport delays during simulations were shown to agree with reality (see section 4.1.2.), only the time-constant is important in this discussion.

In a mass-balance, the time-constant is denoted exchange rate and is described as the ratio between the volume in the space and the transfer rate ($V/\dot{V}$). In this context, the volume refers to the actively ventilated part, and as the one-node representation during simulations took the entire room into account, a smaller share can be expected in reality due to CO_2 stratification and insufficient air propagation. When it comes to the transfer rate, the absolutely largest inconsistency between simulations and experiments is due to different infiltration flow rates, even though a smaller share presumably derives from measurements errors regarding ventilation flow. As presented in section 4.1.3, the infiltration to the office cell corresponded to 3 l/s during experiments while set as insignificant during simulation. This difference stands alone for approximately 25 % of the total transfer rate, while the corresponding share in the meeting room site was more than six times smaller (4 %).

Altogether, these inconsistencies resulted in that the real CO_2 process dynamics in the office cell were considerable faster than represented during simulations, as illustrated in *figure 40*. This means that the CO_2 settled faster and that the maximum ventilation rate was attained for longer periods of time. However, the suggested strategy was unaffected by this aspect due to the static control model for CO_2: as an increased occupancy was registered, the ventilation flow attained the level associated to 1000 ppm, and this level was kept until the next change was registered.

In the meeting room case, the process dynamics were more similar between simulations and experiments for two reasons. First, the additional elements during experiments (infiltration and any measurement errors) only stood for a minor part of the transfer rate. Second, an overall higher ventilation rate means that the propagation of air during experiments is increased and that a larger share of the volume becomes active.

Remark: a shorter time-constant in combination with a maintained transport delay implies a more difficult control task [60]. From this point of view, a lower benchmark setpoint of the kind presented in *table 14* would be necessary during experiments to achieve the same IAQ as during simulations. But, the higher infiltration flow rate provides a dampening effect on the CO_2 source which levels out any setpoint inequalities between experiments and simulations.

Differences in door opening effects

The **second aspect** for explaining the inconsistent ventilation rate savings between theoretical and experimental studies in *table 10* is that the computer model was exaggerating the fresh air transfer through an open door. This event was solely studied in the office cell and the difference between simulations and experiments can be visualized between 14:30 and 15:20 in *figure 40*. It is clear that the **simulated** air transfer through the door was sufficient to cover the entire ventilation demand: the CO_2 level dropped considerably below the setpoint which means that no additional ventilation was required. In comparison, the real effect observed during **experiments** was considerable smaller. The CO_2 level also dropped in this case, but not below the setpoint, which means that mechanical ventilation was required during the event. The modeling error of door openings had on the other hand no influence on the suggested strategy. During both simulations and experiments, the ventilation was shut off directly when the door was opened, and concentration below 1000 ppm could still be maintained.

8.3.3 Influence of different infiltration flow rates

Due to the lack of direct measurements methods, information about infiltration flow rate was regarded as unrealistic to obtain in reality and was hence not provided as exogenous input to the suggested strategy. That is, the experimental level of 3 l/s is characterized as an unmeasured disturbances and the associated influence can be seen in the office cell cases in paper V. The CO_2 concentration during occupied periods then settled and remained about 900 ppm. The reason is that the supporting feed-back controller only was able to increase the ventilation rate (since an identical version of the benchmark was used) while an additional function for allowing negative control signals could resolve this issue. Moreover, these effects were diminished in the meeting room scenario since the infiltration then only stood for a minor share of the mechanical ventilation rate.

8.4 Comparison to MPC

This work was justified by previous publications in which considerable energy savings were observed when conventional BAS for indoor climate control was replaced by model-based controllers. As the model-based controllers in many senses must be regarded as idealized and unrealistic for considering in most building sites, the aim was to adapt the technology for practical considerations. The suggested strategies were inspired by the principle, regarding that information about the present indoor climate and associated disturbances were combined in the generation of control signals. But the entire design was generalized and solely based on standard technology to suite modern office buildings without any major retrofits.

In the following sections, the consequences of this practical approach are reviewed in two ways.

- First, through own results from paper I-III, in which extensive model-based controllers with complete information about indoor climate disturbances, the process as well as the HVAC system were compared to the suggested strategies.
- Second, by comparing the energy savings potential of the suggested strategy and typical model-based controllers from other publications. It is important to emphasize that the second comparison is not definite and only was included as a hint since different benchmarks, control tasks, HVAC systems etc. were considered in the different studies.

8.4.1 Own results

In paper I, several controllers were evaluated through a process in which each design was generated by applying a complexity reducing measure. As the final design was the suggested strategy, the initial was a predictive model-based controller with discretized heat- and mass- balances as control model. Compared to a conventional feed-back controller, the initial design had the ability of reducing energy usage between 7 and 46 % dependent on building structure, type of office room and ambient climate. At the same time, the associated results for the suggested strategy were between 5 and 44 %, which means that the reduced complexity had very little influence on the control performance.

Similar results were also presented in paper II where the suggested strategy was compared to an MPC for a CO_2 control task. It was shown that their performances with respect to a minimized influence of increased occupancy were close to identical when accurate information about the number of people was provided as exogenous inputs.

In paper III, several simplified central SAT control strategies were evaluated, and compared to a conventional approach, the most favorable designs led to energy savings between 6 and 31 %, dependent on building structure and HVAC system. The extensive strategy was in this case made up of an optimal algorithm with complete information about the process, the HVAC system and the entire set of internal and external disturbances. In comparison, the optimal strategy resulted in savings between 12 and 39 %, also dependent on the building structure and HVAC system.

8.4.2 Other publications

The results from the previous section show that it is possible to achieve energy efficient BAS while maintaining practical aspects to facilitate implementation in typical buildings. This conclusion is also confirmed by previous publications in which extensive model-based controllers were considered for system-wide, integrated room and central HVAC system automation. Savings up to 50 % were indicated when applied for integrated room automations, and up to 40 % when applied for central control. Hence, these results are similar to what has been achieved in this work with considerable lower BAS complexity.

But, it is important to remember that a lower level of complexity naturally also leads to a reduced controller function, and the possibility to predict and optimize the operation was omitted in the process. Instead, the suggested strategy was designed by prioritizing present control regarding the ability of maintaining the comfort boundaries even under heavily shifting conditions.

8.5 Comfort Constraints

Several of the papers (IV-VI) have questioned the role of the considered indoor climate constraints. They were introduced as a method to avoid quantifying difference is indoor climate achieved by a suggested strategy and its benchmark. Since similar comfort instead was implied, all benefits were translated into energy quantities. Another way of putting it is that all controllers were compared on equal grounds, by constraining the primary HVAC function of a desirable indoor climate.

But, the relevance can still be argued and the following concern was raised in the appended papers that were dealing with experimental studies regarding integrated room automation, "…in real life situations, such comparison is somewhat insufficient since a desirable indoor climate as base-line cannot be guaranteed". For that reason, results from additional experiments were presented and it was showed that the prior energy savings were reduced as the indoor climate constrains were relaxed for the benchmark.

But, the energy usage associated to the suggested strategy never exceeded the benchmark. This means that an indoor climate quality, that follows the prevailing guidelines and standards for comfort, can be achieved without increasing the energy usage. Presumably, a desirable indoor climate has several other benefits than just comfort whereof some are associated to energy usage. For example, a desirable indoor climate means that the need for airing through open windows is avoided. In turn, the energy demand for temperature control is reduced. Further, insufficient temperature control may led to user induced setpoint shuttling, resulting in a type of “blind” on/off control. In turn, the system would then be out of phase most of the time and the energy usage would probably increase. Finally, discomfort can also lead to productivity losses at work places and more employee sick-days, with associated costs that are many times larger than the cost of operating the HVAC system in a desirable way.

An important remark is that the argumentation above only applies to strategies for integrated room automation. As a matter of fact, it was shown in paper III that substantial energy savings were achievable through central SAT control while leaving the local parts unchanged. In this study, no climate constrains were considered, all components for integrated room automation used the same setpoints throughout, and total energy savings up to 30 % were still indicated.

9 FUTURE RESEARCH

There are several topics that easily could fit within the scope of this work, but were omitted in order to limit the extension within the available period of time. Below, some suggestions for future research are provided:

- In this work, the suggested strategies for integrated room automation and central control were studied separately. Their combinatorial effects were on the other hand briefly addressed in the licentiate thesis [35] and it was shown that the overall energy savings potential was increased even further. However, more thorough investigations are needed until any final statement can be made.
- Central SAT control strategies in multi-zone building sites were only studied through simulations, and the next natural step could include equivalent experimental parts.
- Central control only involved supply air temperature but similar technological solution could also be applied to hydronic heating and cooling systems.
- In the presented work, the integrated room automation part was only conducted for single-room sites. However, the licentiate thesis [35] also involved a theoretical study in which each room of the multi-zone site (building floor plane) was equipped with the suggested controller. Simulations were conducted for one working week and involved mixed-mode HVAC operation. The results showed that a high control performance could be maintained also during these conditions, but equivalent experimental studies would be desirable before any final conclusions can be stated.
- The suggested strategy for integrated room automation was only compared to an MPC during the CO_2 control task in paper II. A possible extension could include a similar comparison regarding temperature control.
- The integrated room automation part could be extended with more thorough investigations regarding other types of indoor climate constraints as well as without.
- In this work, the indoor climate was characterized by the room air temperature and CO_2 while similar control methods also could be applied for humidity control.
- Tuning procedures for the suggested control strategies could be developed in order to further facilitate implementation.
- Throughout, the ventilation system was characterized as an HRV. While several of the appended papers have indicated how the results would be affected by also involving recirculation of exhaust air, the concept needs to be extended until any final statements can be made.
- This work only considered office building but similar technological approaches could furthermore be applied to the residential or commercial sectors as well as in schools, training facilities etc.

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Paper I

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Model-based controllers for indoor climate control in office buildings – Complexity and performance evaluation

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ABSTRACT

Model-based controllers are equipped with an integrated control model and utilize information about disturbances that act on the process. It is well established that the performance of building automation systems can be drastically improved by model-based controllers, but, they also lead to a substantial increase of complexity which is an obstacle for large scale implementation. In this work, model-based controllers with different measured disturbances as exogenous inputs and different types of control models were evaluated to explore the possibility of reducing complexity without compromising performance. The work was performed in a simulated environment and focuses on temperature and CO_2 concentration control in individual office rooms during periods that are dominated by occupancy. All relevant internal and external disturbances in office environments were considered as both single input and combined inputs to six different control models. The key finding is that controllers with simplified control models and fewer exogenous inputs can perform almost as well as more complex controllers.

1. Introduction

Buildings are increasingly expected to meet higher requirements such as being sustainable and energy efficient at the same time as a healthy and comfortable indoor environment should be achieved. Approximately 40% of the global energy is used in buildings whereof about half is used for heating, ventilation and air-conditioning (HVAC) in industrialized countries. At the same time, there are large room for energy efficiency improvements to reduce the running costs and CO_2 emissions. Since energy efficiency measures must be economical feasible in both the existing building stock and in new constructions, there is a demand for energy saving technologies that are relatively easy to implement. A key technology to meet all of these requirements is to improve the building automation system. Such measures can be both cost effective and result in substantial energy savings at the same time as a desirable indoor environment can be maintained or even improved [1].

Model-based controllers refer to a group of controllers that utilize information about the intensity and type of disturbances that act on the process. The disturbances can either be measured or estimated and are used as exogenous inputs to an internal control model. The control model predicts or estimates the corresponding impact on the controlled variables and sequently adjusts the control signals to achieve the desired behaviour of the process. Preferably, the prediction or estimation should be combined with state feed-back based on measurements of the controlled variables. In this way, unmeasured disturbances and errors in the control model are compensated for. Model-based controllers for building automation have been investigated in several works before. Most of the recent ones focused on a type of model-based controller referred to as model predictive controller (MPC). The input to an MPC is usually disturbances and/or state measurements. At each time-step control signals are generated by solving a constrained optimal control problem using a dynamic control model and a cost function. In [2–4] MPCs were used in office buildings and both internal and external disturbances were investigated as controller exogenous inputs. In several works [4–8], weather forecasts were used for example to maximize the renewable part of the energy usage or to optimize the heat stored in the building structure. In the light of these cited works, it is clear that model-based controllers have a large potential for improving the building automation system. A desirable indoor environment can be achieved while the energy usage is decreased substantially compared to when more conventional control systems are used. However, the main obstacle for implementation is that model-based controllers have the tendency of drastically increase the complexity of the control system. In general, the cited works investigated the performance of

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Nomenclature

C	thermal capacity (J/°C)
c	CO_2 concentration (ppm)
c_p	specific heat capacity (J/(kg K))
E	total energy usage, weighted sum of energy terms (W)
h	hour
$\dot{M}$, $\dot{c}$	CO_2 flow rate (ml/s)
n	number (-)
Q	thermal energy (J)
$\dot{Q}$	thermal power (W)
t	Celsius temperature (°C)
u	general input signal
V	volume (m^3)
$\dot{V}$	volume flow rate (m^3/s)
W	electric work (J)
$\dot{W}$	electric power (W)
y	general output signal

Greek letters

τ	time (s)
ρ	density (kg/m^3)

Subscripts

act	activation
adj	adjacent
s	supply
sp	setpoint
r	room

extensive and complex model-based controllers and the measured disturbances were evaluated as lumps which means that their relative value as input were not identified. Hence, the possibility of reducing the complexity of the disturbance sensor system and the control model were not fully addressed.

In order for model-based controllers to be used on a large scale in building automation, a standardized and easy solution must be available. The complexity, and also the performance, depends both on the design of the control model and the design of the disturbance sensor system. Within the group of model-based controllers, the complexity of the control model can range from a full MIMO (Multiple-Input, Multiple-Output) dynamic representation of the process to a simple linear SISO (Single-Input, Single-Output) representation. A complex control model requires an extensive tuning process, both if black-box or physical models are used, as well as continuous maintenance to update for changes of the process. When it comes to the disturbance sensor system, the number of measured disturbances and their measurability determines the complexity of the sensors, but the signals must also be correctly processed in the control model which requires tuning and programming. Further, each measured disturbance is also associated with a cost of hardware (sensor and wires) and labour. Two of the most commonly controlled variables in buildings are the indoor air temperature and the CO_2 level that in turn are indicators for thermal climate and IAQ (Indoor Air Quality) respectively. Both, but especially the temperature, are at each time affected by a large number of intermittent disturbances. However, depending on the occupant activity and type of building some have larger influence than others. To reduce the complexity of model-based control systems, it is of importance to limit the number of exogenous inputs and only target the disturbances that have a large impact on the performance of the building automation system. The rest of the disturbances should preferable be managed by state feed-back.

1.1. Purpose and procedure

This paper investigates model-based controllers for local air temperature and CO_2 control in office buildings through simulations. The aim is to explore the possibility of reducing complexity without compromising control performance. The most common office related disturbances were used as exogenous inputs to six different control models with a varying level of complexity that stretches from a large number of model parameters to just one. In this way, the disturbances that first and foremost should be measured were systematically pointed out and the performances of different control models were determined. Two office rooms that are different both from a structural and occupant activity point of view were considered in the investigation. The rooms were subjected to external and internal intermittent disturbances with patterns that correspond to an office building in Swedish summer or winter climate. The outcome of the investigation is two model-based controller designs referred to as design A and design B. Design A has the highest performance among all of the investigated controllers and has no restrictions on which control model or exogenous inputs that are used. In design B, a simplified control model is instead combined with the exogenous inputs that were shown to have significant impacts on performance. Control performance was indicated by energy usage and peak power and the results are presented as the relative savings by replacing feed-back controllers without information about disturbances.

1.2. Contribution

Complexity contra performance of model-based controllers is the focus of this work and the papers [9] and [10] are closest to that spirit. In [9], an MPC with occupancy as exogenous input was evaluated for indoor climate control and two types of HVAC systems were considered; one with fast responding water-based heating and cooling but no ventilation and the other with ventilation but slow reacting water-based heating and cooling. The value of utilizing predicted or measured occupancy was investigated and one of the main conclusions was that predictions do not lead to any significant increase of performance compared to measurements. Since predictions are increasing the complexity of the control system, the question of complexity contra performance was addressed, even though from another point of view compared to the current work since only measurements were considered here. Also in [10], the value of using occupancy as a controller input was investigated. In this case, the task was to control an all-air HVAC-system and a control model simpler than MPC was also considered.

There are several aspects that distinguish the current work from [9] and [10]. For example, the investigations are considering different HVAC-systems as well as different variants of building structure, type of room and ambient climate. But in particular, there are four features that make the current work unique on a more fundamental level. First, one of the main focuses in the current work is to determine the performance of simplified control models. In [9], MPC controllers were used throughout the study and in [10] one control model simpler that MPC was evaluated. Second, CO_2 control (or rather modulating control of an IAQ indicator) was not investigated in the cited works. Third, only occupancy was considered as exogenous input in the cited works while all relevant disturbances are evaluated in the current one. Finally, the control strategies in both [9] and [10] use temperature and/or ventilation set-back (i.e. relaxed comfort criterions) during vacant periods which presumably have a significant effect on the results. In contrast, the current work focuses on the performance of model-based controllers during periods that are dominated by occupancy. The

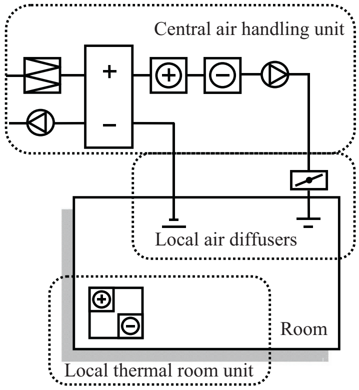

Fig. 1. Scheme of simulated building and HVAC-components.

simulations stretched over one working day, and fixed comfort constraints were used most of the time while fixed setpoints were used during short vacant periods such as lunch. Even though set-back can yield energy savings, it was not considered in order to isolate the performance of different model-based controller designs during times when comfort is of significant importance.

Control tasks which involve fixed indoor climate constraints for IAQ have also been used in previous works. In [11], genetic algorithms were implemented to control the ventilation system in an office building and different CO_2 thresholds were considered. The purpose was to mitigate the effect of disturbances to be able to move the actual CO_2 level closer to the threshold. In [12], scheduled occupancy was used to control the ventilation system in a training facility. The aim was to keep the CO_2 concentration close to 1000 ppm without breaching this limit.

2. Simulations framework

In this section, first the modeling approach of the building and HVAC-system is described and then the variants of the building and disturbances that were considered are introduced. For more information about the component models, consider [13]. The investigation is based on simulations performed in MATLAB Simulink and the simulation platform including HVAC-system and building is presented schematically in Fig. 1. One-dimensional equations were used to describe how CO_2 concentration, temperature and pressure vary over the platform. CO_2 and temperature were calculated by physical balance equations and the relations between pressure and flow were based on empirical data. The latter originate from a number of sources such as manufacturing companies and various publications [14–17].

2.1. Building model

The building part consists of an individual room with adiabatic boundary conditions on the outside surfaces of roof and floor and isothermal boundary conditions in adjacent rooms. The temperature of building elements (BE) such as walls, floor and roof are calculated in two nodes located on the inside and outside surfaces. The heat exchange between a certain building element (i) and the surroundings is described by two coupled ODEs (ordinary differential equation) on the form presented in Eq. (1a). The temperatures of the different building elements are in turn coupled via the temperature of the room air (r) which is calculated in one node using the ODE in Eq. (1b). The right hand side of this equation consists of terms describing the heat exchange between the room air and the building elements ($\dot{Q}_{\mathrm{BE},i\to r} - \dot{Q}_{r\to \mathrm{BE},i}$) and terms describing the heat emitted by internal disturbances ($\dot{Q}_{D,i\to r}$). Also the CO_2 concentration of the room air is calculated in one node using the mass balance in Eq. (1c). The terms on the right hand side describes the CO_2 exchange between the room and the ambience ($\dot{c}_{\to r} - \dot{c}_{r\to}$) as well as the CO_2 emitted within the room by internal disturbances ($\dot{M}_{D,i\to r}$). A less general form of this equation that will be considered further on in this work is given in Eq. (1d). The building model and its variants were tested and validated against IDA ICE by an independent energy consultant. IDA ICE has in turn been tested in the Building Energy Simulation Tests (BESTEST) which were developed under IEA SHC Tasks 8, 12 and 22.

Table 1
Variants of the building model that were considered in the investigation.

Type of room	Size (m^2) (floor area)	External climate	Building structure
Meeting room	18	Summer/winter	Heavy/light
Office room	10	Summer/winter	Heavy/light

$$\frac{dt_{\mathrm{BE},i}}{d\tau} \times C_{\mathrm{BE},i} = \dot{Q}_{\to \mathrm{BE},i} - \dot{Q}_{\mathrm{BE},i\to} \tag{1a}$$

$$\frac{dt_r}{d\tau} \times C_r = \dot{Q}_{\mathrm{BE},i\to r} - \dot{Q}_{r\to \mathrm{BE},i} + \dot{Q}_{D,i\to r} \tag{1b}$$

$$\frac{dc_r}{d\tau} \times V_r = \dot{c}_{\to r} - \dot{c}_{r\to} + \dot{M}_{D,i\to r} \tag{1c}$$

$$\frac{dc_r}{d\tau} \times V_r = \dot{V}_s \times (c_s - c_r) + \dot{V}_{\mathrm{door}} \times (c_{\mathrm{adj}} - c_r) + \dot{M}_{\mathrm{CO_2}} \tag{1d}$$

The building was modeled to reassemble a modern office building with tight and well-insulated walls. The variants of building structure, type of room and external climate that were considered are presented in Table 1. The two building structures were chosen to include the influence of thermal characteristics in the investigation. Both structures represent its own extreme where the heavy structure is entirely of concrete and the light structure is of gypsum, mineral wool and metal sheet. These choices were made so that it can be expected that the results from the investigation are spanned so that most relevant building cases are lying within the range. The purpose of including two different types of rooms was to investigate the influence of different disturbance patterns. The meeting room lack external walls and are therefore not directly affected by the external climate. The internal disturbances can on the other hand be large since the meeting room is designed to contain many people at the time. The office room is instead designed to contain one person. One wall is external and 80% of its surface is covered by a window with external solar shading.

2.2. HVAC-component models

The HVAC-part of the simulation platform consists primarily of two local and five central components models summarized in Table 2. Most of the components in Table 2 contribute to a change in temperature which is described in at least two nodes, one at the outlet and one at the inlet. In the heat exchanger components (air-heater, air-cooler and heat recovery unit) the temperature is calculated in six nodes. The room air temperature is controlled by a local thermal room unit (TRU) with the ability to either heat or cool the room between +1000 and −1000 W. The TRU is modeled as a fan-coil unit with a variable speed fan. The CO_2 level of the room is controlled by a roof mounted supply air diffuser with variable opening. The minimum flow rate is set to zero and the maximum level is dependent on the size of the room and design number of people, both according to national standards [18]. The ventilation air consists entirely of outdoor air that has been conditioned in a central air handling unit (AHU) and distributed to the room via a duct system. The supply air temperature setpoint was set as dependent on the ambient season; 15 °C during summer and 18 °C during winter. The

Table 2
Summary of HVAC-component models used in the investigation.

	Description	Control arrangement
Evaluated automated components		
Local thermal room unit (TRU)	Fan coil unit for local heating or cooling. Circulating room air on one side and hot or cold water on the other	Actuator for room temperature. Room air side: variable drive fan. Water side: on/off valves for hot or cold water, control valve for constant hot or cold outlet air temperature
Local supply air diffuser	For mixed ventilation between supply and room air	Actuator for room CO_2 concentration. Adjustable opening
Not evaluated automated components		
Central heat recovery unit	Rotating non-hygroscopic wheel. Maximum temperature efficiency 0.75	Sequence controlled, constant SAT setpoint. Variable speed drive of the wheel
Central air-heater	Supply air on one side and hot water on the other	Sequence controlled, constant SAT setpoint. Control valve for variable water flow rate
Central air-cooler	Supply air on one side and cold water on the other	Sequence controlled, constant SAT setpoint. Control valve for variable water flow rate
Central supply air fan	Maximum total efficiency of 0.5	Flow controlled, follows the control signal to the local diffuser. Variable speed drive
Central exhaust air fan	Maximum total efficiency of 0.5	Flow controlled, follows the supply air flow rate. Variable speed drive
Not evaluated nor automated components		
Air cleaning filter	Particle filter taking its pressure drop into account	–
Pipes, ducts, branches and bends	For transportation of water and air	–

SAT is an acronym for Supply Air Temperature.

type of HVAC-system used in the investigation allows for the CO_2 level and room air temperature to be controlled almost independently of each other. This system was chosen to isolate the effect of the investigated control system designs on energy efficiency: in the current setup, the realization of the control signals is not limited by the actuators.

2.3. Disturbances

One simulation comprises a 12 h working day, stretching from 7:00 to 19:00 h, with a 3 h stabilization period before and after. During a simulation, the room was subjected to the following time-varying internal and external disturbances.

- People
- Lighting
- Equipment
- Door opening
- Solar heat gain
- Outdoor air temperature (OAT)

As mentioned, only the office room is directly influenced by the external climate and the investigation has been conducted with a summer and a winter variant. Both seasons were modeled using climate data of a reference year from the Swedish coastal city of Helsingborg which has a mild tempered climate and an annual average OAT of 8.2 °C. The modeled internal disturbances due to people are based on statistical data from measurements of occupancy in a Swedish office building [19]. The data comprise occupancy during office hours of 58 office rooms throughout one year. The simulated patterns are presented in Fig. 2 and each person was modeled to emit 18 l_{CO_2}/h and 70 W of sensible body heat. The magnitude of the heat gained from lightning is based on design guidelines (10 W/m^2) and its occurrence was assumed to correlate to occupancy, i.e. the light was switch on during occupied periods and switched off during vacancy [20]. Also equipment correlates to occupancy in the meeting room but was assumed to be constant during the entire working day in the office room (to represent a computer that runs all day but is turned off outside office hours). The door to the office room was open during 15:00 and 16:30 and the door to the meeting room was assumed to be closed at all times.

3. Investigation

In this section, first the performance indicators that were used in the investigation are described and then the controller designs that have been evaluated are presented. Finally, the simulation procedure is described.

3.1. Performance indicators

The most important task of an HVAC-system (including the associated control system) is to keep the thermal climate and indoor air quality within given comfort ranges. Preferably, this should be done while energy usage is minimized. In this work, the investigated controller designs were evaluated based on these aspects and feed-back controllers were used as benchmarks due to their commonness in building automation systems. The benchmark feed-back (FB) controllers lack of information about disturbances, are of PI-type with ideal parameter settings (according to the AMIGO method) and are equipped with state-of-the-art sensors in the control loop (with respect to accuracy, response time and placement). To ensure comparability, each investigated model-based controller design was evaluated against its own benchmark feed-back controller tuned to achieve the same thermal climate and IAQ according to associated comfort constraints. The IAQ was indicated by the room CO_2 level and the associated comfort constraint is presented in Eq. (2). It states that the maximum CO_2 level is not allowed to cross an absolute boundary of 1000 ppm either when

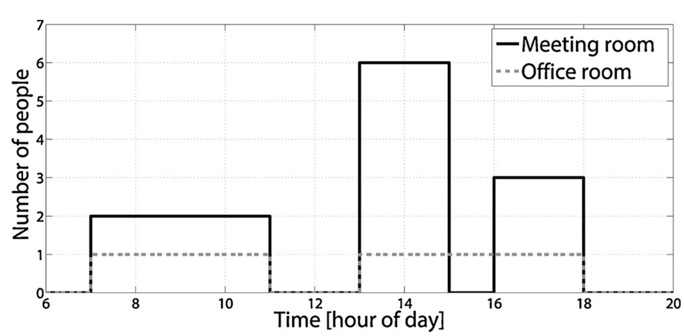

Fig. 2. Occupancy pattern for office and meeting room.

a certain model-based controller MBC or its benchmark controller BFB is used. This level is based on several national recommendations [18] as well as the ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) standard 62-2007. The quality of the thermal climate was measured relative to a room temperature comfort region set between 21 and 22 °C. The associated comfort constraint is presented in Eq. (3) and states that the degree hours outside this comfort region, for times when the room is occupied, should be equal when a certain model-based controller MBC or its benchmark controller BFB is used. To use the deviating degree hours from a fixed comfort region as a metric for thermal climate quality is based on a national guideline [21]. Also ASHRAE [22] (chapter 8) proposes a similar method in which the mean time integral of deviating temperatures is used. The lower thermal comfort boundary in this work was set according to a national recommendation [21] which states that temperatures below 21 °C should be avoided in occupied office rooms. The upper boundary was set 1 K higher, since according to the standard ISO EN 7730-2005, room temperature variations smaller than 1 K does not have a negative influence on the thermal comfort. Similar requirements are also given in ASHRAE standard 55-2004. A more widely used method for estimating the thermal sensation is the PMV (Predicted Mean Vote) [23]. But although PMV is recognized as a good estimation of the thermal sensation, it is derived during steady-state and is hence not suitable during the transient conditions studied in this work.

$$\hat{c}_{r,\mathrm{MBC}} = \hat{c}_{r,\mathrm{BFB}} = 1000 \quad (\mathrm{ppm}) \tag{2}$$

$$\left(\int_{22}^{\infty} t_r dh\right)_{\mathrm{MBC}} = \left(\int_{22}^{\infty} t_r dh\right)_{\mathrm{BFB}} \quad \text{and} \quad \left(\int_{-\infty}^{21} t_r dh\right)_{\mathrm{MBC}} = \left(\int_{-\infty}^{21} t_r dh\right)_{\mathrm{BFB}}$$

$$\text{Provided that the room is occupied} \quad (^{\circ}\mathrm{Ch}) \tag{3}$$

The result from the study is presented as two energy performance indicators. These measures the relative energy usage and peak power of the HVAC-components between a certain model-based controller design and its benchmark. Energy usage was calculated as the sum in Eq. (4). It is weighted according to Energy Efficiency Directive 2006/32/EG and comprises the total energy amount used by the HVAC-system during a simulated period. The relative savings achieved by using a certain model-based controller design MBC instead of its benchmark FB-controller BFB was in turn calculated using Eq. (5). The peak power indicator was calculated using Eq. (6) and comprises the thermal peak (a sum of the AHU and TRU peaks) and the electrical power peak (dominated by central fans) that occurred during a simulated period.

$$E_{\mathrm{total}} = \left|Q_{\mathrm{total,thermal}}\right| + \left(W_{\mathrm{total,electrical}} \times 2.5\right) \quad (\mathrm{kWh}) \tag{4}$$

$$\text{Energy usage indicator} = \left(1 - \left(\frac{E_{\mathrm{total,MBC}}}{E_{\mathrm{total,BFB}}}\right)\right) \times 100 \quad (\%) \tag{5}$$

$$\text{Peak power indicator} = \left(1 - \left(\frac{\dot{Q}_{\max,MBC}}{\dot{Q}_{\max,\mathrm{BFB}}}\right)\right) \times 100$$

$$\text{and} \quad \left(1 - \left(\frac{\dot{W}_{\max,\mathrm{MBC}}}{\dot{W}_{\max,\mathrm{BFB}}}\right)\right) \times 100 \quad (\%) \tag{6}$$

3.2. Control system designs

A number of model-based controller designs were evaluated in order to explore the possibility of reducing complexity without compromising control performance. In Fig. 3, a scheme of the model-based control system is presented along with the benchmark feed-back control system, actuators and the controlled process. The investigated design parameters of the model-based controller are the type of disturbances used as exogenous inputs as well as the type of control model. The considered variants are presented in Table 3 along with an estimation of their complexity associated to installation and commissioning. Since the focus of this investigation is to determine the effect of these design parameters on energy efficiency, all other parameter settings were assumed to be ideal. Previously, it was mentioned that the HVAC-system supports the realization of the control signals as far as possible. It was also assumed that all measurements (of both disturbances and controlled variables) are perfect and that the models for simulation and for control are identical.

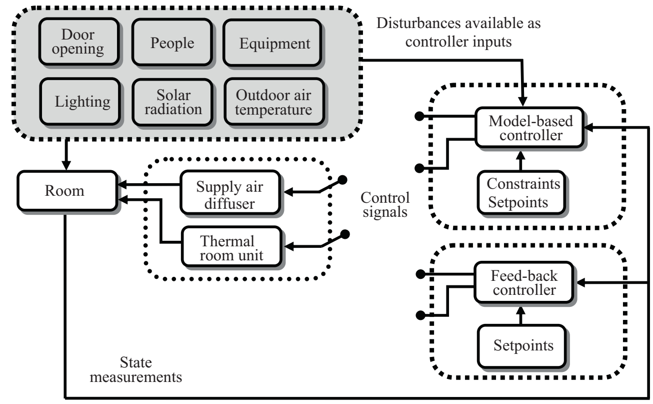

Fig. 3. Scheme of model-based controller along with the benchmark feed-back controller, actuators and controlled process. The available exogenous inputs are indicated by the filled box.

3.2.1. Exogenous controller inputs

The modeled disturbances were presented in Section 2.3 and the available controller exogenous inputs can be seen in Fig. 3 and Table 3. Other disturbances such as outdoor CO_2 concentration, outside air infiltration and temperatures in adjacent rooms were not considered in the investigation and were treated as constants in the simulations. Depending on the design of the model-based controller, the number of unmeasured disturbances will vary. In the most complicated configurations, all time-varying disturbances were used as exogenous inputs. In the simplest configurations, only one single time-varying disturbance was used at the time.

Among the available exogenous inputs, only occupancy can't be measured in a straightforward way but can on the other hand be estimated relatively accurate. Motion sensors can be used in rooms designed for one person and together with an assumed emission rate per person (based on the type of occupant activity that normally is performed) a fair estimation is possible [13]. Another relatively simple solution is to use CO_2 sensor responses to detect and estimate occupancy. This method is functional in all type of rooms and literature shows that both accurate and fast estimations are possible [24–27].

The door opening was treated a bit differently than the other disturbances since the signal requires a two step preprocessing before it can be expressed as corresponding thermal power and CO_2 flow rate. The air-flow rate through an open door was described by the empirical equation (7) [28] which contain three parameters; the height (H (m)) and the area (A (m^2)) of the door as well as a constant (K), which is dependent on the geometries of the controlled room and the adjacent (adj) room. K can either be determined experimentally or standard values given in the reference can be use. Furthermore, to determine the influence on the controlled

Table 3
Control models and exogenous inputs considered in the investigation.

Evaluated control models	Complexity of installation (computational)	Complexity of commissioning (tuning and validation)
Static non-linear filter	Very low	Low
Dynamic non-linear filter	Low	Low
Static predictive model:		
For temperature control	High	Very high
For IAQ control	Medium	Low
Dynamic predictive model:		
For temperature control	Very high	Very high
For IAQ control	High	Medium
Evaluated exogenous inputs	**Complexity of installation (sensor technology)**	**Complexity of commissioning (implementation in controller)**
Occupancy	High	Medium
Lighting	Low	Low
Equipment	Low	Low
Door opening	Low	High
Solar radiation	Medium	Low
Outdoor air temperature	Very low	Very high

The associated increase of control system complexity is graded from very low to very high.

variables, Eqs. (8a) and (8b) were used. This means that also the CO_2 and temperature differences over the door are required as inputs to the control model.

$$\dot{V}_{\text{door}} = K_{\text{door}} \times A_{\text{door}} \times \left(H_{\text{door}} \times \left|t_{\text{adj}} - t_r\right|\right)^{0.5} \quad (\text{m}^3/\text{s}) \tag{7}$$

$$\dot{Q}_{\text{door}} = \dot{V}_{\text{door}} \times \rho_{\text{air}} \times c_{p,\text{air}} \times (t_{\text{adj}} - t_r) \quad (\text{W}) \tag{8a}$$

$$\dot{M}_{\text{door}} = \dot{V}_{\text{door}} \times (c_{\text{adj}} - c_r) \quad (\text{ml/s}) \tag{8b}$$

3.2.2. Control models

Two different control models were tested for CO_2 control (i.e. for controlling the supply air diffuser) and four for temperature control (i.e. for controlling the FCU). Their complexities are primary dependent on the number of model parameters which spans from a large number to just one. One common feature of all investigated control models is that they are non-linear. Linear versions were omitted due to the risk of low performance since buildings behave non-linear when the supply air flow rate is variable [13].

3.2.2.1. Predictive control model. A predictive control model was evaluated for both CO_2 and temperature control by using discretized non-linear balance equations (mass and energy) of the room to predict the impact of measured disturbances. Besides of the evaluated time-varying disturbances, the predictive control model also requires information about the temperatures in adjacent rooms (the thermal boundary conditions) and outdoor CO_2 concentration which all were treated as constants in the simulations (see Section 3.2.1). The control signals are generated by taking the indoor climate constraints in Section 3.1, state measurements and predictions in to account. At each time step, the control signals are updated based on the current state and the predicted impact of measured disturbances. The controller aims to regulate the process from the current states to the least energy intense terminal states within the comfort ranges. This is done by taken the entire impact of the measured disturbances into account, i.e. both short-term impact (on the room air) and the long-term impact (on the building elements). The CO_2 terminal state is the 1000 ppm boundary since the supply air flow rate is then minimized. The room air temperature terminal state is the boundary of the temperature comfort region that requires least energy input; 21 °C if heating is required to stay within the comfort region and 22 °C if cooling is required. The predictive control model is based on the previous presented Eqs. (1a)–(1c) and was evaluated in a static and a dynamic arrangement. The dynamic version uses the full dynamic representation of room temperature and CO_2 while the time-derivatives are set to zero in the static version. The outputs from the dynamic model as a response to a measured disturbance are the minimum control signals for the room to go from the current states to the terminal states along a path of intermediate states. When the static model is used, the room air temperature and CO_2 are interpreted as independent on time, and the output is instead the minimum control signal for the room to go from the current states to the terminal states in one step.

In the temperature case, both the static and dynamic predictive control models become complicated due to the large number of parameters, even though the static version is a bit less extensive. In the CO_2 case, on the other hand, the static control model has a considerably lower complexity than the dynamic. The time-constant of the dynamic version is variable and needs to be estimated by measurements. When implemented, the risk of control model instabilities becomes large since measurement noise might be enhanced. As a consequence, complementary signal processing is then required [29]. Furthermore, also the volume of the room air (V_r (m^3), see Eq. (1d)) is needed in the dynamic case which on the other hand can be determined quite easily by measuring the room or from a blueprint.

3.2.2.2. Non-linear filter. To complement the investigation with a simpler control model for temperature control, a non-linear filter is proposed. The filter works in parallel with a feed-back controller and consists of the two parts in Eqs. (9a) and (9b) that works in sequence; one part for modulating cooling supply and one part for modulating reduction of heat supply respectively.

$$y_{\text{cooling}} = -\left(\left.\left(\frac{t_r - t_{r,\text{act,cooling}}}{t_{r,\text{sp,cooling}} - t_{r,\text{act,cooling}}}\right)\right|_{0,1} \times u\right) \tag{9a}$$

$$y_{\text{heating}} = 1 - \left(\left.\left(\frac{t_{r,\text{act,heating}} - t_r}{t_{r,\text{sp,heating}} - t_{r,\text{act,heating}}}\right)\right|_{0,1} \times u\right) \tag{9b}$$

The inputs to the filter are the measured thermal disturbances in power units (u) and the current room temperature (t_r). The measured thermal disturbances are summed up and transformed into a negative signal to correspond to an actuator control signal. In each part of the filter, this signal is scaled dependently on the current room temperature (t_r), a temperature setpoint ($t_{r,\text{sp}}$) and a parameter denoted as the activation temperature ($t_{r,\text{act}}$). The temperature setpoint and the activation temperature form a region in which the filter part is active. Between one of the activation temperatures and the corresponding setpoint, the exogenous inputs from

Table 4
The identified configurations of model-based controller design A (highest performance among all designs) and design B (highest performance among simplified designs) for CO_2 and temperature control.

	Disturbance sensors	Control model
CO_2 concentration control		
Design A	Number of people, door opening	Static predictive model
Design B	Number of people, door opening	Static predictive model
Room air temperature control		
Design B	All sensors measuring internal disturbances	Dynamic predictive model
Design B	All sensors measuring internal disturbances	Static non-linear filter

the disturbance sensors are scaled down from 99 to 1%. Above the setpoint for cooling, the entire disturbance sensor signals are utilized as cooling supply. Below the setpoint for heating, the output from the filter is zero. The activation temperatures are essentially design parameters that are determined in a similar way as the static gain of a FB-controller. Tuning the activation temperatures is to find a trade-off between stability and speed; activation temperatures close/far from the setpoints are associated to large/small gains. The non-linear filter was evaluated in two arrangements, one static and one dynamic, and the boundaries of the temperature comfort range were chosen as setpoints in both cases. In the static arrangement, the output is only dependent on the parameters and the current room temperature. The dynamic version is a first-order filter and the output from an active filter is in this case also dependent on time. The time-constant is a linear approximation of the room air response to a thermal disturbance as described in Eq. (1b).

3.3. Simulations

As a first step, the individual values of using the considered disturbances as single exogenous inputs to the evaluated control models were tested. It was assumed that the value of utilizing equipment, the thermal part from people and lighting as inputs were more or less the same which limited the number of simulations. Since each type of control model occurred in a pair (static or dynamic) three control models could be rejected after this step. Also, the disturbances that showed insignificant improvements on the control performance were rejected. In the second step, the remaining disturbances were combined stepwise and used as exogenous inputs to the remaining control models. To reduce the number of simulations, equipment and lighting were always used as inputs together. These two steps were repeated for the variants of building structure, type of room and weather. The final outcomes were the model-based controller designs A and B mentioned in Section 1.1. Design A had the highest performance among all of the investigated controllers and all types of control models and exogenous inputs were allowed in this design. In design B, the control model with the highest performance among the simplified control models (in Table 3: static predictive model for IAQ control and any of the non-linear filters for temperature control) was combined with the set of exogenous inputs that was pointed out as having the most significant impact on performance.

4. Results

In this section, the results from the investigation are presented. They derive from a large number of systematic simulations that follows the procedure described in the previous sections. Primary, this section aims to present the performance of controller design B (highest performance among simplified designs) and the difference compared to design A (overall highest performance) in order to determine the effect of varied complexity.

In Table 4, the identified configurations of designs A and B are presented. These results were consistent throughout the investigation which means that they were independent on the variants of the building, room and weather (summer or winter). Note that designs A and B have the same exogenous inputs for both CO_2 and temperature control. This means that the rest of the disturbances led to insignificant improvements of control performance and were thereby rejected. Further note that designs A and B also have the same CO_2 control models. Hence, designs A and B are identical for CO_2 control which means that the simplified design also resulted in the highest performance. To illustrate the features of designs A and B, results from two of the simulations are presented in Figs. 4 and 5. Fig. 4 derives from an office room simulation and Fig. 5 from a meeting room simulation. The figures illustrate how the CO_2 concentration and room air temperature are affected by the various disturbances (see Section 2.3) when the model-based controllers in Table 4 or their benchmark FB-controller were used. In the figures, the effects of the indoor climate constraints are visible. In the CO_2 cases, the maximum peaks have a value of 1000 ppm. In the room temperature cases, the degree hours outside the temperature comfort region (21–22 °C) are the same (zero) for all controllers which means that the benchmark FB-controller to designs A and B are the same.

4.1. Potential energy saving and peak power reduction

In the following tables, the performance indicators (see Section 3.1) for the model-based controller designs A and B are

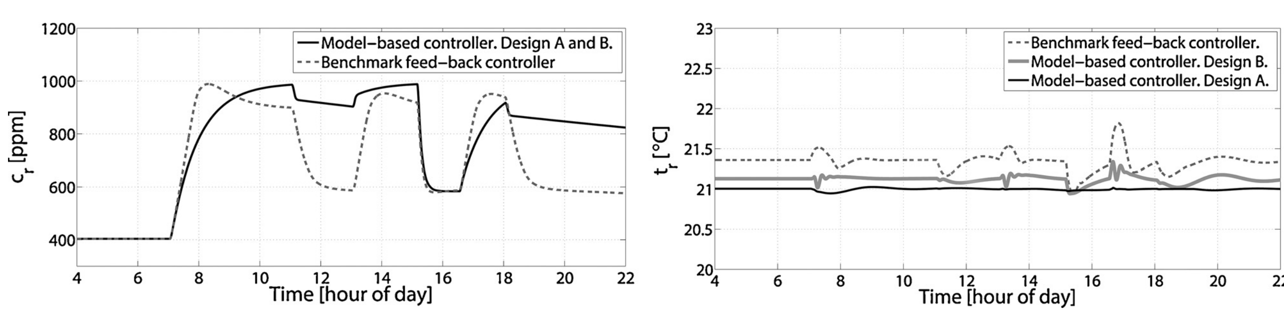

Fig. 4. Room CO_2 concentration (left) and room air temperature (right) controlled by model-based controller of design A, design B or their benchmark FB-controller. Simulated conditions: office room, light structure building and winter ambient climate.

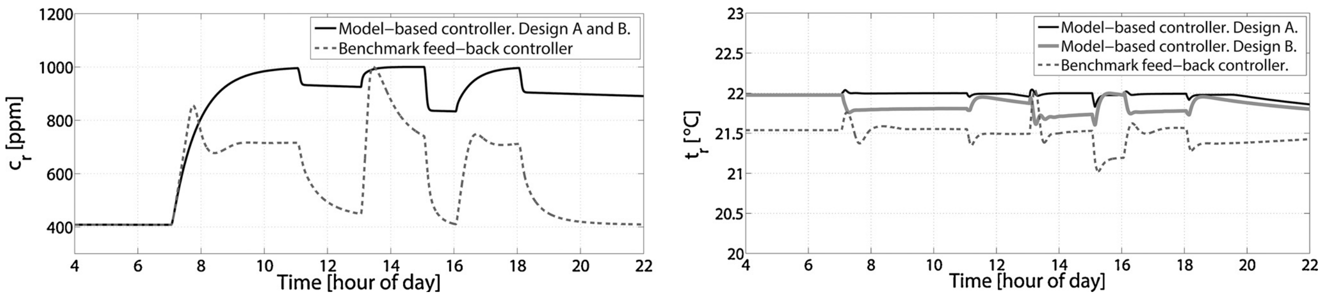

Fig. 5. Room CO_2 concentration (left) and room air temperature (right) controlled by model-based controller of design A, design B or their benchmark FB-controller. Simulated conditions: meeting room, heavy structure building and summer ambient climate.

Table 5
Performance indicators associated to model-based controllers of designs A and B.

Simulated conditions		Design A		Design B	
Ambient climate	Building structure	Total energy savings (%)	Peak power reduction Thermal/electrical (%)	Total energy savings (%)	Peak power reduction Thermal/electrical (%)
Summer	Heavy	8	12/35	6	4/35
	Light	7	11/35	5	6/35
Winter	Heavy	15	16/35	11	10/35
	Light	12	15/35	9	10/35

Simulated conditions: office room, winter and summer, heavy and light building structure.

Table 6
Performance indicators associated to model-based controllers of designs A and B. Simulated conditions: meeting room, winter and summer, heavy and light building structure.

Simulated conditions		Design A		Design B	
Ambient climate	Building structure	Total energy savings (%)	Peak power reduction Thermal/electrical (%)	Total energy savings (%)	Peak power reduction Thermal/electrical (%)
Summer	Heavy	34	37/72	28	23/72
	Light	20	31/72	19	6/72
Winter	Heavy	46	56/72	44	25/72
	Light	39	28/72	39	20/72

presented for all investigated conditions. The results are given as relative energy and peak power savings by replacing the benchmark FB-controllers for both CO_2 and temperature control. Table 5 presents the results from the office room simulations and Table 6 presents the results from the meeting room simulations. The tables show that, depending on the type of room, building structure and weather, design B results in 5–44% energy savings and in 4–25% thermal peak power savings. The electrical power savings are only dependent on the type of room since it is dominated by the fan power (i.e. the supply air flow rate). The tables also show that design A results in an energy savings between 7 and 46%, and a thermal power saving of 11–56%, again dependent on the room, building and weather. Since the ventilation control part is the same for designs A and B the electrical peak power savings are identical. The indicated energy savings in Tables 5 and 6 comes partly from that CO_2 and temperature can reside close to the boundaries of the comfort regions without breaching them when model-based controllers are used. This means that the supply air flow rate and heating or cooling supply are decreased compared to when the benchmark controllers are used. Reduced supply air flow rate leads both to a reduced fan power and reduced energy for air conditioning. Other parts of the energy savings, and most peak power savings, derives from that the response of the model-based controllers to a measured disturbance are faster and more accurate compared to the response of the FB benchmark controllers. The peak power of the FB controllers is a result of the delayed and insufficient initial response which later must be compensated by a large control signal increase.

5. Conclusions and discussion

In the following section, the conclusions from the investigation are presented. The main finding is that the design of model-based controllers for both temperature and CO_2 control can be substantially simplified without compromising the performance to any larger extent. Although a large number of model-based control designs were tested, this section focuses on design B and the differences compared to design A (see Table 4). The influence of the external climate, the type of building and rooms are also discussed.

5.1. Model-based control design

Independent on the type of control model and with no exception, the performance of the model-based controllers was close to unaffected when external disturbances (outdoor air temperature and solar heat gain) were used as exogenous inputs. External disturbances are dampened by the building to such a large extent that the control signals from the benchmark feed-back controllers and model-based controllers coincide from that point of view. On the other hand, all internal disturbances led to similar performance improvements. Internal disturbances directly affect the room air and cause large control activity and fluctuation of the controlled variables when feed-back controllers are used. Hence, without compromising performance to any larger extend, the complexity of model-based controllers can be reduced by only utilizing internal disturbances as exogenous inputs while the variations caused by external disturbances are managed by the state feed-back.

As mentioned, designs A and B were equal from a CO_2 control point of view which indicates that the performance of the static predictive control model was higher than the performance of the dynamic predictive control model. This result is due to a slight advantage of the static version due to the derivative action (which naturally comes from a static control model since the control signal response to a measured disturbance is a step) that indirectly compensated for transport delays in the room and HVAC-system. As indicated in Tables 5 and 6, the difference in energy saving between designs A and B was rather small. The reason is that only a small fraction of the total energy savings (about 5% in Tables 5 and 6) come from the temperature control part while the rest derive from the CO_2 control part. On the other hand, model-based temperature control led to substantial reduction of FCU peak power. Hence, without compromising the energy savings to any larger extent, the complexity of model-based controllers can be reduced by first and foremost manage the CO_2 control part. To reduce the peak power of TRUs, also temperature control can be considered, but then with a simple control model, such as the static non-linear filter.

5.2. Influence of building structure, disturbance pattern and weather

Both the potential of reducing energy usage and peak power by using model-based controllers are dependent on the conditions that were considered in the investigation. In this section, the most dominating influences of weather, building structure and disturbance pattern are presented and discussed.

The indicated savings were in general larger for meeting room simulations than for office room simulations. This result indicates that the potential of model-based controllers are largest in buildings and rooms where internal disturbances are dominating over external disturbances. The supply air flow rate could be reduced by about 50% in the meeting rooms when the model-based controller was used for CO_2 control. The corresponding reduction in the office rooms was about 10%. The overall savings were in general also larger in the heavy structure room simulations. The reason is that the temperature in a light structure is more difficult to control and the room for improvements is smaller. Recall that the heavy structure is made out of concrete and the light structure of gypsum, mineral wool and metal sheet. The features of these materials results in a smaller resistance and a larger capacity in the heavy case compared to the light case. The heavy structure room is thereby more affected by the isothermal boundary conditions and since these were set within the thermal comfort region, less effort is needed to maintain the room air temperature. Further, structures of higher capacity stores more heat which dampens the impact of disturbances and helps to maintain the room air temperature. The energy savings were also larger during winter than during summer due to a more energy intense air handling operation during winter. Finally, the peak power reduction of the TRU was larger during summer than during winter since the heat peaks occurred during vacant periods, i.e. when the controllers used constant temperature setpoints.

6. Summary

This paper investigated model-based controllers for indoor climate control in office buildings and explored the possibility of reducing complexity without compromising control performance. The investigation was performed in a simulated environment and was focused on temperature and CO_2 concentration control in individual office rooms during periods that were dominated by occupancy. Several model-based controller designs of different complexities were evaluated by varying the controller exogenous inputs and type of control model. The main finding is that the design of model-based controllers for both temperature and CO_2 control can be drastically simplified without compromising the performance to any larger extent. The HVAC energy savings were found to be between 5–44% and 7–46% when benchmark feed-back controllers were replaced by a simplified or a complex model-based controller respectively. The span of energy savings is dependent on the type of room, type of building and weather. The corresponding power savings were found to be between 4–25% and 11–56% respectively.

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Paper II

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CO_2 sensors for occupancy estimations: Potential in building automation applications

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ABSTRACT

It is well established that model-based controllers with an integrated control model and information about indoor climate disturbances have the ability to drastically improve the performance of building automation systems. In offices, occupancy is one of the most important disturbances to account for in this context, but the available methods for accurately determining the number of people are commonly too complex for considering at most sites. However, since model-based controllers can be made robust, input deficiencies can to a certain degree be compensated for, and in this work, a two step procedure was applied to investigate the potential of utilizing simplified estimations generated from CO_2 sensor responses. First, the expected time delay and error of such estimations were derived experimentally for various occupancy changes and ventilation flow rates. Next, an office site was simulated and the occupancy information used by a model-based controller for ventilation control was stepwise subjected to various errors and time delays by considering the expected values as references. The results showed that the estimations in many case were sufficient for achieving a high control performance, but beyond a certain level, the deficiencies could only be met by an increased complexity of the controller.

1. Introduction

Model-based controllers are a group of controllers that utilize measurements, predictions and/or estimations of process disturbances as exogenous inputs to an internal control model. In turn, the control model predicts the corresponding impact on the controlled variables and subsequently adjusts the control signals to achieve a desired behavior of the process. Several works have shown that model-based controllers have a large potential for improving the building automation system (BAS): the energy usage can be reduced substantially, compared to when more conventional control methods are used, at the same time as a desirable indoor environment is achieved [1–5]. However, a significant obstacle for a wide spread utilization is that model-based controllers commonly are complex, and in order to avoid a substantial increase of BAS extensiveness when implemented, simplified options for both control models and disturbance sensing system must be available. This topic has previously been addressed in [6–8], whereof the first two evaluated the difference between predicted (complex) and measured (less complex) occupancy as exogenous input, and both found that an increased complexity only led to marginal improvements. The investigation in [8] aimed instead to identify disturbances in office environments with potentially large impacts on control performance, and the main conclusion was that all of internal origin preferable should be utilized as measured exogenous inputs.

Even though these cited works managed to reduce complexity without compromising control performance to any larger extent, a common feature was that the exogenous inputs and the corresponding disturbances were assumed to be equal, which in reality is hard to obtain. In office buildings, this issue especially concerns occupancy (referring to the number of people), which on one hand is an important disturbance to consider in BAS applications, but on the other, cannot be measured directly. Most available options, such as cameras and optical sensors at entrances, are either associated with high complexities or large uncertainties. PIR (Passive InfraRed) motion sensors are relatively cheap but only feasible in rooms designed for one person. Prediction models are in general complex and usually insufficient (even in combination with direct sensors) since the nature of occupancy is highly uncertain [9,10].

1.1. Background

As occupancy is a disturbance with large influence on the thermal climate and IAQ (Indoor Air Quality) in office buildings, its potential as exogenous input to model-based controllers for indoor

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Nomenclature

c	CO_2 concentration [ppm]
$\dot{M}$	CO_2 emission rate [ml/s]
n	number [−]
V	volume [m^3]
$\dot{V}$	volume flow rate [m^3/s]

Greek letters

τ	time [s]

Subscripts

inf	infiltration
o	outdoor
s	supply
sp	setpoint
r	room

climate control is high. But, accurate information about the number of people typically requires extensive systems of sensors and/or models that culminate in a substantial increase of BAS complexity. However, one important aspect is that model-based controllers can be made very robust to deficiencies in the exogenous inputs since a state feed-back function commonly is integrated. Hence, simple estimation methods with relaxed accuracy might be sufficient enough to increase the control performance significantly compared to omitting occupancy as exogenous input. The case for using more elaborate methods for producing more accurate data may be hard to encourage.

This paper investigates a simplified model-based control system by which occupancy in cellular office environments is estimated using CO_2 sensor responses. The obvious advantage of this approach is that the associated sensor is simple and easy to implement. CO_2 level control is already used in many ventilation control strategies, so suitable sensors are commercially available; and in some cases already installed. CO_2 is further an appropriate indicator for the number of people in office building since there are no other disturbances that affect the level to the same extent. However, the quality of the estimations (and in turn the performance of the control system) might also be limited by two factors that are important to consider in the context of this work: first, uncertainties in the accordance between CO_2 sensor responses and the number of people (i.e. the aspect of estimation errors), and second, latency of the CO_2 sensor responses (i.e. the aspect of time delay) [11].

1.2. Purpose and procedure

This work consists of one experimental part performed in an office seminar room, and one subsequent theoretical part in which the same site was simulated. During the experiments, a CO_2 sensor was implemented and responses were recorded for various changes in occupancy and ventilation flow rates. Based on these results, the expected error and time delay for estimating the number of people were quantified. Next, the simulation part considered a scenario in which estimated occupancy was used by a model-based controller to minimize the ventilation rate while maintaining IAQ. The influence of the estimation deficiencies from the first part was evaluated by step-wise increasing the error and delay, while considering the expected values as references. To account for controller robustness (and complexity), the scenario was repeated with a comprehensive closed-loop MPC (Model Predictive Controller) and a simplified open-loop predictive controller (OLPC). Additionally, simulations were also conducted with a feed-back (FB) controller to represent the current state of practice in CO_2 ventilation control.

The focus of previous publications that have studied the occupancy estimation method of concern was primarily to find a suitable algorithm for the conversion between recorded CO_2 and the number of people. Several works have pointed out that the most appropriate choice is a transient CO_2 mass-balance, and the estimation method is then referred to as the direct dynamic approach (to use a mass-balance is in the general case referred to as “the direct approach”). By considering the direct dynamic approach (DDA) as a reference, this work aimed to determine the fundamental possibilities and limitations of the estimation method; specific to the case when the returned occupancy is used as input to model-based controllers for ventilation control. This was done by focusing the experimental study on the fundamental elements that determine the ability of the DDA to estimate the number of people from CO_2 responses, without implementing an occupancy conversion algorithm. In this way, a high level of objectivity was maintained by avoiding any subjective limitation introduced by the algorithm design.

1.3. Literature review and contribution

As described in the previous section, this work consists of two parts. In the experimental study, limiting factors of CO_2 sensor responses for occupancy estimations were quantified. In the simulation part, the corresponding influence on the performance of model-based controllers for IAQ control was determined. No previous works have been found that covers the same topic as the simulations, so, the following section is instead dedicated to the experimental study. First, the most relevant previous publications are reviewed, and then, the aspects that differentiate these from this paper are discussed.

Although occupancy estimations have been covered in several works, only a handful involves non-complex methods that have been experimentally validated. The purpose in [12] was to find a suitable algorithm with the exhaust air CO_2 level as input, and three versions of the direct approach were implemented at two sites (an entire floor of an office building and a lecture hall). The result showed that the DDA was accurate and fast while a static version only performed during high air exchange rates. Similar studies were also presented in [9,13]: the respective sites were an open-office and a lecture hall, the CO_2 levels were measured in the room respectively in the exhaust air, and both showed that the DDA returned fast estimations with accuracies of 20% in [9] and of ±2 people in [13]. A bit different approach was presented in [14]: the purpose was to determine the correlation between occupancy and environmental data (such as CO_2, temperature, humidity and acoustics) collected in an open-office designed for about 50 people. CO_2 alone had approximately a 70% correlation to occupancy and when several of the quantities were combined, the correlation increased above 90%.

There are four major differences between this work and other relevant publications. First, while the estimation error was reviewed in several of the cited works (but under different circumstances than studied here) the time delay was never quantified. Second, none of the works studied the influence of occupancy density on the estimation possibilities. Ref. [11] was the only work that considered a variable ventilation flow rate, but then with the aim to determine the stability of the DDA. Third, this paper seeks to determine the lower performance boundary of a model-based control system that utilizes occupancy information retrieved from CO_2 responses. The investigation was therefore focused on conditions that are unfavorable (but still realistic) for occupancy estimations: accurate and fast estimations become harder with decreased source strength (due to a decreased CO_2 sensor response) as well as with

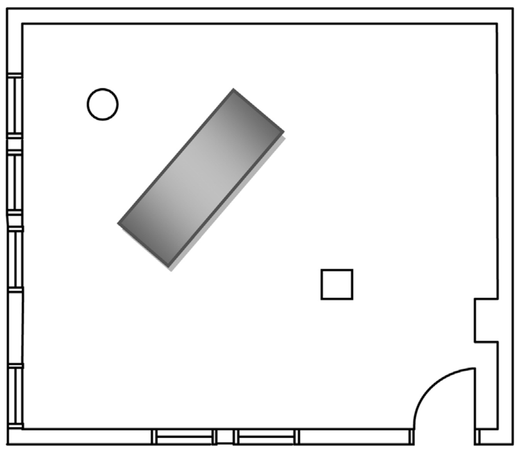

Fig. 1. Layout of the seminar room. Rectangle: occupied space, circle: supply air diffuser, square: exhaust air diffuser.

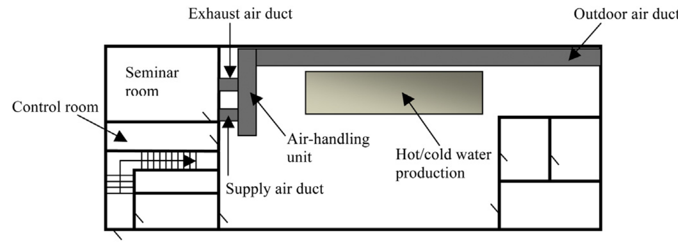

Fig. 2. Layout of the test facility.

decreased ventilation flow rate and increased room volume (since both transport delay and time constant of the room air CO_2 level then are increased). For that reason, the experimental study considered low occupancy densities and low ventilation air flows in a site which is relatively large in cellular office environment terms. The cited works have instead focused on sites with high occupancy densities and of sizes larger than what's common in cellular office buildings. The fourth and final difference is that most cited works aimed to evaluate a certain algorithm and the experiments were conducted during normal operation. In this paper, a more systematic approach was chosen to instead determine the fundamental properties of CO_2 sensors for occupancy estimations. The methodology in [14] is the closest to that spirit since their focus was on determining a correlation between different sensor responses (including CO_2) rather than the more common approach to test a certain algorithm. However, in [14], the site was a large open-office space and neither the influence of time delay, ventilation flow rate or occupancy density were considered.

2. Experimental study

In this part of the work, CO_2 sensors for occupancy estimations were investigated experimentally in a facility located in the city of Gothenburg, Sweden. In the following chapter, the test facility and the procedure are first described and then the outcome is presented and discussed.

The experiments were conducted in a seminar room (Fig. 1) which is located in the north-west corner of the facility (Fig. 2). It has a floor area of 5.6 × 6.2 m, a height of 2.4 m and indoor climate control is primarily managed with underfloor heating and by a VAV (Variable Air Volume) ventilation system. The central part of the ventilation system is made up of an air-handling unit (AHU) which is located in a large open hall that also contains various units for production and storage of hot and cold water. Heating and cooling carriers are in turn used in the AHU to condition outdoor air, while two integrated fans ventilate the seminar room via a duct system. On room level, the ducts are connected to ceiling mounted diffusers that are marked out as a circle (supply air) and a square (exhaust air) in Fig. 1. The HVAC system is controlled and observed from the control room to the left in Fig. 2 in which a BAS for the entire facility is installed. The underfloor heating system is capacity controlled by varying the water inlet temperature by a shunt, while the ventilation air flow is adjusted by a variable speed drive of the AHU fans, as well as by automated diffuser openings. Further, a data acquisition system is used to store measurements of ventilation flow rates as well as temperatures and CO_2 concentrations at different points in the facility, and all sensors that were used in the experiments had been calibrated and adjusted in advance.

2.1. Experimental design

In Table 1, the 10 scenarios that were considered during the experimental study are presented. CO_2 sensor responses were recorded for all combinations of occupancy changes between 1 and 3 people, and ventilation flow rates of 1–3 ACH (Air Changes per Hour, [1/h]), while an occupancy change of 4 also was specifically considered for 3 ACH. These ranges are representative for an office seminar room with hygienic ventilation and a large proportion of vacant space. This provides the desired environment to focus the experimental study on unfavorable conditions for occupancy estimations (small occupancy changes and low ventilation air flows). In turn, these conditions will determine the lower performance boundary of the model-based controllers in the simulation study.

The considered scenarios were investigated separately and the same procedure was followed throughout the study. First, the ventilation air flow rate was set within the considered range, and then, a number of demographically similar test subjects (males of similar age, weight, height etc.), again within the considered range, entered the room. The door was securely closed and the test subjects took places at the table depicted as a rectangle in Fig. 1 and performed office-like activities such as talking, reading and writing on laptops. During the experiments, both the supply air temperature and the room air temperature were closely maintained to levels of 19 °C and 21 °C, respectively, via the AHU air-heater and the underfloor heating system.

2.1.1. Prestudy regarding sensor location

When the DDA is used to estimate occupancy, the associated CO_2 sensor should preferably return measurements that are independent on the relative distance between sensor and source (people)

Table 1
The 10 combinations of ventilation flow rates and changes in occupancy that were considered during the experimental investigation.

Ventilation flow rates ACH (1/h)	Change of occupancy (number of people)			
	1	2	3	4
1	Scenario 1	Scenario 2	Scenario 3	–
2	Scenario 4	Scenario 5	Scenario 6	–
3	Scenario 7	Scenario 8	Scenario 9	Scenario 10

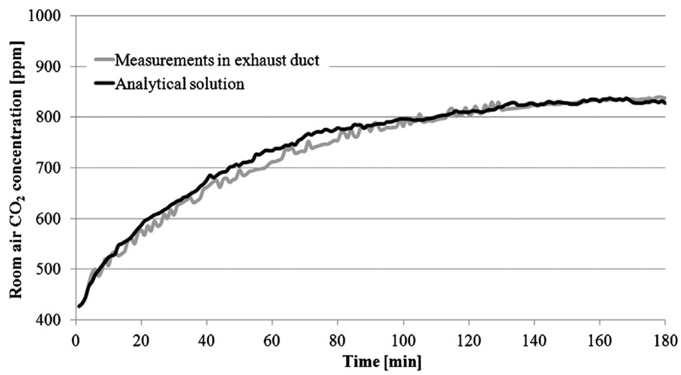

Fig. 3. CO_2 measurements in the exhaust duct vs. an equivalent analytical solution. Conditions: 1ACH and 2 persons.

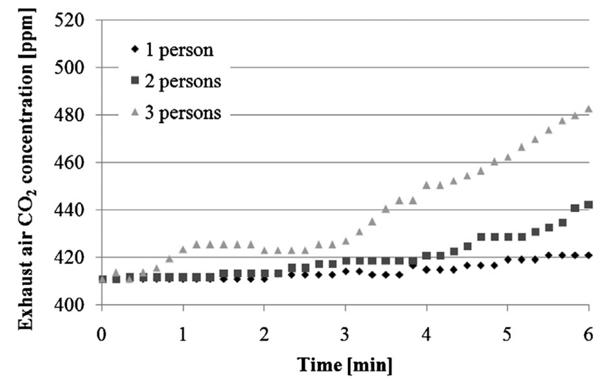

Fig. 4. CO_2 sensor responses as a function of time for scenarios 1–3 in Table 1. Ventilation flow rate: 1 ACH.

as well as uninfluenced by CO_2 stratification. These factors are primarily determined by the sensor location and should be avoided in order for the measurements to approach the system representation in the DDA algorithm. Hence, any measurements and the corresponding solution of a transient CO_2 mass-balance should be as similar as possible (provided that they were generated from identical conditions). While no definite answer about sensor location was given in the cited works, a prestudy was applied to determine the relevance of choosing the exhaust air duct as a measuring point. In this section, the procedure of this prestudy is first explained which is followed by a presentation of the outcome.

The CO_2 sensor in the exhaust air duct has a working range of 0–2000 ppm and an accuracy of ±40 ppm. During the prestudy, measurements that covered the complete response of the room were generated for the arbitrary case when two people entered the seminar room with a ventilation flow rate of 1 ACH. The equivalent conditions were plugged in to the mass-balance presented in Eq. (1b), together with measured supply air CO_2 concentration and an estimated infiltration flow rate ($\dot{V}_{\text{inf}}$) (Eq. (1a) [8] is in a more general form which will be considered later on).

$$\frac{dc_r}{d\tau} \times V_r = \dot{c}_{\to r} - \dot{c}_{r\to} + \dot{M}_{CO_2,i\to r} \tag{1a}$$

$$\frac{dc_r}{d\tau} \times V_r = \dot{V}_s \times (c_s - c_r) + \dot{V}_{\text{inf}} \times (c_o - c_r) + \dot{M}_{CO_2} \tag{1b}$$

The outcome is presented in Fig. 3 and it is obvious that the considered sensor location provides stable measurements that furthermore can be described by the mass-balance in Eq. (1b). Since the calculation was performed at one well-mixed node (and thereby represents the average CO_2 in the room), it could also be concluded that the measurement were not influenced by CO_2 stratification to any larger extent.

2.2. Results from experimental study

During the experimental study, the responses of a CO_2 sensor located in the exhaust air duct were recorded for various combinations of occupancy changes and ventilation air flow rates. Among this data, the least preferable conditions for converting the responses into occupancy estimations were identified, and by considering the fundamental elements of the DDA, the associated error and time delay were derived. This procedure begun by grouping the experiments according to the ventilation flow rate for which they were conducted. By referring to the designations in Table 1, the first group contained scenarios 1–3, the second group contained scenarios 4–6, and the third group contained scenarios 7–10. Under this grouping methodology, all group experiments spanned occupancy changes of at least 1–3 persons. For each group, the expected time delay was then determined as the elapsed time until the majority of experiments (at least 2) could be differentiated from each other by distinct CO_2 levels. This is the most fundamental factor to consider in this context since a distinct difference in CO_2 levels follows from a distinct difference in CO_2 gradients, which in turn is the indicator used by the DDA to estimate changes in occupancy. Next, the expected estimation error was determined as the difference in occupants between experiments that could not be differentiated from each other after the previously derived time delay. Finally, the largest time delay and estimation error among all groups were selected and passed over to the simulation part of the work.

The CO_2 measurements that were recorded during the 10 experiments in Table 1 are presented in Figs. 4–6 according to the grouping performed during the data analysis. At time zero, the occupancy changed from zero to the value indicated in the legends, and the figures are associated to a constant ventilation flow rate of 1–3 air changes per hours, respectively. As indicated, the CO_2 concentration was registered every tenth second, and 6 min of data was sufficient to draw the desired conclusions about all investigated scenarios. By first reviewing Fig. 4, it can be seen that a time delay of about 4 min was required until a distinct difference between the scenarios associated to 2 and 3 people (number 2 and 3 in Table 1) was achieved. The same applies to Fig. 5 (scenario 5 and 6 in Table 1), but in this case the difference was lost after about 4 min due to a declining gradient associated to the 3 people scenario. In Fig. 6, on the other hand, 3 min was sufficient to differentiate all four cases from each other (number 7–10 in Table 1).

2.3. Outcome of the experimental study

From Figs. 4–6 it is clear that the estimating ability of a CO_2 sensor is dependent on both the ventilation flow rate and the

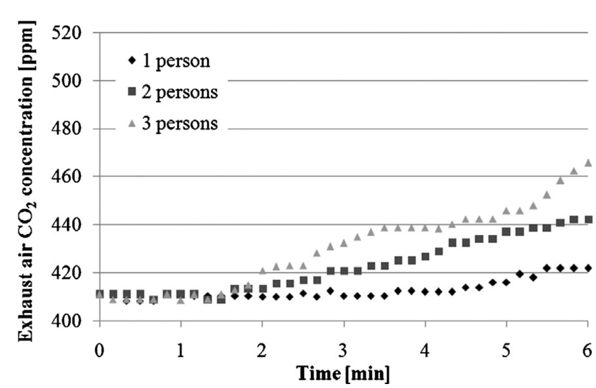

Fig. 5. CO_2 sensor responses as a function of time for scenarios 4–6 in Table 1. Ventilation flow rate: 2 ACH.

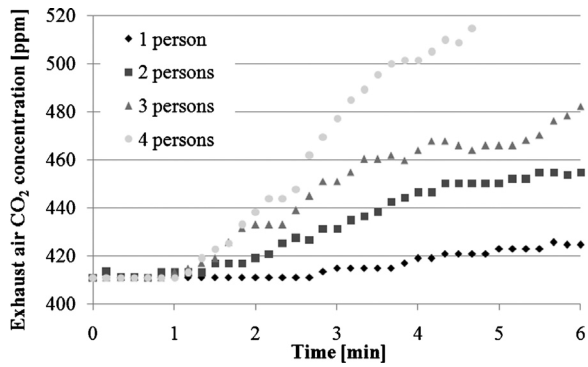

Fig. 6. CO_2 sensor responses as a function of time for scenarios 7–10 in Table 1. Ventilation flow rate: 3 ACH.

number of occupants. But generally, for the considered flow rates of 1–3 ACH, there was a distinct difference in the CO_2 levels associated to the 2–4 people scenarios after about 3–5 min (4 persons were only considered in the 3 ACH case). Hence, in these cases, time delays smaller than 5 min can be expected. On the other hand, when 1 person entered the room (scenario 1, 4 and 7), the time delay was typically longer, and it took about 6 min until the deviation from the initial CO_2 level was noticeable (in these cases, the CO_2 had increased with 10–15 ppm after 3–5 min which is in the range of being mistaken for measurement noise). Hence, if a time delay of 5 min is selected as an input value, it is reasonable to have an estimation error between −1 and 0 persons.

Remark 1. A commercial CO_2 sensor typically has an accuracy of about ±50 ppm, and calibration drifts can furthermore be expected. However, since occupancy is estimated by changes in CO_2 (i.e. the deviation from an initial level), the absolute level is of less importance in this context.

Remark 2. According to Swedish common practice, the supply air during the experiments was entirely made up of conditioned outdoor air, while several of the cited works considered sites in which recirculation of exhaust air was used. When implementing the DDA, the only difference between these cases is that the supply air CO_2 concentration term (c_s) in the mass-balance (Eq. (1b)) either is a constant or a variable. Hence, since this system aspect is taken into account by the algorithm, it has no influence on the estimations. This means that the quality of the estimations in both cases is entirely dependent on the properties of the room CO_2 responses, and that the results in this paper are of equal relevance.

Remark 3. One way of reducing the effect of prolonged delays for small changes in occupancy is to combine the CO_2 measurements with a motion sensor (for example PIR). A motion sensor response indicates that a vacant room has been occupied, and if the corresponding short-term CO_2 response is very low, it is reasonable to assume that also the change of occupancy was small.

Remark 4. It is worth mentioning that a CO_2 sensor located inside the room also was tried out during the investigation. The results showed that the time delay was shorter (just a few seconds) but the fluctuations of the measurements were quite large which led to inconsistent results.

3. Simulation study

It was previously established that a combined time delay of 5 min and an estimation error between −1 and 0 is reasonable to expect when the number of people is estimated with CO_2 responses during unfavorable conditions. In this part of the work, the influences of these factors were investigated through simulations for a case when occupancy information was used by a model-based controller for ventilation control in an office room. The task of the control system was to maintain the IAQ (indicated by the CO_2 level) as the number of occupants was increased, and simulations were repeated for various time delays and errors subjected to the information used by the controllers. To consider the influence of controller complexity, the model-based controller was evaluated in one comprehensive and one simplified version. Further, a conventional feed-back controller with no information about occupancy was used as benchmark.

3.1. Simulation framework

In this section, first the modeling approach is briefly described and then the different controllers that were considered are introduced. The simulations were performed in a MATLAB® Simulink® model consisting of a building and an HVAC (Heating, Ventilation and Air-Conditioning) part. These are in turn made up of a large number of component models that describe how temperature and CO_2 is varied throughout the system. In the following text, the CO_2 part of the system model is described: the remaining parts were not involved in the investigation and is therefore left out in further considerations. For more information about the component models, consider [15].

3.1.1. Models for simulation

Both the office room and the associated HVAC system were modeled to reassemble the site from the experimental part, i.e. a seminar room equipped with a VAV (Variable Air Volume) ventilation system (see Section 2). The functions of the modeled and experimental HVAC systems are identical and the simulated model-based controllers were used to control the CO_2 concentration inside the room by varying the speed of the supply air fan. Further, secondary control loops were used to control the exhaust air fan to achieve balanced ventilation. The building part was modeled as a single seminar room and the CO_2 level was calculated in one node by the mass-balance in Eq. (1a). The terms on the right hand side describes the CO_2 exchanged to the room ($\dot{c}_{\rightarrow r} - \dot{c}_{r\rightarrow}$) and the CO_2 emitted within the room by people ($\dot{M}_{CO_2,i\rightarrow r}$). Assumptions made in the CO_2 mass-balance include the following:

- Infiltration of outdoor air is constant and low.
- Occupants are the only source of CO_2.
- CO_2 generation rate is constant for all occupants.
- Supply and room air are perfectly mixed.

3.2. Controller formulations

The controllers that were considered in the investigation are presented in the following sections. Their general schematics are given in Fig. 7, and in this work, the state measurement input refers to the current CO_2 level in the room, the exogenous input refers to occupancy (i.e. the number of people) and the control signal refers to the ventilation supply air flow rate. In total, three controllers were considered; the model-based controller was evaluated in an open-loop and a closed-loop version, and a feed-back controller was used as benchmark. To ensure comparability, the considered controllers were constrained to maintain an acceptable IAQ defined as CO_2 levels below 1000 ppm. This metric has been suggested in several national recommendations [16] as well as by ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) in standard 62-1989 [17]. An important remark in this context is that CO_2 itself is not considered as harmful until in concentrations way above 1000 ppm. On the other hand, the CO_2 level in buildings correlates to human metabolic activity and is therefore commonly used to indicate the perceived IAQ. The purpose of the

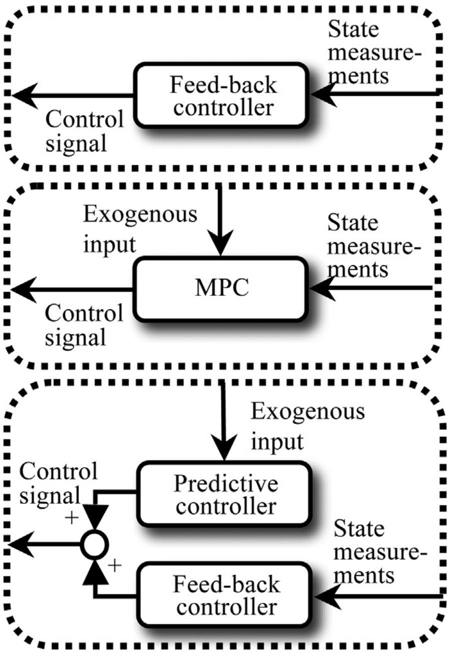

Fig. 7. Schematics of (from top to bottom) (1) Benchmark feed-back (FB) controller. (2) Closed-loop model predictive controller (MPC). (3) Open-loop predictive controller (OLPC).

metric is hence to maintain acceptable levels of other emissions that derive from occupancy such as bio affluences and body odor [18].

The performances of the controllers were measured by the maximum CO_2 setpoint deviation that subsequently followed from the increased number of occupants (Eq. (2)). By using identical setpoints of 1000 ppm for all considered controllers, this metric indicates how much the setpoints need to be reduced in order to fulfill the IAQ constraint and remain inside the acceptable region. Small setpoint deviations are associated to high controller performances since the CO_2 level then can reside close to the 1000 ppm limit which means that an overall lower supply air flow rate is required. In turn, the associated energy for fans and air handling is then decreased.

$$\text{Maximum } CO_2 \text{ setpoint deviation} = \left(c_{r\,max} - c_{r\,sp}\right) \text{ [ppm]} \quad (2)$$

3.2.1. Benchmark feed-back controller

The benchmark feed-back controller (top of Fig. 7) was introduced to represent the conventional approach for CO_2 ventilation control in office buildings. It is of PI-type with ideal settings of static gain and I-time (according to the AMIGO method). The control signals are solely based on measurements of the current state (i.e. the CO_2 level inside the room) and the corresponding sensor was modeled as state-of-the-art regarding response and without measurement errors.

3.2.2. Model-based controllers

Both versions of the model-based controller (see number 2. and 3. in Fig. 7) use a discretized variant of the CO_2 mass-balance in Eq. (1a) as control model. Besides of occupancy, the model-based controller also uses information about the outdoor CO_2 concentration (treated as constant in the simulations) as well as the current state (CO_2 level in the room). The mass-balance is used to predict the impact of occupancy on the room CO_2 and to determine the required ventilation flow rate to fulfill the IAQ constraint (below 1000 ppm) at the same time as the energy usage is minimized (by minimizing the ventilation flow rate). Since the focus of this investigation is to determine how model-based controllers with estimated occupancy as exogenous input are affected by time delays and errors, all other parameter settings were assumed to be ideal. Therefore, the models for simulation and for control are identical in this work.

3.2.2.1. Closed-loop model predictive controller (MPC). The closed-loop version of the model-based controller (middle of Fig. 7) is equipped with the full dynamic representation of the room and is characterized as a receding horizon controller (RHC) MPC. The closed-loop denotation refers to that the predictions are based on both the current state and occupancy (as exogenous input) which makes the MPC robust to errors associated to the control model and to the inputs. The control signals are generated by minimizing the objective function J (Eq. (3)) which is constrained to restrict the solution to the allowed states, (x_k, i.e. CO_2 concentrations below 1000 ppm) as well as to the allowed region of supply air flow rates (u_k). At each time step, the current state and the exogenous input were registered and the optimization problem was solved over a 90 min control horizon (N). N was set to cover the entire dynamic of the room CO_2 and it was confirmed that a longer horizon did not improve the control performance. The solution is a sequence of future optimal control signals (U) that are associated to an optimal future process trajectory from the current state (x_k) to the terminal state (x_N) that satisfies the dynamics and constraints of the process while the energy usage is minimized. However, only the first control signal in the sequence is implemented. The horizon is then moved forward and the procedure is repeated again for the next time step until the system has converged to the terminal state; hence the name receding horizon. Since any applied control signal is a function of the previous state and the previous exogenous input, the receding horizon introduces feed-back and the solution corresponds to a closed-loop approach [2].

$$\begin{aligned} J &= \min_{U} \quad x'_N P x_N + \sum_{k=0}^{N-1} x'_k Q x_k + u'_k R u_k \\ U &= \left[u'_0, \ldots, u'_{N-1}\right] \\ &s.t. \\ &(x_k, u_k) \in x_k, u_k \end{aligned} \quad (3)$$

The quadratic form of the objective function in Eq. (3) is suitable for optimization purposes since the least-square method can be used. The weights P, Q and R were tuned to assure stability and persistent feasibility (i.e. that the control task can be fulfilled without violating the constraints). Stability can be guaranteed by designing the objective function as a Lyapunov function [19]. But in practice, this property is generally relaxed for stable systems with slow dynamics, such as buildings, which means that the objective function could be designed by focusing on performance criterions.

3.2.2.2. Open-loop predictive controller (OLPC). The open-loop version of the model-based controller (bottom of Fig. 7) is a predictive controller that was introduced as a simpler alternative to the MPC. It is equipped with a static representation of the room and is not characterized as an MPC since the optimization part is removed. Occupancy is still used as exogenous input to the control model but the continuous state measurements are replaced with information about the initial state. Instead, a feed-back controller, identical to the benchmark used in this work, was connected in parallel to the predictive part. As a response to a changed level of occupancy, the prediction part computes the smallest control signal (a single one, due to the static interpretation of the room) required to remain at the setpoint. This signal is kept until the next change is received which means that any adjustments from the predicted trajectory are managed by the feed-back controller. The complexity of the

OLPC is considerable lower than the complexity of the MPC, both from a commissioning and computational point of view, due to a number of reasons. First, when implementing the MPC, the risk of instabilities is imminent since CO_2 measurement noise might be enhanced. As a consequence, complementary signal processing and/or noise models are required [12]. Second, the volume of the room air (V_r [m^3], see Eq. (1b)) as well as the transport delays and time constant of the HVAC system components (including sensors) are needed to design the MPC while they can be omitted in the OLPC case due to the static control model. Third, the tuning of the weights in the objective function can be an extensive and time consuming process. In the OLPC case, only the feed-back part needs to be tuned which is a procedure for which several well-established methods are available.

3.3. Simulations

The simulation study was conducted for one controller at the time. Initially, the seminar room was subjected to one person and when the CO_2 level had reached the controller setpoint, the occupancy was increased by three. The maximum CO_2 setpoint deviation was documented, the time delay or error of the occupancy signal was slightly increased and the procedure was repeated. These two parameters were studied separately by performing stepwise modifications of one while the other was set to zero. The time delay was varied within an interval between 0 and 30 min, where the largest value is beyond the effective maximum when the settling time of the room CO_2 is exceeded. The estimation error was in turn varied between −3 and +3, where the smallest value corresponds to the absolute minimum when the error cancels the actual increase. Further, the span of errors was set to account for scenarios in which the number of present people is underestimated (errors below zero: estimation <actual) as well as overestimated (errors above zero: estimation> actual) by the algorithm.

Remarks. An occupancy increase of three was chosen since this magnitude was investigated for all considered ventilation flow rates in the experimental part. Further, to initiate the simulations with one person inside the room was chosen as a worst case scenario, since then, the CO_2 initially resides at the setpoint. A fast controller response is then of certain importance which means that the quality of the occupancy estimations has a large influence on the performance of the model-based controllers.

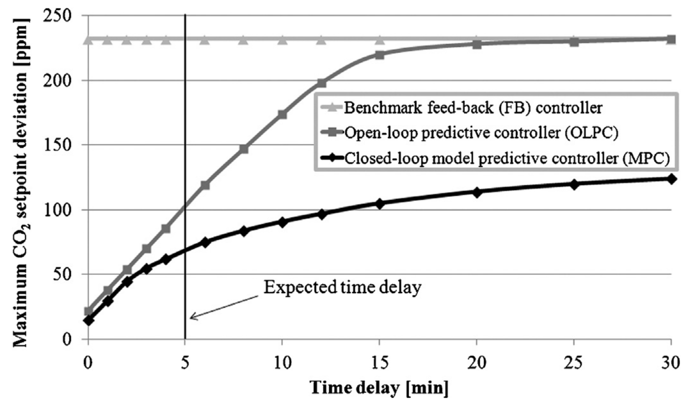

Fig. 8. Maximum CO_2 setpoint deviation as a function of time delay subjected to the occupancy information used by the model-based controllers. The expected time delay derived in the experimental part of this work is marked out.

3.4. Results

In this section, the results from the simulation study are presented. The aim was to determine how the performance of model-based controllers is affected by deficiencies in occupancy information (with respect to time delay and error) when utilized as exogenous input. The controllers were applied for IAQ control in an office room (see Section 3.1.1), the study was conducted for two types of model-based controllers and a feed-back controller was considered as benchmark (see Section 3.2). In Figs. 8 and 10, the performance metric of the controllers (i.e. the maximum CO_2 setpoint deviation) are presented as a function of time delay and estimation error subjected to the occupancy information. To clarify these results, the simulations associated to the expected quantities of these deficiencies (as marked out in Figs. 8 and 10) are further presented in Figs. 9 and 11. Recall that the benchmark FB-controller solely relies on the CO_2 level inside the room and its performance was therefore unaffected throughout the investigation.

Fig. 8 presents the maximum CO_2 setpoint deviation as a function of time delay subjected to the occupancy information used by the model-based controllers, and Fig. 9 presents the simulation associated to the expected delay of 5 min. At and below this quantity, the performances of the two model-based controllers are similar, but the difference increases rapidly for longer delays since

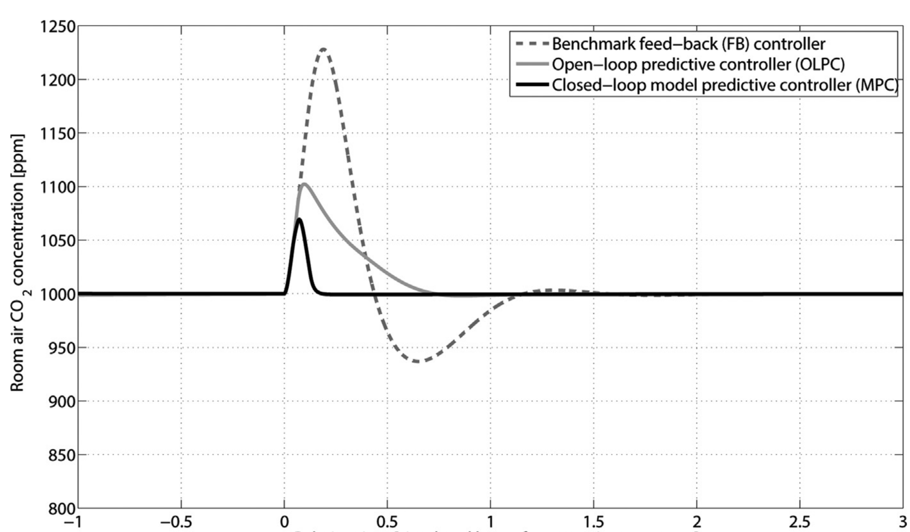

Fig. 9. Simulation associated to the expected time delay of 5 min subjected to the occupancy information used by the model-based controllers.

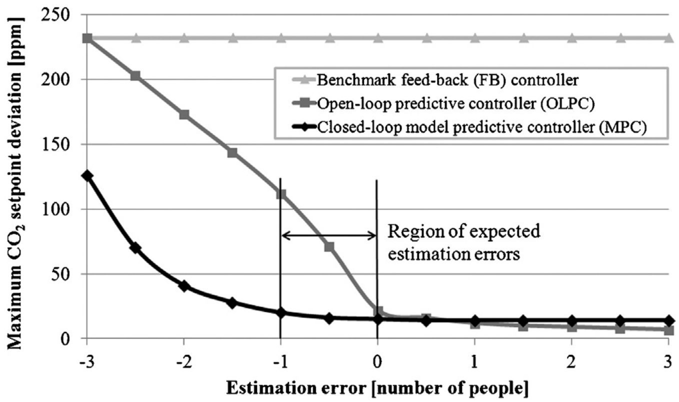

Fig. 10. Maximum CO_2 setpoint deviation as a function of estimation error subjected to the occupancy information used by the model-based controllers. The expected estimation error derived in the experimental part of this work is marked out.

the setpoint deviation associated to the OLPC grows considerable faster. For both model-based controllers, it is clear that the setpoint deviation converge to a value which is reached when the time delay exceeds the settling time of the system. After that, the change in occupancy level is not taken into account and the controllers solely rely on information about the current state. When the MPC is used during these circumstances, the setpoint deviation is still about 60% lower compared to when the benchmark FB-controller is used, due to the ability of performing predictions even when the exogenous input is missing. The prediction part of the OLPC requires on the other hand the exogenous input to function, and eventually, the entire control is managed by the parallel feed-back controller (which is identical to the benchmark feed-back controller).

Fig. 10 presents the maximum CO_2 setpoint deviation as a function of estimation error subjected to the occupancy information used by the model-based controllers, and Fig. 11 presents the simulation associated to the expected error of −1 person. Recall that estimation errors below zero in Fig. 10 refer to people not picked up by the model-based controllers and errors above refer to overestimations of the actual number. Also recall that the magnitude of the simulated occupancy increase was 3. Hence, an error of ±3 persons means that the change was registered as twice as large, respectively, not registered at all. As can be seen, the largest setpoint deviation associated to the model-based controllers in Figs. 8 and 10 coincide, since in both of these cases, the occupancy change was not taken into account. For estimation errors above zero, the setpoint deviations associated to the model-based controllers are small which is due to overcompensations: the estimation exceeds the actual occupancy change, the controller immediately responds with a higher ventilation flow rate than required and the CO_2 level is momentarily decreased below the setpoint.

3.5. Conclusion and discussion

In the following section, the main conclusions from the investigation are presented and discussed. First, the potential of model-based controllers for IAQ control is discussed in general, which is followed by a conclusion associated to the potential of CO_2 sensors for estimating the number of people in the studied application. Then, the interconnection between time delay and estimation error is briefly touched upon.

3.5.1. Model-based controller for IAQ control

It can first and foremost be concluded that the control performance can be substantially increased by using model-based controllers for ventilation control instead of feed-back loops. The simulation study showed that if the number of people can be estimated with small errors and time delays, the performances of the OLPC and the MPC were very similar and the associated setpoint deviation were then about 10 times lower compared to when the benchmark feed-back controller was used. It was also found that the MPC could reside relatively close to the setpoint even for large estimation errors and delays.

3.5.2. CO_2 sensors for occupancy estimations

Another conclusion is that CO_2 sensors are well suited to estimate occupancy as an input to model-based controllers for IAQ control. Even though the expected estimation error and time delay were derived during unfavorable conditions, a small setpoint deviation could still be achieved when these were subjected to the estimations. But, an important aspect is that the choice of model-based controller must be weighed against the quality of the estimations. For the expected time delay of 5 min, the performances of both considered model-based controllers were regarded as acceptable, but for longer delays, the performance of the OLPC dropped rapidly, and for the expected estimation error of −1 person, the OLPC resulted in an 80% larger setpoint deviation than the

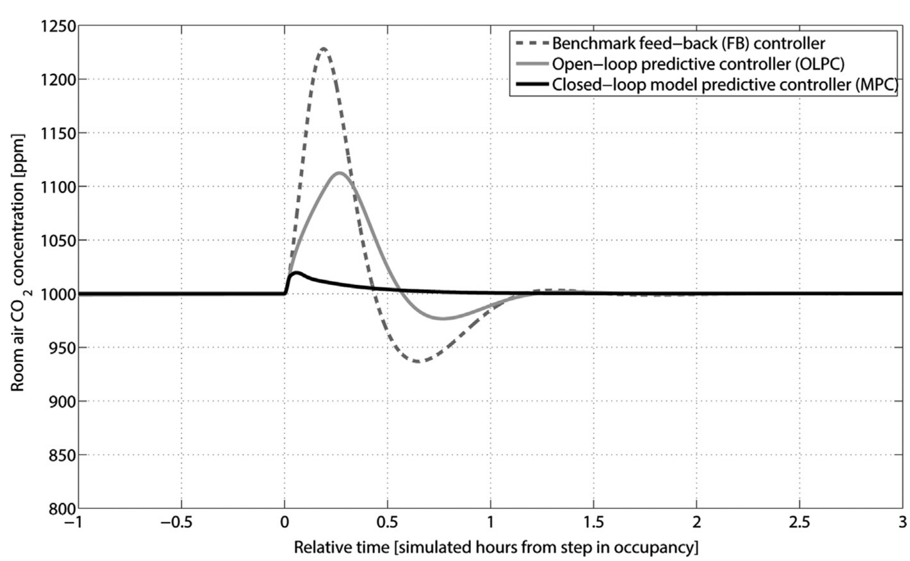

Fig. 11. Simulation associated to the expected estimation error of −1 person subjected to the occupancy information used by the model-based controllers.

MPC. This means that if accurate and fast estimations are possible, the complexity of the model-based controller can be reduced by choosing a simpler alternative such as the OLPC. This also means that poor estimations can be compensated for by choosing a more complex controller: even without estimations, the MPC performed relative well compared to the benchmark FB controller.

An important remark is that the considered performance metric is not sensitive to estimation errors above zero (i.e. when the estimated occupancy is larger than the actual value) which mean that the control performance can be increased by consistently overestimating the number of people. However, this means that also the ventilation flow rate is overestimated by the model-based controllers and that the actual CO_2 in turn is decreased below the setpoint momentarily with an increased energy usage as a consequence.

3.5.3. Combined effects

The cumulative effect of the two CO_2 measurement deficiencies was intentionally not evaluated in this work. In the experimental study, it was shown that all considered occupancy changes could be distinctively differentiated from each other by their CO_2 levels after about 6 min. This means that a long time delay leads to a small estimation error and vice versa. Hence, it is possible to avoid that both long time delays and large estimation errors coexist when the investigated occupancy estimation method is used.

4. Summary

This work investigated the possibility of estimating occupancy from CO_2 sensor responses for exogenous input to model-based controllers in office buildings. The procedure was divided in two parts that were conducted through experiments and simulations, respectively. The fundamental time delay and estimation error are two important factors in this context, and they were first derived during unfavorable conditions in a test facility consisting of a single seminar room. Then, the same site was simulated while considering two types of model-based controllers with different robustness (and complexity) for ventilation system control. The room was subjected to a step in occupancy which both controllers used as exogenous inputs, and while this information was subjected to various time delays and errors, the influence on control performance was asses using the setpoint deviation as a performance metric. The simulations showed that if the experimentally derived time delay of 5 min was subjected to the controller input, a simple model-based controller was sufficient to maintain a small setpoint deviation. But if the time delay was increased beyond that, or if the occupancy information was subjected to any estimation errors smaller than zero (underestimations), the more complex alternative was a better option. This means that poor estimations can be compensated by a more complex controller and that the complexity of the controller can be reduced if accurate and fast estimations are possible.

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Paper III

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Alternative strategies for supply air temperature control in office buildings

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ABSTRACT

A key element for a reduced energy usage in the building sector is to improve the systems for indoor climate control. But, it is important that such measures are fairly simple and easy to implement in order to facilitate a widespread utilization. In this work, four alternative strategies for supply air temperature control in offices were investigated through simulations. Their level of complexity stretches from linear SISO (single-input, single-output) structures with standard inputs to an optimal algorithm with information about the entire set of disturbances acting on the building. The study was conducted with a conventional outdoor-air-temperature based method as benchmark, and two different heating, ventilation and air-conditioning (HVAC) systems as well as two types of building structures were taken into account. Compared to the benchmark, all alternative strategies resulted in lower energy usages while thermal comfort and indoor air quality were satisfied, and simple strategies could perform almost equally well as more complex. But, it was also shown that the benefits were highly dependent on the considered HVAC system and somewhat dependent on the considered building structures.

1. Introduction

Approximately 40% of the global final energy is used in buildings, and in the European countries, 76% of this share goes towards systems for heating, ventilation and air-conditioning (HVAC). The purpose of an HVAC system is to achieve a desirable indoor climate and a key element for reducing the associated energy usage is to improve the building automation system. Many systems for indoor climate control consist of both local (on room level) and central components, and since their functions in many cases coincide, an important aspect in this context is to synchronize their operation. [1]

An established technology for ventilation system control is DCV (demand controlled ventilation). The supply air flow rate to each space is then controlled individually and a common application is to use zone measurements (typically temperature or CO_2) as input to a feed-back loop. The supply air temperature (SAT) is in turn first and foremost controlled centrally which means that the level should suite the entire range of demands within the building zones simultaneously. Conventionally, SAT control strategies are often based on external disturbances, and typically the outdoor air temperature (OAT) since the whole building is affected by its variations. This means that the SAT is increased for decreased OATs and vice versa [2]. But, such strategy can be problematic in office buildings since internal disturbances (such as people, lighting and equipment) are commonly dominating over the external climate during working hours. Then, a cooling demand can be expected almost regardless of the OAT (especially in modern office buildings with tight and well insulated envelopes), at the same time as the quality of the indoor climate is of utmost importance. Unsuitable supply air temperatures in certain zones can partly be compensated for by local components, but with an increased energy usage as a consequence. However, in more severe cases, the function of the HVAC system can be compromised.

An emerging technology for achieving a SAT control that coincides with the remaining functions in DCV systems is to treat the HVAC operation as a global optimization problem by involving various objectives and variables. For example, an entire building's energy usage can be minimized at the same time as the quality of the indoor climate is ensured. This approach has been studied in several previous works, as for example in [3], where the solver genetic algorithm (GA) was used in an office environment during two summer weeks by incorporating thermal climate and energy for air-handling in the objective function. A similar investigation was presented in [4], and it was found that up to 30% of

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Nomenclature

C	thermal capacity [J/°C]
c	CO_2 concentration [ppm]
c_p	specific heat capacity [J/(kg K)]
E	total energy, weighted sum of energy types [W]
$\dot{M}, \dot{c}$	CO_2 flow rate [ml/s]
Q	thermal energy [J]
$\dot{Q}$	thermal power [W]
t	Celsius temperature [°C]
V	volume [m^3]
$\dot{V}$	volume flow rate [m^3/s]
W	electric work [J]
$\dot{W}$	electric power [W]

Greek letters

τ	time [s]
ρ	density [kg/m^3]

Subscripts

max	maximum
min	minimum
r	room
s	supply
tot	total
vent	ventilation

the energy could be saved by employing GA for SAT control in an educational environment instead of maintaining a constant level. These findings are moreover consistent with the reported results of [5] where genetic fuzzy optimization was used for climate control in an academic building scale model. Compared to maintaining constant SAT levels between 12 and 14 °C, the strategy yielded energy savings between 54 and 61% during summer and winter ambient conditions, and this range was furthermore assessed as equivalent to savings between 29 and 36% on an annual basis. A final example of an investigation considering SAT control through global optimization algorithms is [6] in which GA was evaluated for ventilation system control in a multi-zone simulation platform. Simplified adaptive control models of the process were used to estimate the response to various external and internal conditions while the solver searched for a trade-off between air-handling energy and comfort aspects. Simulations were conducted for four different weather conditions and it was found that up to about 40% of the energy could be saved using the optimal approach compared to maintaining constant setpoints. A bit different approach to the same problem was in turn chosen in [7]. Instead of using numerical tools, expressions for the HVAC energy usage were formulated for a number of conditions and the optimal SAT was derived analytically. The theory was applied on a ventilation system in an office building and an energy saving potential between 8 and 27% compared to constant setpoint cases was indicated.

1.1. Background and purpose

In the light of the previously cited works, it is clear that optimal SAT control strategies have a large potential for reducing the HVAC energy usage while maintaining a desirable indoor climate. However, a major drawback is that the associated level of complexity normally is high since a complete model of the process (building and HVAC system) is required together with extensive information about internal and external conditions. The process model is used to predict the influence of choosing a certain SAT under the present conditions, and an optimization algorithm typically performs a search to find the most appropriate level. Even though physical models have the potential of describing the process sufficiently accurate, a large number of parameters would then be required whereof several are uncertain or hard to determine. Another alternative is black-box models that are constructed from observed data in terms of input/output measurements. But since the accuracy immediately becomes uncertain when operated in a range from where the training data lack information, the commissioning phase can be an extensive process. When it comes to gathering information about internal and external conditions, the customary set can be divided into a number of disturbances whereof several could be determined using established measurement technology (for example OAT, lighting, solar radiation). But for others, this is not an option (considering people and infiltration flow rate for example) without involving models for predictions and/or estimations, and these are typically afflicted with the same problem as the process models [8].

The aim of the present paper is to contribute in the search for simple SAT control strategies with a potential of reducing energy usage while achieving a desirable indoor climate. The investigation was performed in a simulated office environment and the core consists of three SISO (Single-Input, Single-Output) strategies that primarily are based on information inside the building through standard inputs. While a conventional OAT-based strategy was included as a benchmark, the upper boundary of potential energy savings was represented by an optimal algorithm, and it was furthermore examined if patterns in the solution could be utilized to formulate a more general and simple strategy.

During simulations of a 11 room office building over two working weeks of Swedish summer and winter respectively, all strategies were individually evaluated for generating central SAT setpoints in two different DCV-HVAC system applications: an all-air system with re-heaters in each room, and a system with hygienic ventilation and local water-based cooling and heating. In both cases, the thermal climate and indoor air quality (IAQ) within the zones were controlled with temperature and CO_2 as indicators, respectively. The investigation was moreover conducted for different variants of the building and the results are presented as the total energy used by the HVAC system during the simulated periods.

This paper is organized as follows: first, the simulation platform, including HVAC system and building, is presented together with its considered variants and simulated conditions. This is followed by a description of the evaluated SAT control strategies, and finally, the results from the study are presented and discussed.

2. Simulation framework

The investigation is based on simulations performed in MATLAB® Simulink® and the platform consists of a building and an HVAC part. These are in turn made up from a large number of component models with one-dimensional equations used to describe how the simulated variables vary over the platform. The controlled variables of the rooms (CO_2 and temperature) were calculated by physical balance equations and the relations between pressure and flow in the HVAC system were based on empirical data. In this section, the modelling approach is first described briefly and if more detailed information is desired reference [9] or [10] can be considered. Further on, the variants of the building and HVAC system are introduced which is followed by a description of the disturbances that were considered.

2.1. Building platform

The building part is presented in Fig. 1. It was modelled to represent part of a floor in a modern office building with tight and well

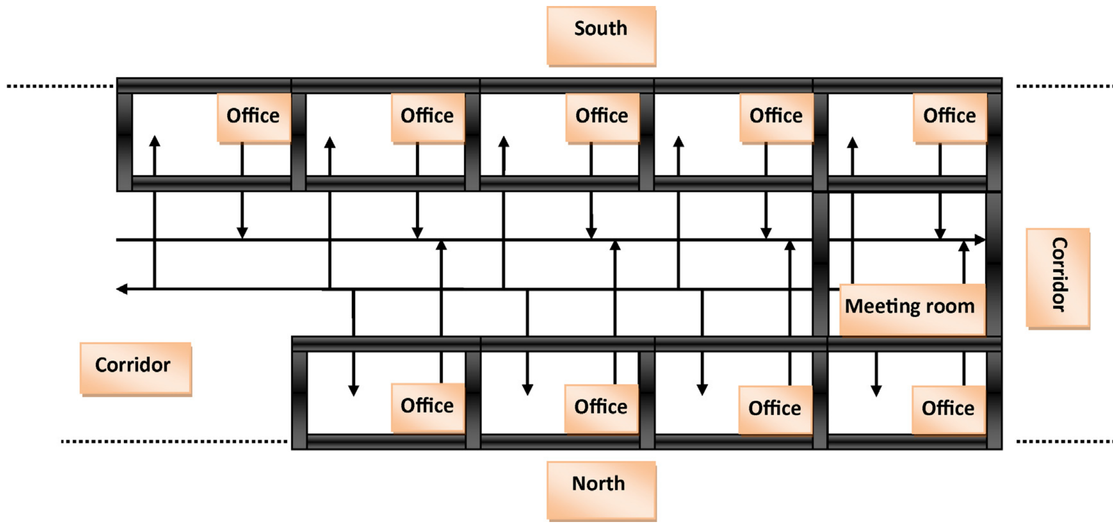

Fig. 1. Layout of the modelled building with associated duct system for supply and exhaust air ventilation.

insulated outside walls, and consists of 11 individual rooms that are thermally connected to its neighbours. Most (9) rooms were modelled as cellular offices with a maximum occupancy of one person and a floor area of 10 m^2. While three of the consecutive walls are facing adjacent rooms, one is external and 80% of its surface is covered by a window with outside solar shadings. The platform also contains a corridor and a meeting room, both without external walls, and with floor areas of 140 and 18 m^2 respectively. All rooms except the corridor have individual supply and extraction of ventilation air via the duct system depicted by arrows in Fig. 1. Air can also be directly exchanged between the rooms via open doors and the corridor, while leakage through internal walls is neglected.

All rooms have adiabatic boundary conditions on roof and floor and the temperature of building elements (BE) such as walls, floors and roofs were calculated in two nodes located on the inside and outside surfaces. The heat exchange between a certain building element (i) and the surroundings is described by two coupled ODEs (ordinary differential equation) as presented in Eq. (1a). The room air temperatures (t_r) were calculated in one node per room using the ODE in Eq. (1b). The right hand side of this equation consists of terms describing the heat exchange between the air in a certain room and the building elements ($\dot{Q}_{BE,i\to r} - \dot{Q}_{r\to BE,i}$) and terms describing the heat emitted by internal disturbances ($\dot{Q}_{D,i\to r}$). Also the air CO_2 concentrations (c_r) were calculated in one node per room using the mass-balance in Eq. (1c). The terms on the right hand side describe the CO_2 exchange between a certain room and the ambience ($\dot{c}_{\to r} - \dot{c}_{r\to}$) as well as the CO_2 emitted by internal disturbances ($\dot{M}_{D,i\to r}$). The building model and its variants were tested and validated against IDA ICE which in turn has been tested in the Building Energy Simulation Test (BESTEST) developed under IEA SHC Tasks 8, 12 and 22.

$$\frac{dt_{BE,i}}{d\tau} \times C_{BE,i} = \dot{Q}_{\to BE,i} - \dot{Q}_{BE,i\to} \tag{1a}$$

$$\frac{dt_r}{d\tau} \times C_r = \dot{Q}_{BE,i\to r} - \dot{Q}_{r\to BE,i} + \dot{Q}_{D,i\to r} \tag{1b}$$

$$\frac{dc_r}{d\tau} \times V_r = \dot{c}_{\to r} - \dot{c}_{r\to} + \dot{M}_{D,i\to r} \tag{1c}$$

The building was considered in two structures: a heavy entirely out of concrete with additional layers of mineral wool and brick on external walls, and a light primary out of gypsum, wood and mineral wool with outside surfaces of metal sheet. Both structures represent its own extreme from a thermal characteristic point of view and these choices were made to span the results from the investigation over most relevant cases.

2.2. HVAC systems description

The HVAC system was investigated in the two variants (denoted as systems A and B) that are differentiated by their local components in Table 1. As all functions related to indoor climate control were managed with ventilation in system A, only the CO_2 part was air-based in system B. Hence, both cases represent its own extreme with an extensive and minimal use of the ventilation system respectively, and these choices were made to span the results from the investigation so that most relevant HVAC systems can be found within the range.

2.2.1. Indoor climate considerations

System A is an all-air HVAC system with DCV and re-heaters (RH) in each zone for temperature control, and with minimum ventilation flow levels to maintain the IAQ. System B is equipped with DCV to control the room CO_2 concentrations while heating and cooling were supplied by local water-based thermal room units (TRU). All subsystems were in both cases controlled by feed-back PI-controllers with ideal parameter settings (according to the AMIGO method) and state-of-the-art sensors in the loop (with respect to accuracy and response). Identical setpoints for the local components were used throughout the study and the levels were set to ensure that the quality of the indoor climate was fulfilled at all times. In the room air temperature case, 21 °C was chosen as setpoint for heating according to a national recommendation [11] which states that lower temperatures should be avoided in occupied office rooms. The setpoint for cooling was set 1 K higher, since according to the standard ISO EN 7730-2005, smaller room air temperature variations do not have a negative influence on the thermal comfort. A desirable IAQ was defined as CO_2 concentrations below 1000 ppm according to several national recommendations [12] as well as the ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) standard 62-2007. This criterion was fulfilled by adjusting the CO_2 level setpoints in system B and the minimum ventilation flow rates in system A.

2.2.2. Central components

Throughout the study, the ventilation air consisted entirely of outdoor air that had been conditioned in a central air-handling

Table 1
Summary of local (on room level) HVAC component models used in the investigation.

Local components	Description	System A	System B
Thermal room unit (TRU)	Fan-coil unit for heating or cooling. Circulating room air on one side and hot or cold water on the other. Room air side: variable drive fan. Water side: valves for constant hot or cold outlet air temperature.	N.A.	Actuator for room air temperature.
Re-heater (RH) of supply air	Small hot water-connected air-heater located directly before the supply air diffuser. Water side: valve for controlling supply air temperatures above the central setpoint.	Actuator for room air temperature.	N.A.
Supply air diffuser	For mixing ventilation of supply and room air. Adjustable opening.	Actuator for room air temperature.	Actuator for room air CO_2 concentration.
Exhaust air diffuser	Adjustable opening for balanced ventilation.	Tracks the control signal to the supply air diffuser.	Tracks the control signal to the supply air diffuser.

Table 2
Summary of central HVAC component models. Both HVAC systems in the investigation used the same kind but with different dimensions.

Central components	Description	Control arrangement
Heat recovery unit	Rotating variable speed drive non-hygroscopic wheel. Maximum temperature efficiency of 0.8.	First actuator in sequence for SAT control.
Air-heater	Supply air on one side and hot water on the other. Control valve for variable water flow rate.	Second actuator in sequence for SAT control.
Air-cooler	Supply air on one side and cold water on the other. Control valve for variable water flow rate.	Third actuator in sequence for SAT control.
Supply air fan	Maximum total efficiency of 0.5. Variable speed drive.	Flow controlled, tracks the control signals to the supply air diffusers.
Exhaust air fan	Maximum total efficiency of 0.5. Variable speed drive.	Flow controlled, tracks the control signals to the exhaust air diffusers.

unit (AHU) and distributed to the zones via the duct system. The central components for air-handling are presented in Table 2, and both of the considered HVAC systems used the same kind, but with different dimensions to fulfil a national recommendation of a maximum SFP (specific fan power [kW/(m^3/s)]) of 2. The first three components in Table 2 were used to control the SAT in a sequence to avoid unnecessary energy usages: the air-heater could only be actuated if the heat recovery unit was in full operation, and the air-cooler could only be actuated if both the heat recovery unit and the air-heater were deactivated. The two final components in Table 2 are the central supply and exhaust air fans, and both were modelled to track the control signals of the local air diffusers in Table 1. This means that the opening of the supply air diffusers determined the ventilation air flow rates to the rooms and that balanced ventilation was achieved since the exhaust air diffusers followed the supply air diffusers.

2.2.3. Local components system A

System A was introduced to consider an HVAC system in which the ventilation part manages all functions associated to indoor climate control and therefore is used to a large extent. The actuators for room air temperature (supply air diffusers and RHs) were controlled according to the dual maximum logic which is both efficient and relatively common in existing buildings [13]. The dual maximum logic consists of the four modes presented with different patterns in Fig. 2 as functions of the thermal power supplied by the ventilation system to the room air. For room air temperatures above the cooling setpoint (cooling supply mode), the supply air flow rate is increased while the RHs are off. Between the setpoints for cooling and heating (the dead-band mode) the RHs are still off and the supply air flow rate attains a minimum level which was set to ensure that the IAQ in the zone was maintained for the design number of people. If the room air temperature falls below the heating setpoint (and enters the first part of the heating supply mode), the RHs are actuated while the supply air flow rate is not increased until the SAT has reached its maximum (and the second part of the heating supply mode is activated).

2.2.4. Local components system B

System B was introduced to consider an HVAC system in which the ventilation system only manages a minor part of the indoor climate control and therefore is used to a small extent. The room air temperatures were primary controlled by the local TRUs (Table 1), modelled as fan-coil units with the ability to either heat or cool the rooms. The IAQ was in this case maintained by directly controlling the CO_2 levels by varying the openings of the supply air diffusers. The minimum flow rate was set to zero and the maximum level as dependent on the size of the room and the design number of people, both according to national guidelines [12].

2.3. Disturbances

Each simulation stretched over a working week of 5 days and nights, and was conducted by subjecting the building to time-varying sequences of the following internal and external disturbances:

- People
- Lighting

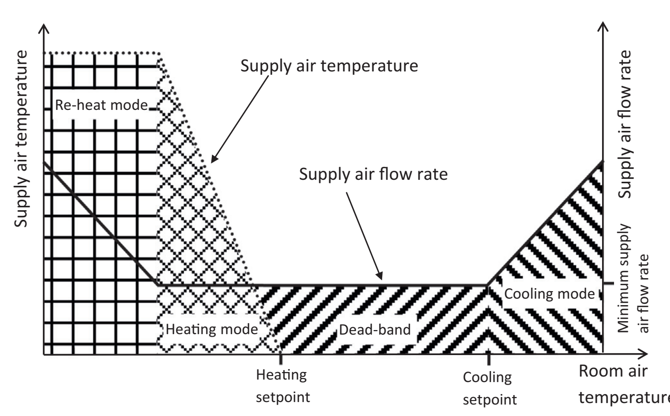

Fig. 2. Overview of the dual maximum control logic for the all-air HVAC system A with local re-heaters.

- Equipment (such as computers and other office appliances)
- Opening of internal doors
- Solar heat gain
- Outdoor air temperature (OAT)

Since the corridor and the meeting room lack external walls, only the office rooms were directly influenced by the external climate and the investigation was conducted with a summer and a winter variant. Both seasons were modelled using climate data of a reference year from the Swedish coastal city of Helsingborg which has a mild tempered climate and an annual average OAT of 8.2 °C. During day time, the office rooms were subjected to solar radiation from a northern (4 rooms) and a southern direction (5 rooms), and the part not blocked by the external shadings was transferred through the windows as heat.

The number of people was modelled separately for each room in accordance with statistical data regarding annual occupancy in 58 rooms of a Swedish office building [14]. The outcome was a sequence in which the building could be occupied between 7:00 and 19:00 h, with normal occupancy factors (total number of occupants/maximum number of occupants) between 20 and 50%, and a maximum of 70% that occurred during one separate occasion. Further, both equipment and lighting were assumed to correlate to occupancy (i.e. light, computers and other appliances were switched on during occupied periods and switched off during vacancy). Each person was modelled to emit 18 l_{CO2}/h and 70 W of sensible body heat while the heat gain from lighting corresponds to 10 W/m^2 according to the standard SS-EN 12464-1. The doors between the office rooms and the corridor were opened according to a stochastic variable with probability of 20% to occur during day time while the door to the meeting room was assumed to be closed at all times.

3. SAT control strategies

In Table 3, the investigated SAT control strategies are summarized. Throughout, an open-loop structure was used to generate central SAT setpoints as a function of some input(s), while the room air temperature and CO_2 control were managed by local HVAC components in each zone. The strategies were denoted according to their most characteristic features (which normally is the type of input signal) and can be divided in three groups depending on their purpose in the investigation. First, the OATS was considered as a benchmark and represented a conventional approach with outdoor air temperature as input. Second, the TOS, OLSS and RATS were introduced as low-complexity alternative strategies and are based on some limited information about the activities in the building. Third, the optimal strategy is extensive, has information about the entire set of disturbances and was primarily introduced to serve as an upper boundary of possible energy savings. But, the solution was moreover analysed for patterns that could be used to formulate a more general and simple strategy.

All strategies were design to operate within a SAT span between 15 and 21 °C. The lower boundary was set according to comfort recommendation to avoid draught and the upper boundary was the highest observed temperature for which all strategies could perform during all simulated conditions without an accelerated energy usage. The corresponding input signal values to attain these boundaries are also presented in Table 3 whenever possible. Since the focus of this study was to evaluate the performances of simple alternative strategies, it was assumed that all signals used for control were ideal. Further, no other control related energy efficiency measures were not applied during the simulations (such as relaxed comfort constrains during night time using re-circulation of ventilation air and/or reset of room air temperature setpoints).

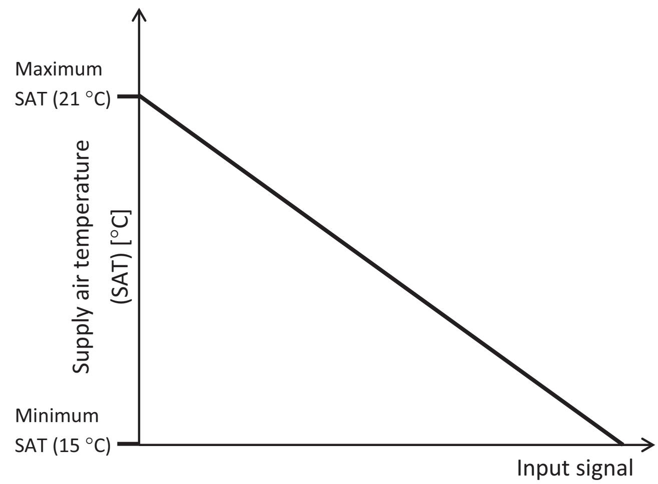

Fig. 3. General linear and static SISO supply air temperature control strategy.

3.1. Linear SISO strategies

All strategies except for the optimal are linear, static and of SISO type as presented graphically in Fig. 3. The linear representation was chosen since this form is in accordance to how the considered input signals affect the demand for heating and cooling in the building. In practice, it is possible to counteract the OATS strategy in a non-linear version but this is probably a result of a tuning process to compensate for unmeasured disturbances, such as solar radiation, which often coincide with high outdoor air temperatures.

One of the main reasons for evaluating the alternative SAT control strategies was to find simpler variants to more complex control strategies such as the optimal. All of the linear SISO strategies in this investigation are regarded as non-complex due to their simple form and the measurability of their input signals. The input to the OLSS is the sum of the heating power emitted by all local units (the RHs in system A and the TRUs in system B) and a decline is interpreted as an increased cooling demand which is met by a decreased SAT. In practice, the OLSS could for example be implemented by considering Eq. (2) at each local unit. In HVAC systems like A and B, information about the water flow through each RH respective TRU would then be required together with the corresponding supply and return water temperatures. Compared to what is custom in most buildings, some additional sensors must hence be installed, but nothing outside the frames of standard products on the market. The input to the TOS is the total number of occupied rooms in the building. An increased occupancy is interpreted as an increased cooling demand which is met by a decreased SAT. This strategy could for example be realized by installing motion sensors in each space, and once again, the associated technology is then standard in building automation applications (commonly used for lighting control). In the RATS strategy, the mean room air temperature in the office and meeting rooms is used as input. This strategy only requires temperature sensors in each zone which presumably are available at most sites.

$$\dot{Q}_{heat} = \dot{V}_{water} \times \rho_{water} \times c_{p,water} \times (t_s - t_{return}) \quad [W] \tag{2}$$

3.2. The optimal strategy

The energy used by an HVAC system to meet an instantaneous demand in a building can be optimized from two perspectives. First, an HVAC system consists of central and local components that can be operated individually or partly individually of each other, but, the operation of the central system also determines the operation of the local. If the supply from the central system is mismatched with

Table 3
Considered SAT control strategies.

Name	Input signals	Input signal values to attain SAT boundaries
Outdoor air temperature strategy (OATS)	Outdoor air temperature.	The lowest (−11) and the highest (25) simulated outdoor air temperatures [°C].
Total occupancy strategy (TOS)	Number of occupied rooms in the building.	0 and the maximum number of rooms that can be occupied (10) [–].
Operation of local system strategy (OLSS)	Sum of heating power emitted by the local units (re-heaters of TRUs).	0 and dimensioning heating power of local units times the number of rooms [W].
Room air temperature strategy (RATS)	The mean room air temperature of the zones (not including the corridor).	The local setpoint for heating (21) and the local setpoint for cooling (22) [°C].
Optimal strategy	All internal disturbances and the outdoor air temperature.	Multiple input and non-linear. Solution is presented further on.

the demand, the energy usage of the local components is increased. In this work, a mismatched SAT is met by an increased supply air flow rate and/or an increased power of the RHs in system A, and by an increased operation of the TRUs in system B. It is also important to emphasize that since a mismatch in one zone might be a match in another, the entire building and the variations within must be taken into account when an optimization problem is formulated. Second, dependent on the conditions, different HVAC components have different energy intensities which means that a certain cooling or heating demand can be met by using different amounts of energy. The energy intensity of the AHU is in this work dependent on the OAT and the ability to recover heat while the power of RHs and TRUs are disconnected to the external conditions. Further, the energy for central and local fans (in the AHU and TRU respectively) increases exponentially with the flow and grows faster than the energy used for air-conditioning or re-heating.

The optimal strategy was derived by solving the previously described optimization problem for a static system. The heuristic solver GA was used to find the SAT that minimizes the objective function in Eq. (3a) which is a sum of all energy terms allocated to the HVAC system. Off-line solutions were returned for the considered variants of HVAC system, building and disturbances (internal and external), and in the next step, these were implemented in the simulations as the optimal strategy. This means that the optimal strategy requires information about internal and external disturbances (which naturally leads to a high level of complexity) and should therefore not be regarded as an implementable alternative in its initial form.

3.2.1. Procedure

In this section, the procedure that was followed to derive the optimal strategy is presented. The building and the HVAC systems were first described as static energy balances (remark: the solution is hence optimal from a static point of view) which was done by omitting the corridor since this space is neither conditioned nor ventilated directly. The individual terms in the objective function in Eq. (3a) were then specified as functions of SAT, according to the procedure given in Eqs. (3b)–(3f). The third step was to determine the required ventilation flow rate to fulfil the indoor climate criterions in occupied rooms with heat surplus: in system A, to maintain the cooling setpoint (Eq. (3b)), and in system B, to remain below a CO_2 concentration of 1000 ppm. Eq. (3c) was in turn used to specify the corresponding energy usage for air-conditioning (not including recovered heat) for a specific OAT. In the fourth step, the thermal energy usage of the local components (RHs and TRUs) was specified by Eq. (3d): in system A, as the increase of SAT needed to cover any heat deficits, and in system B, as the additional heating or cooling not covered by the ventilation system. For cases when the heating demand was not covered by the RHs in system A, the supply air flow rate was also increased to the necessary level. Eqs. (3e) and (3f) were then used to specify the associated electricity usage of central fans and the TRUs. In the last step, the optimization problem in Eq. (3g) was formulated, and all constraints that were considered are also summarized under this index. Constraint 1–3 were embedded in the objective function (as described in the previous text) while 4–5 were managed by the solver. Most constraints (1–5), are associated to comfort considerations; the first and second state the criterions set to fulfil a satisfying indoor climate quality (see Section 2.2.1) and the third and fourth state the limits of the supply air temperature from the central and local (TRU and RH) components. The last constraint states the limitations of the air flow rate in each room (see Section 2.2).

$$J=\left(\dot{W}_{\mathrm{AHU}}(ts)+|\dot{Q}_{\mathrm{AHU}}(ts)|+\sum_{i=1}^{10}|\dot{Q}_{\mathrm{local},i}(ts)|+\sum_{i=1}^{10}\dot{W}_{\mathrm{local},i}(ts)\right) \quad (3a)$$

$$\dot{Q}_{\mathrm{vent},i}=\dot{V}_{s,i}\times\rho_{\mathrm{air}}\times c_{p\,\mathrm{air}}\times(t_s-t_{r,i}) \quad (3b)$$

$$\dot{Q}_{\mathrm{AHU}}=\dot{V}_{s\,\mathrm{tot}}\times\rho_{\mathrm{air}}\times c_{p\,\mathrm{air}}\times(t_s-t_o) \quad (3c)$$

$$\dot{Q}_{\mathrm{vent},i}+\dot{Q}_{\mathrm{local},i}=\dot{Q}_{\mathrm{demand},i}=\dot{Q}_{\mathrm{external},i}-\dot{Q}_{\mathrm{internal},i} \quad (3d)$$

$$\dot{W}_{\mathrm{AHU}}=\dot{W}_{\mathrm{AHU\,max}}\times\left(\frac{\dot{V}_{s\,\mathrm{tot}}}{\dot{V}_{s\,\mathrm{tot\,max}}}\right)^3 \quad (3e)$$

$$\dot{W}_{\mathrm{local}}=\dot{W}_{\mathrm{local\,max}}\times\left(\frac{\dot{Q}_{\mathrm{local\,tot}}}{\dot{Q}_{\mathrm{local\,tot\,max}}}\right)^3 \quad (3f)$$

$$t_{s\,\mathrm{central}}=\min(J)$$

subjected to

$$\begin{aligned}
&1.\quad 21\,^\circ\mathrm{C}\le t_{r,i}\le 22\,^\circ\mathrm{C}\\
&2.\quad c_{r,i}\le 1000\,\mathrm{ppm}\\
&3.\quad 15\,^\circ\mathrm{C}\le t_{s\,\mathrm{local}}\le 30\,^\circ\mathrm{C}\\
&4.\quad 15\,^\circ\mathrm{C}\le t_{s\,\mathrm{central}}\le 21\,^\circ\mathrm{C}\\
&5.\quad \dot{V}_{s\,\mathrm{min},i}\le\dot{V}_{s,i}\le\dot{V}_{s\,\mathrm{max},i}
\end{aligned} \quad (3g)$$

3.2.2. Optimal solutions

The previously described procedure was repeated for the building and HVAC system variants, and GA was used to find solutions for all considered combination of internal and external disturbances. The results are presented in Figs. 4 and 5 for HVAC systems A and B respectively, while it was found that the solutions were more or less independent of the type of building. To facilitate visualization, the optimal SAT is presented as functions of the OAT and the number of people, which is possible in this work since the influence of solar radiation could be neglected due to external shadings and since the number of people are correlated to the rest of the internal disturbances. Further, the solution for system B remained constant below an OAT of 15 °C which is the reason to why the *x*-axis in Fig. 5 is limited.

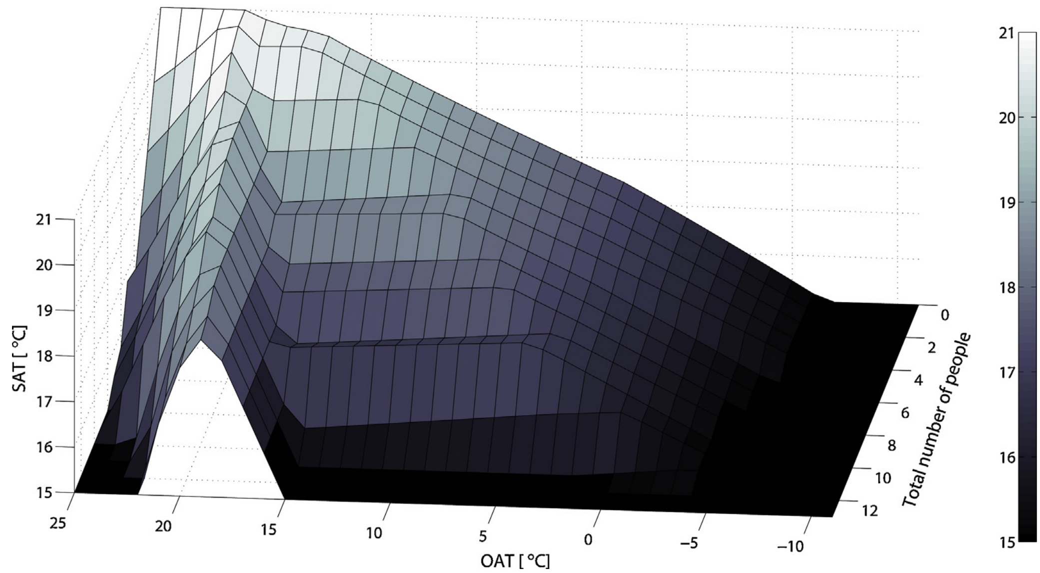

Fig. 4. Optimal supply air temperature control strategy for HVAC system A.

In Fig. 4, the optimal strategy for HVAC system A is presented. It is best explained by dividing the solution into three regions with respect to OAT, as well as by differentiating between periods with large and small internal disturbances. The first region is associated to OATs below −8 °C, and by attaining the lowest SAT boundary, energy for air-conditioning was minimized while local components were favoured in rooms with heating demands. In the second region between −8 and 19 °C, the allowed SAT span between 15 and 21 °C could be maintained solely by recovered heat. As the cooling demand was increased during periods with large internal disturbances, the supply air flow rate (and in turn the associated energy for fans and air-conditioning) was reduced by lowering the SAT. As the heating demand was increased during periods with small internal disturbances, the energy for RH was reduced by increasing the SAT up to the maximum temperature achievable by heat recovery. As the OAT was increased into the third region above 19 °C, a more and more homogenous demand during periods with large and medium internal disturbances was met by a decreased SAT (as the transmission losses were decreased with higher OATs, even vacant rooms got a demand for cooling due to the heat transferred from occupied rooms). During periods with small internal disturbances, on the other hand, a high SAT was favoured in order to reduce the energy associated for cooling outdoor air.

The optimal strategy for HVAC system B is presented in Fig. 5. The SAT is in this case independent of the internal disturbances and consistently follows the OAT, which means the strategy can be implemented only with an external temperature sensor as input. The solution indicates that the ventilation system was disconnected from temperature control considerations by the solver: since the supply air flow rate was locked by the IAQ demand, the ventilation system was unable to provide the necessary span of heating and cooling demands within the building simultaneously, and this function was instead allocated to the TRUs.

4. Results

In this work, simulations were used to investigate three low-complexity strategies for central SAT control in an office building,

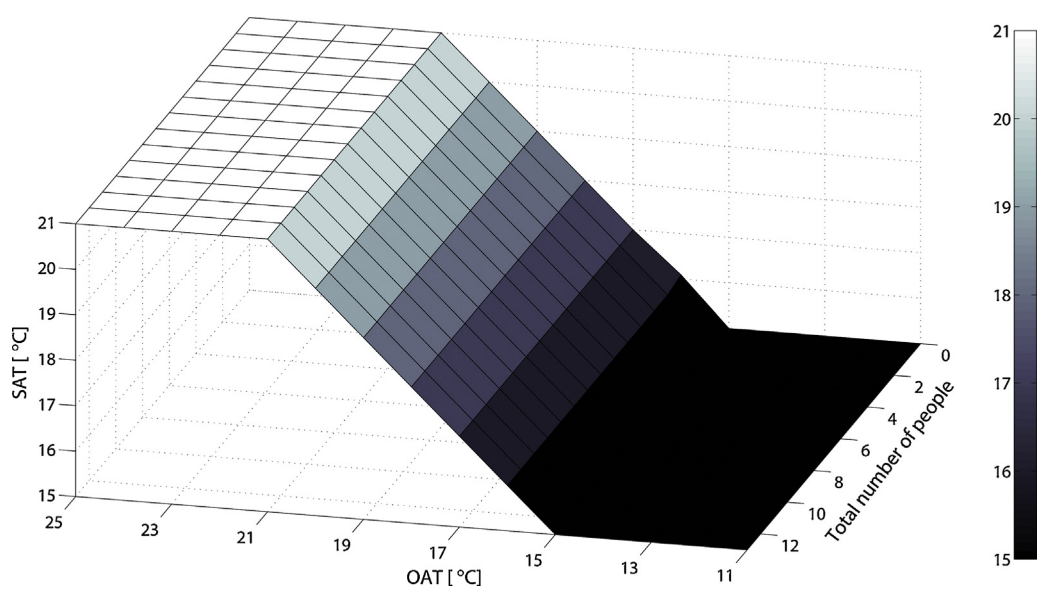

Fig. 5. Optimal supply air temperature control strategy for HVAC system B.

by comparing to an optimal algorithm as an ideal case and a conventional OAT-based strategy as benchmark. Two different HVAC systems, two types of buildings and two weather seasons were considered. The results in the following text were calculated using Eq. (4) and consists of the HVAC system energy usage during two working weeks of Swedish summer and winter climate (E_{total}) respectively, weighted according to Energy Efficiency Directive 2006/32/EG.

$$E_{total} = (|Q_{thermal}| + (W_{electricity} \times 2.5))_{summer} + (|Q_{thermal}| + (W_{electricity} \times 2.5))_{winter} \quad [\mathrm{kW\,h}] \qquad (4)$$

In Figs. 6 and 7, the energy usage of HVAC system A is presented for the heavy and light buildings respectively. The ranking provided by sorting the alternative strategies according to their potential of saving energy compared to the benchmark (OATS) was throughout consistent. That is, the optimal strategy had the highest performance (with savings of 31 respectively 39% in the heavy and light building cases), subsequently followed by TOS (27 respectively 31%), RATS (19 respectively 29%) and OLSS (12 respectively 24%). Hence, from these figures it is clear that the energy savings achieved by replacing the benchmark with the investigated strategies were in general larger in the light building case, both in relative and absolute terms.

In Figs. 8 and 9 the energy usage associated to HVAC system B is presented for the heavy and light buildings respectively. Compared to the system A cases, there are three significant differences. First, both the absolute and relative savings associated to the alternative strategies were in general lower. This is because the supply air flow rate was independent of the SAT control at the same time as a smaller part of the energy usage derived from the ventilation system. Second, also the absolute energy usages were in general lower since the ventilation system was shut down during the night (due to the absence of CO_2 sources.) Third, the ranking of energy savings achieved by the alternative strategies was (although consistent) of a different order. That is, the optimal strategy still had the highest performance (with savings of 12 respectively18% in the heavy and light building cases) but was subsequently followed by OLSS (10 respectively 15%), RATS (9 respectively 13%) and TOS (6 respectively 7%). Hence, the highest energy savings potential was also in this case associated to the light building cases.

5. Conclusions and discussion

The aim of this work was to find low-complexity SAT control strategies for a decreased HVAC system energy usage and a maintained indoor climate quality. Constant and identical setpoints for local components were used throughout the simulations to ensure a desirable indoor climate while the investigated strategies were generating setpoints for central SAT.

The results showed that all alternative strategies resulted in lower energy usages compared to a conventional OAT-based, and in some cases substantial reductions were indicated. It was found that up to 30 and 15% of the total energy usage could be saved by applying a low-complexity strategy to HVAC system A and B respectively; compared to 39 respectively 18% when under the control of the optimal algorithm. While major energy savings with optimal strategies already have been proclaimed in previous works (e.g. about 30–40% in [4–7]), the main conclusion from this paper is that similar results can be reached with a considerable lower level of complexity. Moreover, it can also be concluded that the possible savings were highly dependent on the considered HVAC system and somewhat dependent on the considered building structures. In the following text, these aspects are first discussed which is followed by an evaluation of the alternative control strategies.

5.1. Influence of HVAC system and building structure

In general, the energy savings potential was considerable larger in HVAC system A because the entire energy usage was allocated to ventilation, and that a major share went for air-conditioning. Further, the strategies had the possibility of decreasing all energy accounts by indirectly reducing the supply air flow rate by assigning more appropriate SATs. This means that both additional energies for air-conditioning were saved at the same time as the central fan operation was reduced. In the HVAC system B cases, only the air-conditioning energy associated to SAT control could be affected by the strategies. Further, most of the thermal control was managed by the TRUs while a considerable smaller part of the energy usage derived from the ventilation system due to relatively low air flows and off-line mode during unoccupied periods.

Regarding the influence of building structure, the overall savings were in general larger in the light cases, and the explanation lies in the properties of the respective building materials. Recall that the heavy structure primarily was made out of concrete and the light structure of gypsum, mineral wool and metal sheet. The outcome was a smaller thermal resistance and a larger capacity in the heavy case, which is equivalent to smaller impacts of disturbance on individual rooms. A higher capacity means that disturbances were dampened to a larger extent and a lower resistance means that heat was transferred more easily between the rooms (hence, temperature differences between occupied and empty rooms was reduced). To sum up, these two features resulted in that the light structure was more difficult to control, and in turn, the room for improvements became larger because a mismatched SAT was more penalized by an increased operation of the local HVAC components. In this context, it is also worth mentioning that the different thermal characteristics of the buildings also led to considerable higher cooling demands in light occupied rooms (visualized by the absolute scale in Fig. 9).

5.2. Evaluation of alternative strategies

5.2.1. Optimal strategy

Independent of the considered HVAC systems and building variants, the optimal strategy led to the largest energy savings, and in particular when used in HVAC system A (Fig. 4). Since the optimal strategy in this case was specific and required both internal and external disturbances as inputs, it represents an upper boundary of possible energy savings and not a realistic strategy for implementation. For HVAC system B, on the other hand, the optimal strategy was general and the only necessary input signal was the OAT (Fig. 5). That is, an external temperature sensor is the only element required for implementation, which means that all other strategies are more complicated at the same time as their performances furthermore are lower in comparison.

5.2.2. SISO strategies

The ranking of energy savings associated to the alternative SISO strategies was on a declining scale: TOS, RATS and OLSS for system A and OLSS, RATS and TOS for system B. In the following text, these ranking orders will be discussed and explained.

All of the alternative SISO strategies utilized information about internal disturbances (either directly or indirectly) and were intended to provide a reflection of the demand within the building. The differentiation is regarding how and how fast they reacted when a shift in internal disturbances occurred. The TOS considered whether there was a cooling or a heating demand in single zones and acted directly, before the impacts of internal disturbances were observable; RATS considered whether there was a cooling or a heating demand on average and acted when the impact was seen on the room air temperatures; the OLSS utilized the operation of local

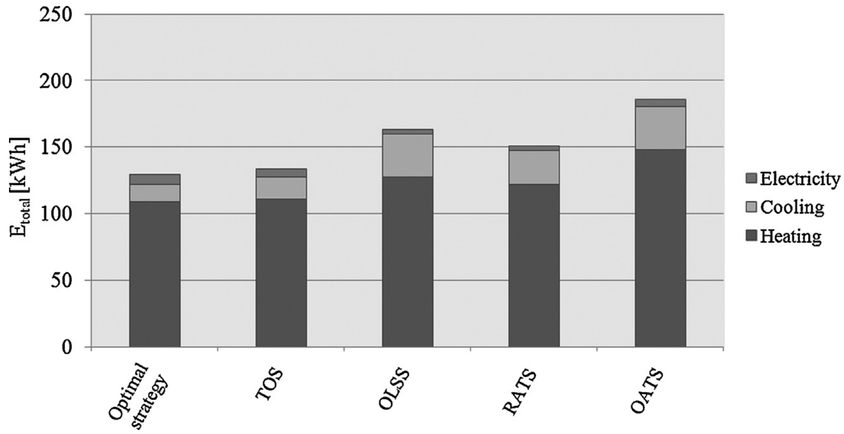

Fig. 6. The energy used by HVAC system A during two working weeks of Swedish summer and winter climate in a heavy office building. Each bar is associated to a specific SAT control strategy.

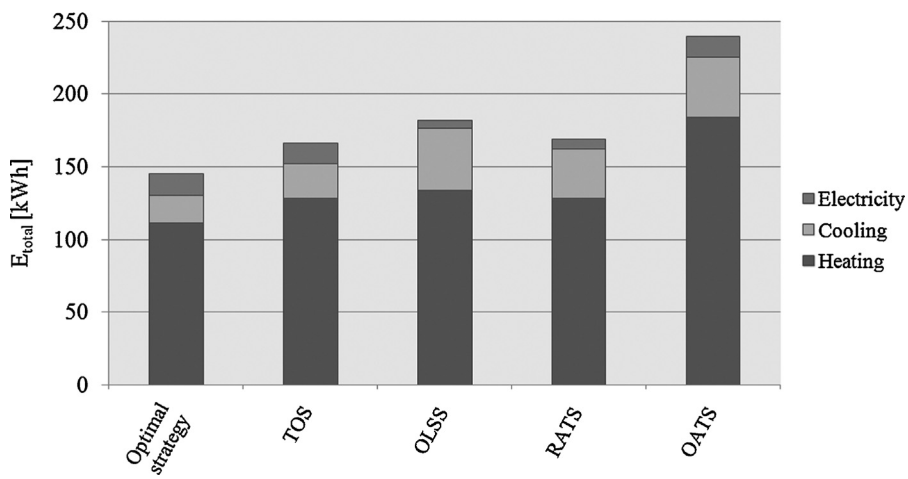

Fig. 7. The energy used by HVAC system A during two working weeks of Swedish summer and winter climate in a light office building. Each bar is associated to a specific SAT control strategy.

systems for heating and did not act until they responded. These diverse input signals led among other things to different levels of independence: while the TOS acted independently of the local systems, the RATS acted in parallel and the OLSS acted dependently. This feature explains the ability of the strategies to save energy in the two HVAC system cases. In HVAC system B, the local systems should first and foremost manage the room temperature control while the ventilation system remains passive (according to the optimal strategy) which means that the TOS was unsuitable and the OLSS was preferable. In the system A case, the situation was the opposite and the strategy which reduced the use of local system (RHs) was most preferable (the TOS).

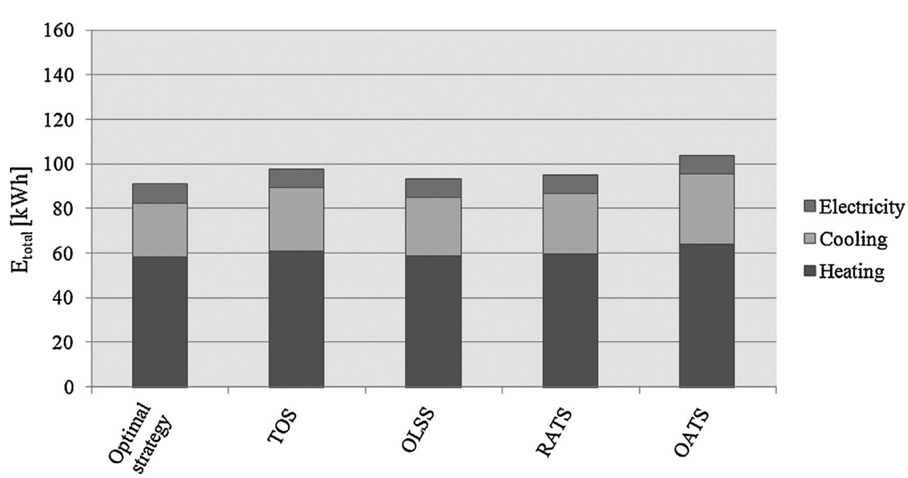

Fig. 8. The energy used by HVAC system B during two working weeks of Swedish summer and winter climate in a heavy office building. Each bar is associated to a specific SAT control strategy.

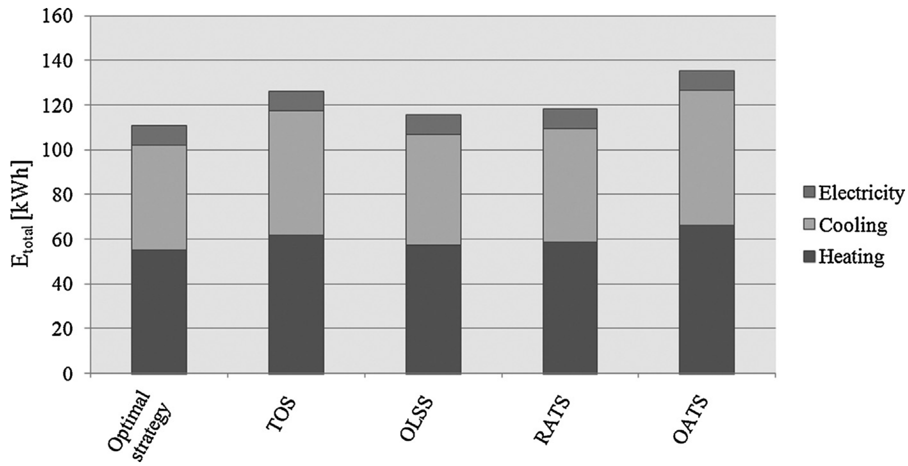

Fig. 9. The energy used by HVAC system B during two working weeks of Swedish summer and winter climate in a light office building. Each bar is associated to a specific SAT control strategy.

Summary

In this work, supply air temperature (SAT) control strategies for a reduced energy usage and a maintained indoor climate in office buildings were investigated through simulations. In total, five strategies were considered, whereof three were proposed as low-complexity alternatives, one was optimal and represented the upper boundary of possible energy savings, while the last was a conventional outdoor-air-temperature-based approach used as benchmark. Two different heating, ventilation and air-conditioning (HVAC) systems and two types of buildings were considered and the results were presented as the energy used during two working weeks of Swedish summer and winter climate respectively. It was shown that while satisfying thermal climate and indoor air quality, up to 30% of the energy usage could be saved by a low-complexity strategy while the optimal resulted in up to 39%. Moreover, it was found that the optimal strategy in one of the HVAC system cases was general and only dependent on the outdoor air temperature. This means that the solution can be used to generate a simple version while maintaining the high energy savings potential. Overall, it can hence be concluded that there is a large potential for revising SAT control, and that simple strategies are sufficient to drastically reduce the energy usage. But, it can also be concluded that the benefits were highly dependent on the considered HVAC system and somewhat dependent on the considered building structures.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2014.06.056.

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Paper IV

Energy efficient climate control in office buildings without giving up implementability

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Nomenclature

c	CO_2 concentration [ppm]
c_p	specific heat capacity [J/(kg K)]
$\dot{Q}$	thermal power [W]
t	celsius temperature [°C]
u	controller input of thermal disturbances [W]
$\dot{V}$	volume flow rate [m^3/s]
y	controller output in ventilation flow quantities [m^3/s]

Greek letters

ρ	density [kg/m^3]

Subscripts

act	activation
adj	adjacent
s	supply
sp	setpoint
r	room

Abstract

The adaptation between a building and its automation system can potentially be increased by model-based controllers with an integrated control model and information about indoor climate disturbances. The associated energy savings potential is large but a widespread utilization is typically prevented by high complexities. From that point of view, a trade-off technology that combines implementability with an overall higher performance than the system of current practice would be a better option at most sites. This work presents an experimental evaluation of an alternative controller that follows the same principle as model-based, but has gone through a large number of simplification measures for a reduced overall complexity and a limited function. The controller was evaluated for indoor climate control by automating the ventilation flow rate during a typical office working day that was re-created in a laboratory environment. Experiments were conducted in two different office sites, as well as during two weather seasons of Swedish summer and winter. From the investigation, it was concluded that despite of the reduced complexity, the investigated controller could save between 12-19 % of indicated energy compared to a system of common practice at the same time as the quality of indoor climate was maintained.

Keywords

Heating, ventilation and air-conditioning; Office buildings; Indoor climate control; Implementability; Air-based heating and cooling; Building automation; Energy efficiency; Model-based controller; Anticipating controller

1. Introduction

A way of achieving cost- and energy efficient retrofits in buildings is to improve the building automation system (BAS). A high energy savings potential follows from that the BAS manages the operation of the HVAC (heating, ventilation and air-conditioning) system which in turn stands for approximately 76 % of the total energy usage in European buildings [1]. At the same time, implementation of new technologies is to a certain degree possible without major system changes, which means that installation costs can be small compared to the revenues. As the BAS acts as an interface between the building and the HVAC system, improvements refer to increasing the adaptation to prevailing conditions by incorporating relevant information about building characteristics, the activities inside the building, the ambient climate etc. In this way, the necessary actions for achieving a desirable indoor climate from a static and dynamical point of view can be estimated in advance - before any deviations from desirable comfort regions occur. Also, the control activity could be planned ahead by anticipating future demands which opens up for the possibility of reducing energy usage by deciding on the most preferable actions. In its broadest sense, this technology is referred to as model-based control. A typical configuration includes a sensing system that gathers information about indoor climate disturbances as exogenous inputs to an integrated control model. The control model is used to predict the corresponding impact on the controlled variables, and to adjust the HVAC control signals to achieve a desired behavior of the process, based on some given criterion.

Several previous works have indicated that model-based controller have the ability of achieving substantial energy savings without compromising comfort [2-6]. However, a typically high level of complexity means that implementation at most common sites are prevented along with a widespread utilization. Important aspects in this context are the number of disturbances considered as exogenous inputs, their quantifiability, how the associated information is processed by the control model as well as how input errors and deficiencies are compensated for [7, 8]. A complete correspondence between process and control model as well as information about all relevant indoor climate disturbances would potentially lead to a perfect adaptation between BAS and building. But, such controller is also associated to high installation costs, comprehensive commissioning as well as continuous maintenance to update for changes in the process. For that reason, extensive controller designs are unrealistic for considering in the majority of buildings. On a large scale, a compromise between simplicity and performance would instead be a more suitable option, given that a sufficiently high implementability can be combined with a considerable higher performance than associated to the BAS of current practice.

1.1. Purpose and procedure

This paper contributes in the search for simple and energy efficient BAS by providing an experimental evaluation of an alternative controller that follows the same principle as a model-based but has gone through a large number of complexity reducing measures. This process was described in a previous publication [9] and followed a step-wise procedure in which a number of proposed simplifications individually were applied on the control model or on the exogenous inputs, while their cumulative effect on control performance consistently was evaluated through simulations. Several alternative control models were then evaluated and a systematic search for the disturbances with the largest potential as exogenous inputs was conducted. An overall low complexity was achieved by limiting the exogenous inputs to the most common internal disturbances and by replacing a complete process model with a closed-loop non-linear filer. The function of the controller was thereby limited to achieving a desirable indoor climate using as little energy as possible by anticipating the short-term and current effects of the considered disturbances. Therefore, the controller will from now on be referred to as a simplified anticipating controller (SAC).

This paper belongs to a larger research project in which a similar methodology was applied for evaluating different HVAC system variants in office environments with respect to automation possibilities of the SAC. Previous publications have considered hydronic heating/cooling via a fan-coil unit as well as fresh air supply via a mechanical VAV (Variable Air Volume) ventilation system [10]. These two subsystems were mainly differentiated by their dynamical properties, and it was shown that the SAC was most beneficial for automating the ventilation part due longer transport delays in system and process. For that reason, the present paper focuses on an all-air HVAC system for heating, cooling and supplying fresh air via mechanical ventilation.

Experiments were conducted during a typical working day that was re-created in a test facility by imitating internal disturbances in sequences. The task of the SAC was to maintain the IAQ (Indoor Air Quality) and thermal climate indicated by measured CO_2 and temperature, respectively, through integrated room automation of ventilation flow rate. Experiments were conducted in two separate spaces representing a meeting and an office room with respect to working activity, layout and size. Furthermore, two weather seasons of Swedish summer and winter were considered, and each scenario was repeated, first with the SAC, and then with a conventional feed-back controller as a benchmark for current practice.

As an experiment stretched over a working day, the investigation focused on circumstances when a desirable indoor climate is of utmost importance for avoiding discomfort and productivity losses. Further, a typical consequence during such periods is high HVAC energy usages; partly due to high loads, and partly since the room for energy reducing measures such as setpoint resets or free-cooling etc is small. These two features were emphasized in the comparison between SAC and benchmark, by constraining the controllers to achieve equally desirable indoor climates while the associated HVAC energies were used as a performance metrics.

2. Investigation

The investigation was conducted during one calendar year in a 300 m^2 large university test facility located in Gothenburg, Sweden. The facility (*fig.1*) is commonly used for research and education within the field of building services engineering, and contains multiple sites and various equipments for studying different areas involved in the subject. An experimental HVAC system stretches throughout the building whereof most parts were involved to some extent in this work at the same time as the actual experiments took place in the seminar room located at the entrance floor in the north-west corner (*fig.2*). To facilitate for the reader, the site and the associated systems are in the following text divided into three levels, based on their purposes during the investigation. Further on, this description is followed by presentations of the re-created working day and the associated experimental design.

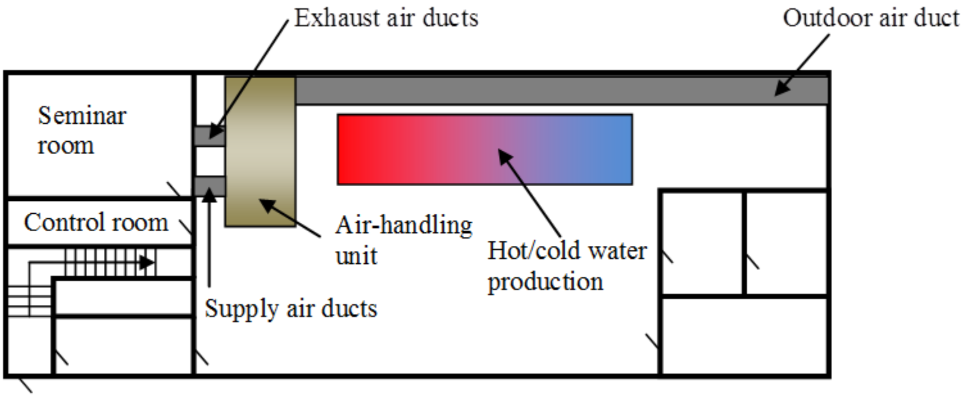

Figure 1. Layout of the test facility including the seminar room, a control room and an open hall.

2.1. Experimental framework

The seminar room in figure *2* has a floor area of 5.6 × 6.2 m and a height of 2.4 m. The envelope is of gypsy and mineral wool while the framing is of concrete and steel. The walls represented as left and top in the figure are external, whereof the left has a section of outside solar shaded windows over most of its length. The remaining walls as well as the ceiling are adjacent to other parts of the building, while the floor is made up of a ground connected concrete slab. Indoor climate control with respect to heating, cooling and air renewal is provided by a VAV (Variable Air Volume) mechanical ventilation system. In table *1*, the parts of the HVAC system involved in the investigation are presented together with an overview of their purposes and how they were controlled during the experiments.

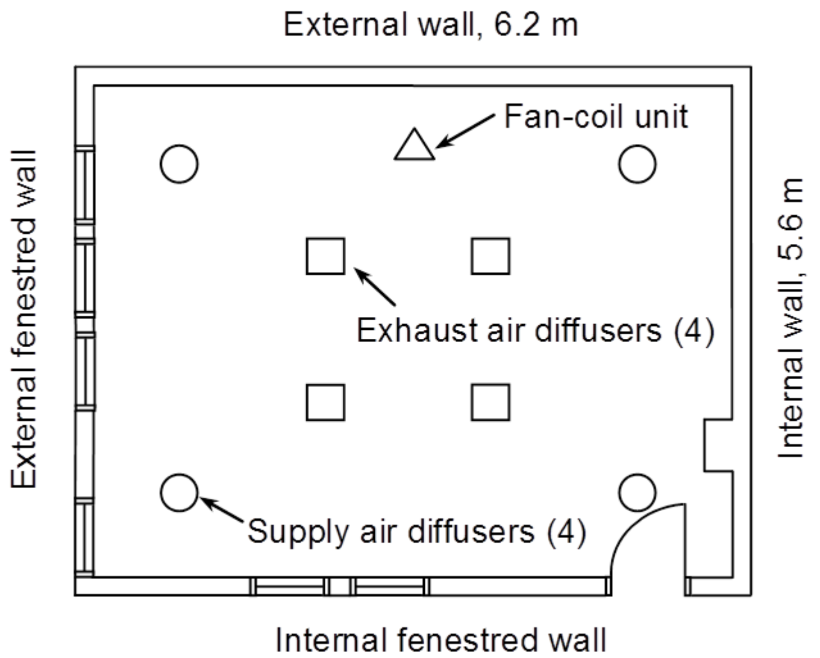

Figure 2. Layout of the experimental site, i.e. the seminar room. The walls representing left and up are external while the remaining are internal. Explanation of symbols: circles: supply air diffusers, squares: exhaust air diffusers.

The first level in table *1* is made up of an open hall in which a number of units for production and storage of hot and cold water are installed. During the experiments, a dry cooler together with a combined heat pump/chiller (simultaneous production of hot and cold water) managed the base supply while an electrical boiler functioned as auxiliary system. During the experiments, sequence control was applied to maintain constant temperature setpoints in a number of tanks from which heating and cooling carriers in turn were distributed through a piping system. The second level is made up of an air-handling unit (AHU) in which two speed-controlled fans were used to ventilate the seminar room (third level) via four ducts each for supply and exhaust air. On the supply-side of the AHU, OA (Outdoor Air) was conditioned over two finned water-connected air coils with the carriers as heating and cooling media respectively. The air temperature and humidity were controlled by varying the inlet temperature on the water-side with an automated by-pass, 3-way valve for mixing of the primary supply and the coil return. On the third level, the ventilation air was supplied and extracted through mixing roof-mounted diffusers in the seminar room. During the experiments, the investigated controllers were evaluated for integrated room automation of supply air flow rate by varying the opening of the associated diffuser. The same control signal was furthermore used on the second level to adjust the speed of the supply air fan, and at the same time, the exhaust system was controlled to follow the supply side to achieve balanced ventilation.

Table 1. Summary of HVAC components involved during the experiments. OA (Outdoor Air)

First level (Production units)	**Purpose**	**Control strategy**
Electrical boiler	Hot water production	On/off
Combined heat pump and chiller (2)	Simultaneous production of hot and cold water	On/off
Ground source heat pump	Cold water production	Variable bore-hole flow rate
Dry cooler (2)	Heat exchange between water and OA	Variable flow on OA-side
Hot and cold water tanks (5)	Storage of heating and cooling carriers	-
Distribution system 1st ↔ 2nd levels	**Purpose**	**Control strategy**
Pipings of three temperature levels	Transportation of carriers	-
Circulation pumps (3)	Pressure control	Variable speed drive
Second level (Air handling unit)	**Purpose**	**Control strategy**
Hot water connected air coil	Heating of OA	Variable water inlet temp.
Cold water connected air coil	Cooling / dehumidifying of OA	Variable water inlet temp.
Circulation pumps (2)	Pressure control at coil inlets	Variable speed drive
Supply air fan	Track control signal to the supply air diffusers	Variable speed drive
Exhaust air fan	Track flow on the supply air side	Variable speed drive
Distribution system 2nd ↔ 3rd levels	**Purpose**	**Control strategy**
Four ducts in each direction	Transportation of ventilation air	-
Third level (Seminar room)	**Purpose**	**Control strategy**
Supply air diffusers (4)	Actuator for room air temperature	Automated opening
Exhaust air diffusers (4)	Extraction of room air for balanced ventilation	Manual balancing dampers

Remark: In this work, the supply-side of the ventilation system was entirely made up of conditioned OA while the exhaust air was discharged to the ambience. This principle is in accordance to Swedish common practice and is referred to as heat recovery ventilation (HRV) which is characterized by that heat is recovered from the exhaust to the supply by the means of a heat exchanger instead of recirculation of exhaust air [11].

2.2. Experimental design

Due to the symmetrical distribution of supply and exhaust air diffusers as illustrated in figure *2*, the seminar room can be divided into separate modules. In this work, two variants (*fig.3*.) were considered on separate occasions by enclosing floor areas of 10 or 18 m^2 with temporary walls (marked as filled) of glued sheets of thick Styrofoam. The sizes and layouts corresponded to an office (left) respective a meeting room (right) and ventilation was in both cases managed by a single pair of diffusers (marked out in *fig.3*). Each module could be accessed through a built-in door, and was assembled to represent spaces in modern office buildings, with tight and well-insulated envelopes.

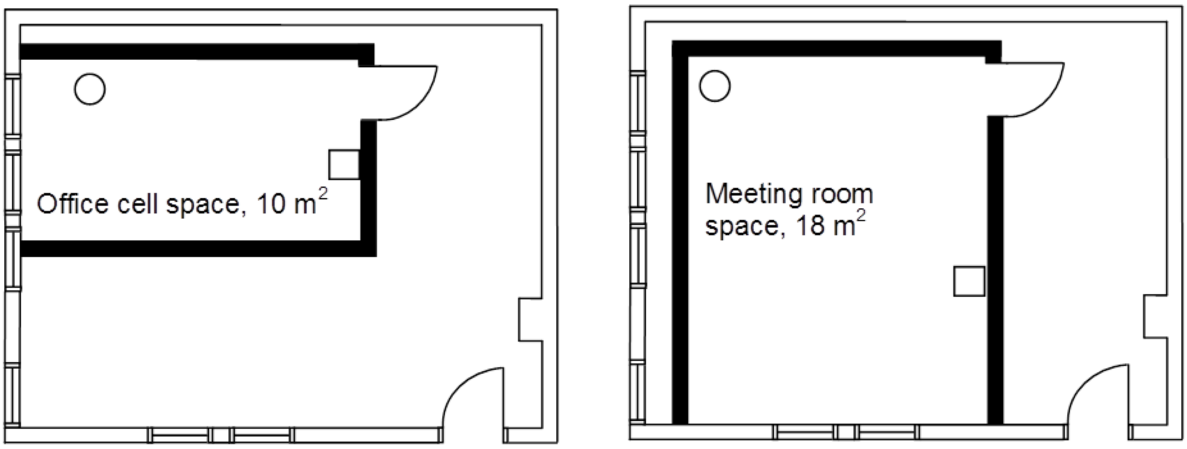

Figure 3. The two variants of office environments that were considered in the seminar room. Left: office room space, right: meeting room space. Temporary walls of Styrofoam are marked as filled.

2.2.1. Re-created working day

During the experiments, typical working days of meeting or office room activities were re-created in the associated space by imitating the following internal disturbance in 9 hour sequences.

- Occupancy (referring to the number of people)
- Lighting
- Equipment
- Door opening

Occupancy was re-created as the sequences in figure *4* that were constructed using annual statistical data from a 58 room large Swedish office building [12]. By comparing these sequences to recommendations regarding the design number of occupants for the associated space and activity [13], the office room was fully occupied except during lunch time (11:30 -13:00), while the maximum occupancy factor in the meeting room reached about 70

%. The occupants were in turn imitated by burning candles of a type that was confirmed to have a close correspondence to the heat and CO_2 emitted by an office worker as presented in figure *5*. These results were produced by measuring and comparing temperature and CO_2 responses in a confined space with either one person performing office activities or one burning candle. Further, lighting and equipment were assumed to be dependent on the occupancy sequences, and were imitated by modulating the heating power output of a white-painted electrical panel radiator. According to the national standard SS-EN 12464-1 [14], a sufficient lighting corresponds to 10 W of heat per m^2 of floor area which was re-created as ON during occupied periods and OFF during vacancy. The equipment part in the meeting room was consistently re-created with 50 W/imitated person, while set to 100 W between the initiation and finalization of the occupancy sequence in the office room (to represent a computer that runs all day but is turned off outside office hours). Finally, the door was throughout closed in the meeting room scenario, while open for approximately one hour (14:30 -15:20) during the afternoon in the office room case.

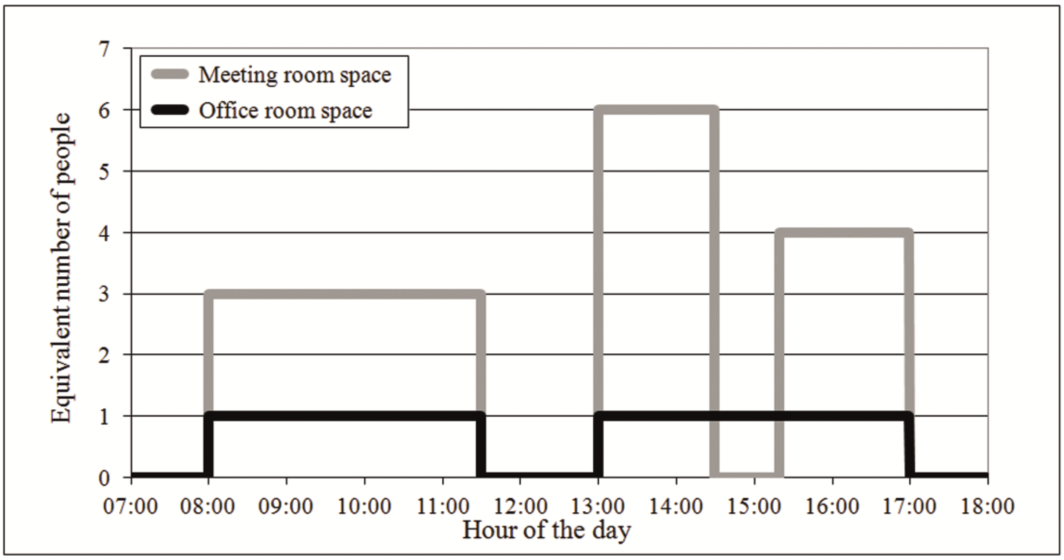

Figure 4. Sequences of equivalent number of people (with respect to heat and CO_2 emission) applied to the spaces during the re-created working day.

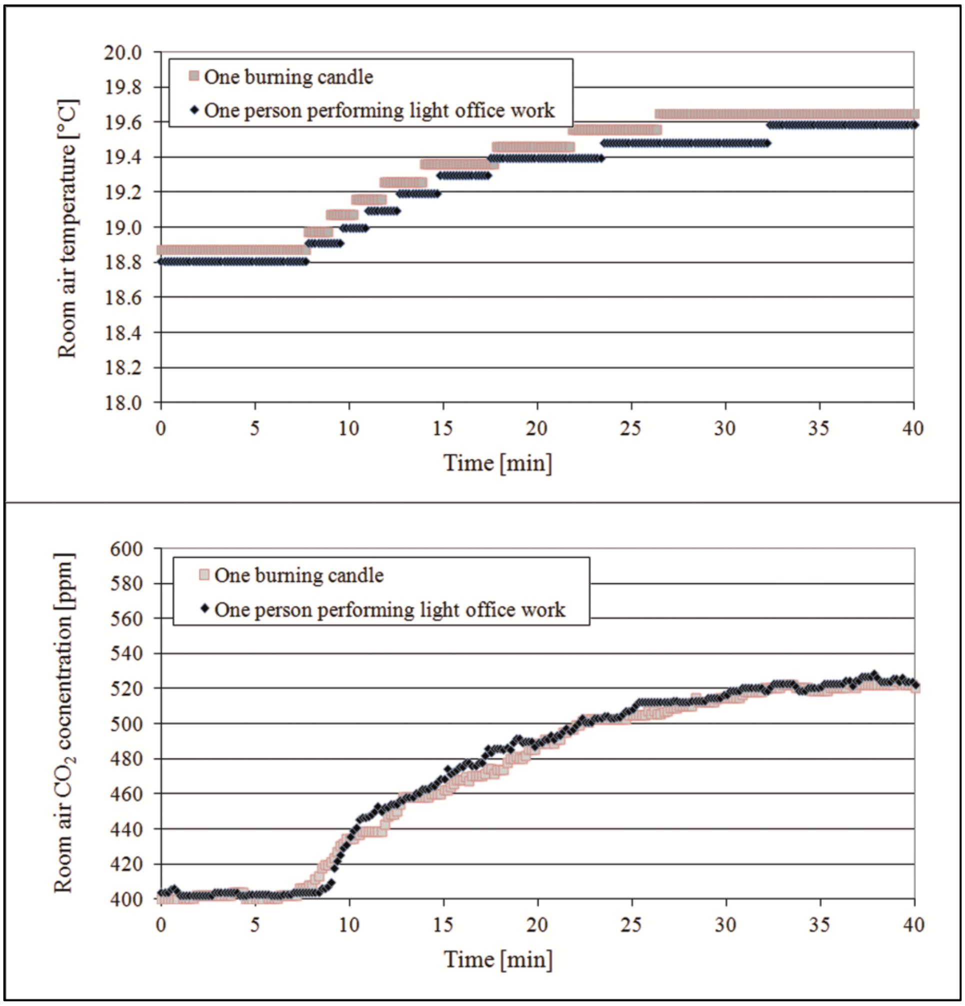

Figure 5. Validity of correspondence in heat and CO_2 emission between an office worker and the considered burning candle through measurements of temperature and CO_2 responses in a confined space.

2.2.2. Internal vs. external disturbances

In the meeting room space, the ambient influence on the indoor climate was minimized by providing sufficient air-gaps between temporary and external walls, as can be observed in figure *3*. In contrast, the associated internal disturbances were occasionally large since the respective occupancy sequence exclusively contained more than one person at the same time. In the office room case, the proportions were the opposite due to the external fenestrated wall in combination with a design-occupancy of one person. Hence, the two spaces represented its own extreme regarding the dominating origin of indoor climate disturbances, and this experimental layout was chosen to span the results from the investigation so that most relevant cases can be found within the range. Moreover, the design of the office room environment and diverse outdoor air temperature (OAT) during the considered time period enabled the investigation to span over scenarios when the HVAC system operated in heating as well as cooling mode by repeating these trials for cold (about -10 °C) as well as warm (about +20 °C) ambient climates. On the other hand, the governing conditions in the meeting room did not allow the same extension and these trials were throughout characterized by consistent cooling demands.

2.2.3. Supply air temperature levels

Throughout the study, constant supply air temperature levels of either 15 or 25 °C were maintained during cooling and heating mode, respectively. This strategy was primary chosen to maintain generality by preventing the results from being influenced by any subjective elements in a supply air temperature algorithm. Furthermore, the comparability between trials repeated with the SAC and benchmark was also increased in this way. The levels were in turn chosen to achieve a high transparency by providing ideal prerequisites for the investigated controllers in each trial: the lower level is the minimum for avoiding draught [15] while the higher is the observed maximum for a maintained ability of providing the desired heat via ventilation without compromising IAQ. That is, the supply air temperature implied a minimum of required ventilation flow rate throughout the study, which means that less effort was put on the investigated controllers.

2.3. Experimental setup

In accordance to the common methodology that previously was applied in [9,10], the test equipment was equivalently placed along a straight line between the active pair of air diffusers (see fig.3). In order to maximize the propagation of emitted heat and CO_2, the burning candles and the radiator were placed in the middle on a 1 m high table and on the floor, respectively. The indoor climate was in turn indicated by measured room air CO_2 and temperature using uncovered sensor-elements with accuracies of ±50 ppm and ±0.1 °C, respectively. To avoid these measurements from being directly influenced by walls, the supply air stream or disturbances, the sensors were mounted in the free air on a tripod located at least 2 m from the disturbances on their exhaust air diffuser side [16]. The vertical positions were in turn selected using the BBR19 comfort zone, in which indoor climate constraints are valid and regions close to floor, ceiling and walls are excluded [13]. Since the considered weather seasons both implied heating and cooling modes, the temperature sensor was placed in the middle of this zone to avoid higher or lower temperatures than the average. The CO_2 sensor was in turn placed on the upper boundary were the highest concentrations were expected.

3. Controllers and control systems

The SAC and the benchmark were separately evaluated for room air temperature control through flow rate automation of the VAV ventilation system, while the minimum allowed level was set to maintain a desirable CO_2 level during the experiments. In this section, it is first presented how the controllers were evaluated for these tasks. Then, a detailed description of their structures and designs are provided.

3.1. Evaluation method

The controller comparison was performed according to the method in [9] which is based on the two most important HVAC system functions: indoor climate is to be kept within given comfort ranges, by preferably using as little energy as possible [17]. The indoor climate aspect was taken into account by considering current standards and guidelines to formulate two comfort criterions (one each for IAQ and thermal climate) that both controllers were constrained to fulfill within feasible limits. These are presented in the following text and were realized by first applying the SAC in a certain scenario. The same scenario was then repeated with the benchmark after applying appropriate setpoint adjustments for similar comfort as observed in the first case. In turn, the performances of the controllers were measured by the associated HVAC system energy usage and these coherent experiments were performed during two consecutive days in order to reduce the influence of weather variations. The maximum allowed difference of average OAT was set to 2 °C, and for larger variations, one of the experiments was repeated during more suitable conditions.

The IAQ was indicated by the room air CO_2 concentration (c_r) and the associated comfort constraint is presented in equation *1*. It states that the level was not allowed to cross an absolute boundary of 1000 ppm, either when the SAC or the benchmark controller was implemented. This constraint is based on several national recommendations [18] as well as the ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) standard 62-2007 [19].

$$\hat{c}_{r,SAC} = \hat{c}_{r,benchmark} = 1000 \quad \text{[ppm]} \qquad (1)$$

The quality of the thermal climate was indicated relative to a room air temperature (t_r) comfort region between 21 and 22 °C. The first endpoint was set according to a national guideline [15] which states that lower temperatures should be avoided in occupied office rooms. The second endpoint was set 1 K higher, since according to the standard ISO 7730:2005 [20], smaller room air temperature variations do not have a negative effect on the thermal comfort, and similar recommendations are also given in ASHRAE standard 55-2004 [21]. The associated comfort constraint is presented in equation *2* and states that the deviating degree hours above and below this region should be similar when the SAC and the benchmark were applied. This metric derives from the European standard EN-15251 [22] and solely applied during occupied periods while drifts were allowed during vacancy without any penalties. It is worth pointing out that a more common metric in this context is the PMV (Predicted Mean Vote) [23], but although recognized as a good estimator of thermal sensation, it was formulated during steady-state and is hence not suitable for the transient conditions studied in this work.

$$\begin{cases} \left(\sum \Delta t_{high}\Big|_{\infty,0} \times time\right)_{SAC} \approx \left(\sum \Delta t_{high}\Big|_{\infty,0} \times time\right)_{Benchmark} \\ \left(\sum \Delta t_{low}\Big|_{\infty,0} \times time\right)_{SAC} \approx \left(\sum \Delta t_{low}\Big|_{\infty,0} \times time\right)_{Benchmark} \end{cases} \quad [°Ch] \quad (2)$$

Provided that the space is occupied

Where

$$\begin{cases} \Delta t_{high} = t_r - 22 \\ \Delta t_{low} = 21 - t_r \end{cases}$$

3.2. Benchmark feed-back controller

The benchmark feed-back (FB) lacked information about disturbances and solely relied on measured room air temperature as input. Its general structure is presented in figure *6* (top), and the control signals were generated by first forming a control error as the difference between input value and a fixed setpoint. This signal was in turn processed by proportional (P) and integrating (I) blocks and a final transformation from ventilation flow rate quantities to actuator compatible signals was performed by a second cascade connected controller. The PI-blocks were tuned using the AMIGO step response method. It is not the most common method but derives from a large number of optimization procedures and approximately returns the controller parameters that minimize the deviation from the setpoint [24].

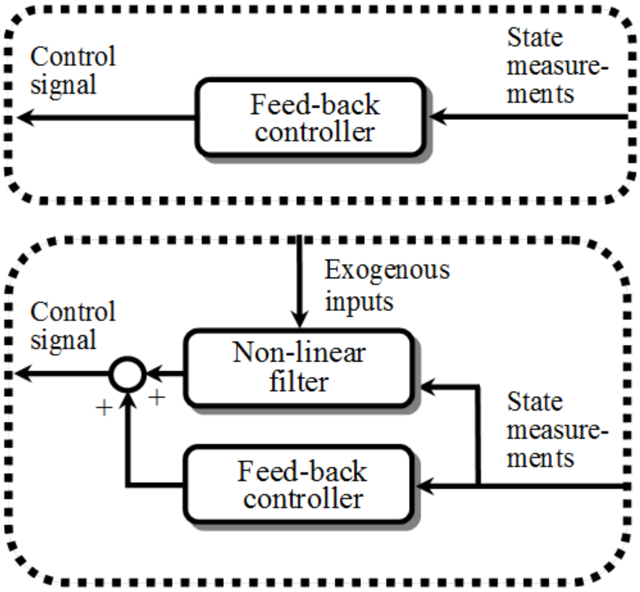

Figure 6. General schematics of the considered controllers: top; benchmark feed-back controller, bottom; simplified anticipating controller (SAC). In this work, the state measurements refer to measured room air temperature, the control signal refers to a ventilation flow rate and the exogenous input refers to the total heat emitted by the imitated internal disturbances.

3.3. Simplified anticipating controller (SAC)

The schematics of the investigated controller are presented in the bottom of figure *6:* the exogenous input constitutes the total heat from the imitated internal disturbances and the control model is made up of a non-linear filter assisted by a feed-back controller. As mentioned, the overall principle was adopted from model-based controllers, but while reducing the complexities of both control model and inputs in the process. The function was thereby limited to anticipating the current and short-term effects of measured disturbances in order to achieve a desirable indoor climate using as little energy as possible.

3.3.1. Exogenous inputs

While model-based controllers in most previous publications had information about the entire set of disturbances (including external such as OAT, solar radiation, infiltration etc.), the exogenous inputs to the SAC is limited to the imitated sequences presented in section *2.2.1*. To reduce the number of parameters influencing the result from the investigation, an ideal disturbance sensing system was assumed and the sequences were directly utilized by the controller. This is primary a simplification from an occupancy point of view due to the lack straight forward measurement methods (for further information about the connection between uncertainties in the exogenous input and control performance, [25] can be considered).

The non-linear filter was designed to process exogenous inputs expressed in thermal power units, and this quantity was known for all imitated disturbances after applying a two-step processing to the door opening in the office room scenarios. In the first step, the infiltration flow rate through the open door was described by the empirical equation *3* [26] by acquire three parameters: the height (H [m]) and the area (A [m^2]) of the door as well as a constant (K) which is dependent on the geometries of the controlled space and the adjacent (*adj*) room. K was in this work determined experimentally but standard values given in [26] can also be used. Secondly, the temperature on the adjacent side of the door was measured and used in equation *4* together with the estimated infiltration flow rate.

$$\dot{V}_{door} = K_{door} \times A_{door} \times \left(H_{door} \times \left|t_{adj} - t_r\right|\right)^{0.5} \qquad [m^3/s] \qquad (3)$$

$$\dot{Q}_{door} = \dot{V}_{door} \times \rho_{air} \times c_{p,air} \times \left(t_{adj} - t_r\right) \qquad [W] \qquad (4)$$

3.3.2. Non-linear filter

A typical model-based controller utilizes a complete model of the process for predicting the short- and long-term influence of exogenous input. In order for physical models to be sufficient for this task, a large number of parameters would be required whereof several are uncertain or hard to determine. Another alternative are black-box models that are constructed from observed data in terms of input/output measurements. But since the accuracy immediately becomes uncertain in ranges not covered by past data, the commissioning phase can be an extensive process. The control model of the SAC was instead reduced to a non-linear filter assisted by a feed-back controller identical to the benchmark. The individual parts were designed to return supply quantities (i.e. ventilation flow rates) and the outputs were summed up and transformed into actuator compatible signals (by a cascade connected controller). As the assisting feed-back was used to compensate for errors (such as unmeasured or faulty measured disturbances) and thereby managed the base supply, the purpose of the non-linear filter was to act fast and accurate to changes in the exogenous inputs.

As the present room air temperature was used as input, the filter is characterized as of closed-loop type, and the associated output signal dependence is presented in figure *7*. The separate parts in equations *5a* and *5b* were used during cooling and heating modes respectively, through an IF-condition for automatic selection by comparing the supply and room air temperatures: that is, IF t_s-$t_r < 0$, THEN *5a*, ELSE *5b*. The total heat emitted by the imitated disturbances (u) were in both cases used to generate control signal outputs in power units; either associated to an increased cooling supply ($0 \rightarrow u$, *5a*) or to a decreased heating supply ($-u \rightarrow 0$, *5b*). In turn, equation *6* transformed these signals into the corresponding ventilation flow rate by acquiring the current room- and supply air temperatures (t_s). In accordance to figure *7*, the filter parts were featured to modulate their output (y) by scaling the exogenous inputs (u) with respect to the current room air temperature (t_r). The scaling properties were in turn determined by a pair of parameters, including the comfort region boundaries (t_{low}: 21 °C and t_{high}:22 °C), and associated activation temperatures (t_{act}). As the activation temperatures were assigned values inside the comfort region close to the coherent boundary, each parameter-pair covered a certain temperature area. For room air temperatures inside any of these areas, the filter output consisted of the exogenous input scaled down between 1 and 99 %. For room air temperatures above the comfort region (presuming cooling mode), the entire registered heat emission was utilized as cooling supply, and for room air temperatures below, the filter output was zero (presuming heating mode). Between the two activation temperatures, the outcome is dependent on the current mode as illustrated in the figure.

$$y_{cooling\,mode} = \left(\left(\frac{t_r - t_{act,high}}{t_{act,high} - t_{high}} \right) \Bigg|_{0,1} \times u \right) \qquad [+W] \qquad (5a)$$

$$y_{heating\;mode} = -\left(\left(1 - \frac{t_{act,low} - t_r}{t_{act,low} - t_{low}} \right) \Bigg|_{0,1} \times u \right) \qquad [-W] \qquad (5b)$$

$$\dot{V}_{vent} = \frac{y}{\rho_{air} \times c_{p,air} \times (t_s - t_r)} \qquad [m^3/s] \qquad (6)$$

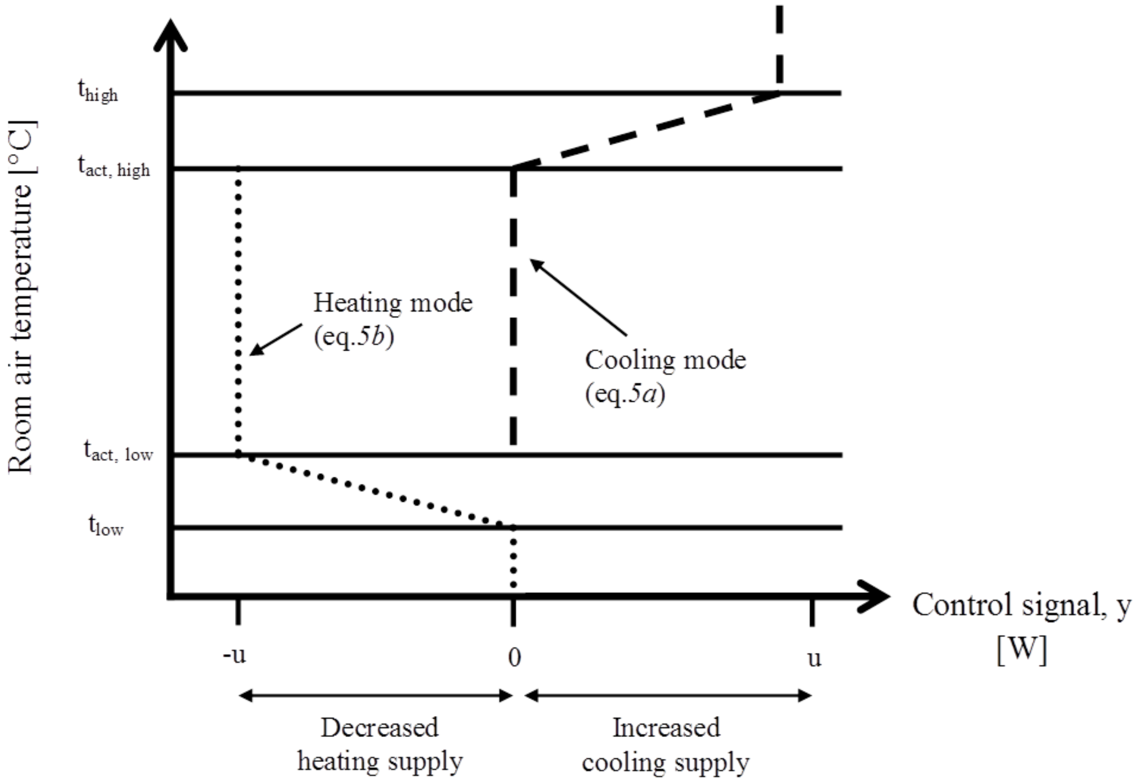

Figure 7. Working principle of the non-linear filter. The control signal output dependency on the current room air temperature during HVAC system heating and cooling mode.

4. Results

Table *2* presents the scenarios for which the investigated controller and the benchmark were compared. The associated results in the following section are presented as the HVAC energy usages indicated by the ventilation rates measured with an accuracy of ±2 l/s. Since equal and constant supply air temperature setpoints were used during all coherent experiments, this indicator is directly proportional to the air-handling energy. At the same time, the results were prevented from being influenced by OAT dependent air-handling energy and by operational dependent efficiencies due to unequal controller setpoints (for fulfilling the comfort constraints).

Table 2. Evaluated scenarios. (SAC=Simplified Anticipating Controller)

Controller	**Ambient climate**	**Space**	**HVAC system mode**
SAC	Winter	Office room	Heating
Benchmark	Winter	Office room	Heating
SAC	Summer	Office room	Cooling
Benchmark	Summer	Office room	Cooling
SAC	Irrelevant	Meeting room	Cooling
Benchmark	Irrelevant	Meeting room	Cooling

Three actions were applied in this chapter to facilitate for the reader. First, only the room air temperature part of the control task is presented, while continuous observations during the experiments ensured that also the IAQ constraint (CO_2 concentrations below 1000 ppm) was fulfilled. Second, the energy indicator for each scenario is presented graphically in cumulative distribution functions (CDF) (i.e. sorted values from low to high on an increasing x-scale). In this way, the left parts of the cooling mode graphs (in fig. *9* and *11*) are associated to vacant periods and the right to periods with extensive loads. Consecutively, the vice versa applies for the heating mode graph in fig. *9*. As a third action, the supply air flow rate was presented relative to the maximum allowed level which, in each scenario, was set to provide the necessary thermal power for a maintained thermal comfort.

4.1. Office room scenarios

In figure *8* and *9*, the controlled room air temperatures as well as the supply air flow rate are presented for the office room scenarios. During cooling mode, the largest strain on the thermal climate occurred at 08:00. Then, all internal disturbances were initiated at the same time and thereafter, the equipment part was active throughout the rest of the day which means that the event that occurred at 13:00 had less influence. The comfort constraint was fulfilled by reducing the setpoint of the benchmark with 0.5 °C, and the corresponding influence on energy usage was equivalent to about 5 l/s which is visualized as the offset during vacant periods in figure *9*.

In heating mode, the largest strain on the thermal climate was instead due to the opening of the door at 14:20, which was the only heat sink that occurred during an occupied period. The comfort constraint was in this mode fulfilled by increasing the setpoint of the benchmark with 0.2 °C which, according to figure *9*, had a negligible influence on the supply air flow (i.e. the ventilation rates during vacant periods coincide). An important remark to figure *8* is that the temperature drops below 21 °C occurred during vacant periods and had therefore no negative influencing on the thermal climate according to the comfort constraint.

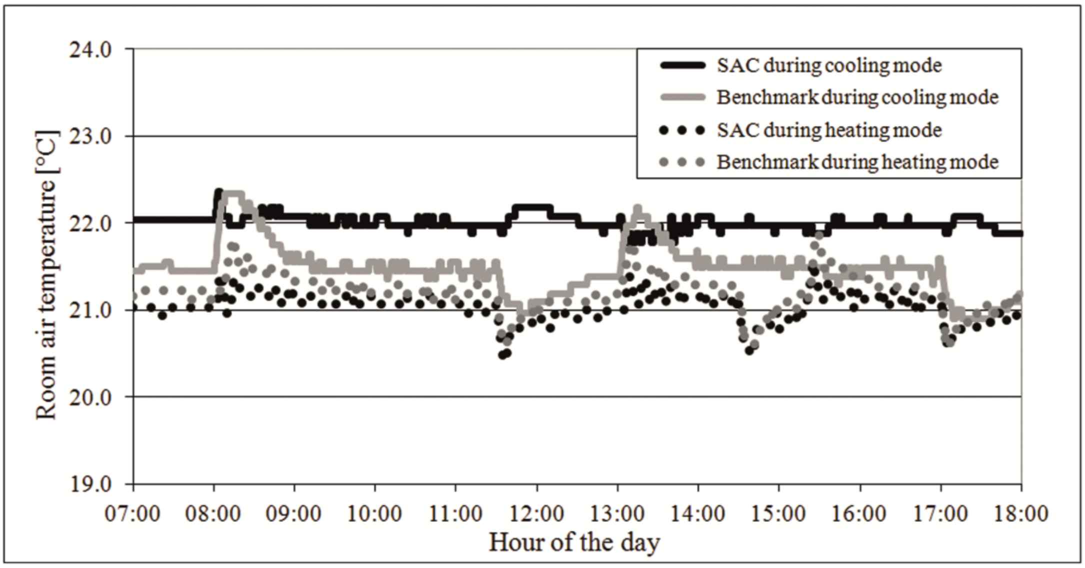

Figure 8. Variations of controlled room air temperature, measured in the office room during the re-created working day. The figure includes both the winter (heating mode) and the summer (cooling mode) season scenarios. (SAC = Simplified Anticipating Controller)

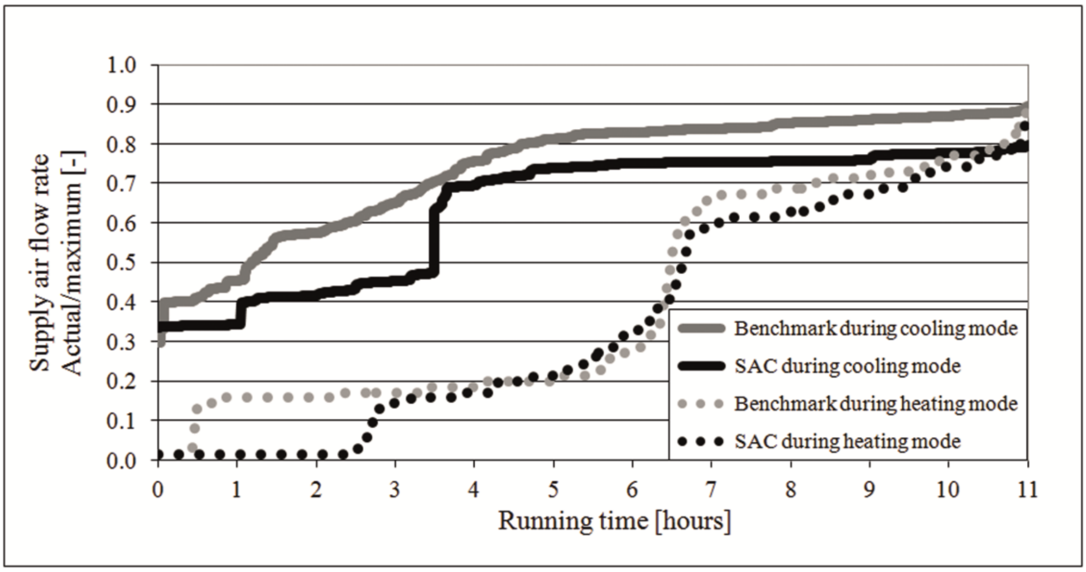

Figure 9. Cumulative distribution function of measured ventilation flow rate to the office room during the re-created working day. The figure includes both the winter (heating mode) and the summer (cooling mode) season scenarios. (SAC = Simplified Anticipating Controller)

4.2. Meeting room scenario

In figure *10* and *11*, the results from the meeting room scenario are presented. The largest strain on the thermal climate was associated to the largest heat gain at 13:00. Similar comfort was achieved by reducing the setpoint of the benchmark with 1 °C which was equivalent to a supply air flow rate of about 9 l/s. Also in this case, the temperature drops below 21 °C in figure *10* occurred during vacant periods and had therefore no negative influencing on the thermal climate according to the comfort constraint.

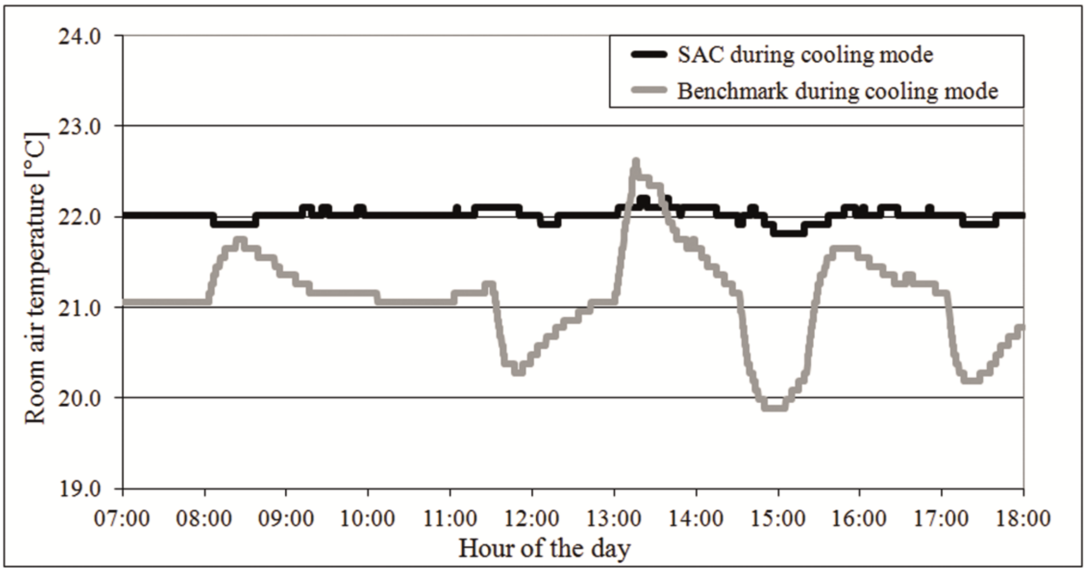

Figure 10. Variations of controlled room air temperature, measured in the meeting room during the re-created working day. (SAC = Simplified Anticipating Controller)

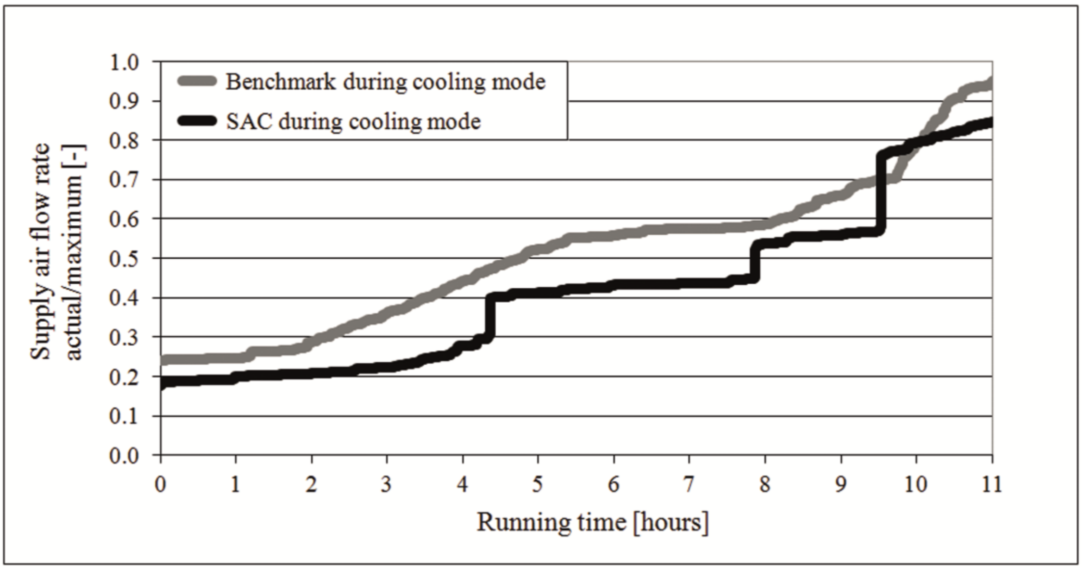

Figure 11. Cumulative distribution function of measured ventilation flow rate to the office room during the re-created working day. (SAC = Simplified Anticipating Controller)

5. Conclusions and discussion

It can be concluded that the investigated controller has the ability of reducing the HVAC energy usage and improving the indoor climate considerably compared to the benchmark. But, it was also shown that these benefits were somewhat depended on the considered conditions.

The room air temperature variations inside the space were extensively decreased when the controller was implemented during cooling mode (especially in the meeting room case) but insignificantly during the heating mode. On the other hand, as presented in table *3*, considerable energy savings potential were indicated for all scenarios. From these findings, it can furthermore be concluded that the potential of the investigated controller is dependent on the extensiveness of measured internal disturbances, and is slightly larger for cooling than heating modes.

Table 3. Indicated energy savings associated to the investigated controller when compared to the benchmark for the considered scenarios.

Scenario		Total ventilation flow savings [%]
Office Room	- Summer	14
	- Winter	12
Meeting room		19

5.1. Sources of energy savings

The indicated energy savings in table *3* can be explained by two features of the SAC which furthermore can be visualized in figures *9* and *11*. First, the main part is due to a fast response when a reduction of internal disturbances was registered. Then, the output of the control model directly went from the initial state to a relatively accurate terminal state while the benchmark modulated between all intermediate states with an increased energy usage as consequence. This is visualized as the step-shaped and smooth curves in the CDFs associated to the SAC and the benchmark respectively. The second part of the energy savings derive from a fast response when an increase of internal disturbances was registered. The main benefit of this feature was an increased comfort since the deviation from the associated region was limited. But, energy was also saved because the setpoint of the benchmark was adjusted for similar comfort, and this part stands for the entire savings potential during static conditions (vacancy and long-lasting occupied periods).

5.2. The influence of comfort constraints

Even though the comfort constraints were based on current indoor climate standards and guidelines, their role in this study can be argued. Their purpose was to provide a comparison of the controllers on equal grounds, i.e. what energy usage can be expected if the primary function of a desirable indoor climate already has been fulfilled. But in real life situations, such comparison is somewhat insufficient since a baseline of a desirable indoor climate cannot be guaranteed. Hence, even if it is obvious that the indoor climate can be improved if a conventional feed-back controller is replaced by the investigated controller, it is uncertain if the energy usage at the same time will be reduced. This aspect is of course dependent on the conditions provided by the controller that is replaced, but to offer a hint, the benchmark parts of the experiments were repeated with the boundaries of the temperature comfort region as setpoints. In turn, the average room air temperature during the working day became approximately the same when the two controllers were implemented. The prior energy savings was then reduced to between 8 and 17 %. At the same time, the maximum comfort region deviation associated to the benchmark increased to about – 0.5 °C below +1.5 above during occupied periods, which is equivalent to a major loss of comfort according to the considered metric.

Summary

This work evaluated an anticipating controller for indoor climate control in office environments that used the same principle as model-based controllers but had gone through an extensive complexity reducing process. The investigation was performed through experiments by re-creating a working day in a test facility, and two spaces, representing a meeting and an office room, as well as two weather seasons were considered. From the investigation, it could be concluded that the controller had the possibility of reducing energy usage and improving the indoor climate compared to a conventional feed-back controller as benchmark. The ventilation air supplied during the re-created working day was reduced between 12 and 19 %, dependent on type of space and weather season. At the same time, the deviation from a predetermined temperature comfort region was decreased which indicated thermal climate improvements. Hence, the work showed that it is possible to combine the aspects of implementability and energy efficiency when designing building automation systems, and these features are furthermore regarded as highly desirable for promoting a wide-spread utilization of new technologies.

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Paper V

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Combining performance and implementability of model-based controllers for indoor climate control in office environments

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ABSTRACT

Measures for an improved indoor climate control can potentially increase the energy efficiency in commercial buildings while comfort is maintained. Substantial energy reductions are possible by revising conventional building automation systems for an enhanced adaptation to process characteristics and current conditions. However, maintaining a low complexity to facilitate installation and commission of new technologies is also necessary to promote a widespread utilization. This work suggests a compromise between these two aspects by providing an experimental evaluation of a simplified model-based controller for indoor climate control in office environments. A working day was resembled in a test facility, and the task of the controller was to automate the heating, cooling and ventilation system in order to maintain a desirable indoor climate. The investigation considered two office environments, representing a meeting and an office room, as well as two weather seasons. From the investigation, it was concluded that the suggested model-based controller had the possibility of reducing energy usage and improve the indoor climate compared to a conventional feed-back controller as benchmark. But, these benefits were highly dependent on the investigated scenarios, which is important to consider in practice.

1. Introduction

Approximately 40% of the global final energy is used in buildings, and in the European countries, 76% goes towards systems for heating, ventilation and air-conditioning (HVAC) [1]. The purpose of an HVAC system is to achieve a desirable indoor climate, and potentially, the associated energy could be reduced substantially. But in order for any energy efficiency measures to have a large scale impact, they must be economical feasible, relatively easy to implement and applicable in a large variety of buildings. Further, energy savings are never allowed to compromise the primary functions of the HVAC system, and any comfort considerations must therefore be promoted.

A key element in fulfilling the necessary requirements for a reduced energy usage in the building sector is to improve the building automation system (BAS). An emerging technology is so called model-based controllers with information about indoor climate disturbances. The information is gathered through measurements, predictions or estimations by a disturbance sensing system, and is used as exogenous inputs to an internal control model. The corresponding impact on the controlled variables is then predicted and the control signals are subsequently adjusted to achieve a desired behavior of the process. It is well established in literature that model-based controllers have a large potential for improving the BAS; the energy usage can be reduced substantially compared to when more conventional control systems are used, at the same time as a desirable indoor environment is achieved. Furthermore, the application possibilities are vast and can virtually involve a single task up to a global level where the entire building and its system are taken into account.

Several previous publications have focused on model-based controllers (MBC) with single exogenous inputs for indoor climate control in office buildings. In Ref. [2], for example, each room in a simulated office building was equipped with a MBC that utilized future occupancy profiles to adapt local heating. The control models consisted of complete dynamic energy-balances of the rooms and were used to optimize a trade-off between energy usage and deviating degree hours from a temperature setpoint. Compared to the mean performance of a number of conventional controllers, it was shown that the energy usage could be reduced with about 13% at the same time as the comfort was increased with 37%

Abbreviations: BAS, building automation system; BFB, benchmark feed-back controller; CDF, cumulative distribution function; FCU, fan-coil unit; IAQ, indoor air quality; MBC, model-based controller; PMV, predicted mean vote; VAV, variable air volume.

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Nomenclature

c	CO_2 concentration [ppm]
c_p	specific heat capacity [J/(kg K)]
h	hour
$\dot{M}$	CO_2 flow rate [ml/s]
$\dot{Q}$	thermal power [W]
t	celsius temperature [°C]
u	information about thermal disturbances [W]
V	volume [m^3]
$\dot{V}$	volume flow rate [m^3/s]
y	controller output in supply quantities

Greek letters

ρ	density [kg/m^3]
τ	time [s]

Subscripts

Act	activation
Adj	adjacent
s	supply
r	room
w	water

according to the considered metric. Occupancy information was also used in Ref. [3] but to control the ventilation rate in a training facility. In this case, a CO_2 mass-balance was used to calculate the amount of fresh air required to maintain a desirable IAQ (Indoor Air Quality) during a training session. The number of people was presumed to be known through a schedule and it was shown that energy savings up to 26% were possible compared to a conventional control approach. Similar studies were further presented in Refs. [4,5], but in these cases, the building sites were made up of one and two office room zones respectively, while the control task primary considered room air temperature and involved the whole ventilation system. Moreover, both of these works also studied the additional aspect of retrieving occupancy information from predictions and measurements, respectively. Both studies showed that measurements were sufficient for achieving energy savings around 50% in comparison to conventional controllers, while only small additional benefits were provided through predictions.

A number of previous publications have also considered control tasks that involve a larger part of the HVAC system, as in Ref. [6], where a MBC with weather forecasts was used to automate the entire heating system in an office building by optimizing comfort and energy usage. The study was conducted during a heating season and the results showed that between 17 and 21% of the energy could be saved compared to a conventional weather-compensated strategy. Similar studies were also presented in Refs. [7–10], but by furthermore including occupancy schedules in the control to distinguish between periods with stringent and relaxed comfort criterions. The majority of these publications considered office buildings during heating seasons, and it was shown that up to 30–40% of the associated energy usage then could be saved. In Ref. [11], the application was extended a bit further by considering a MBC with information about outdoor air temperature, occupancy and illumination for temperature and lighting control in an office building. The thermal part was formulated as a trade-off between energy usage and comfort indicated by PMV (Predicted Mean Vote), and the controller was allowed to automate the ventilation rate, lighting as well as the opening of windows and solar shadings. The results show that the annual total energy usage was reduced with 38%, when compared to a reference case with on/off HVAC control and manual lighting.

From these citations, it is clear that the possibilities for energy efficiency measure through BAS improvements are huge, and that MBC in that sense is a beneficial technology in a vast variety of applications. On the other hand, a common feature of these publications was that the evaluated controllers were associated to high levels of complexity. This is a problem in the general case, since like any other energy efficiency measures, BAS improvements must be cost effective and relatively easy to implement in a large variety of buildings in order to contribute to any significant energy usage reductions in the building sector.

The overall complexity and cost of a MBC for building automation are primary determined by the design and extensiveness of its two major parts (the disturbance sensing system and the control model) and how these are interconnected. As the complexity of the disturbance sensing system is directly related to the number of registered disturbances and their measurability, the complexity of the control model is determined by how these signals are processed and how unmeasured signals are compensated for. Ideally, a complex MBC achieves a high control performance since all relevant data is gathered and processed in the most relevant way. But, such controller is also associated to a high cost, extensive tuning and programming as well as continuous maintenance to update for changes in the process. Hence, on a large scale, a compromise between these two aspects would be sufficient; a simple design to promote implementability but with a considerable higher performance than the system of current practice. This topic has previously been addressed in Ref. [12], where a simplified MBC for indoor climate control in office buildings was derived through simulations, by systematically identifying feasible complexity reducing measures by evaluating their impact on the performance. First, the control model was drastically simplified; from a complete process representation to static models with only one parameter in total. Second, the set of exogenous inputs was rationalized and reduced to only include measurements of the most common internal disturbances.

1.1. Purpose and contribution

This paper contributes in the search for energy efficient and simple BASs by providing an experimental evaluation of the MBC from Ref. [12]. The investigation belongs to a larger research project in which different HVAC system variants were considered, and this part focuses on integrated room automation of a VAV (Variable Air Volume) ventilation system and a fan-coil unit (FCU) in office environments.

Experiments were conducted by imitating sequences of the most common internal disturbances in a test facility. Meanwhile, the purpose of the controller was to maintain the IAQ (Indoor Air Quality) and thermal climate indicated by measured CO_2 and temperature, respectively, at the same time as the humidity was observed. Further, two office environments (representing an office and a meeting room) as well as two weather seasons were considered. Each scenario was also repeated, first with the MBC and then with a conventional feed-back controller as benchmark (BFB). One experiment stretched over a resembled working day of 9 h, and the controllers were hence tested during circumstances when an effective and well functioning control is of utmost importance (daytime in office environments is typically associated to high energy usages and stringent indoor climate). The indoor climate aspect was accounted for by applying fixed comfort constraints while the performances of the controllers were measured by the associated HVAC energy usages.

2. Investigation

The investigation was performed in Gothenburg, Sweden during one calendar year. The site was a test facility which is described in the following text together with a presentation of the experimental design.

2.1. Experimental framework

The experiments were conducted in a seminar room (Fig. 1) which is located on the entrance floor in the north-west corner of the facility (Fig. 2). It has a floor area of 5.6 × 6.2 m and a height of 2.4 m. As the ceiling and two of the walls are adjacent to other parts of the facility, the remaining walls (left and top) are external, whereof one has a section of outside solar shaded windows over most of its length.

In an open hall of the facility, several units are involved in the production of hot and cold water. Heating and cooling carriers are in turn utilized for indoor climate control in the seminar room via an FCU and an air-handling unit for ventilation. The FCU (triangle in Fig. 1) is a ceiling mounted terminal unit with an integrated speed controlled fan for circulation of room air. As the air is taken in from below, it is heated or cooled over a stack of tubes and discharged in the directions corresponding to down and left in the figure. The ventilation system is in turn of mixing VAV type with balanced supply and exhaust sides, and the distribution system is made up of ducts and ceiling mounted diffusers. In the air-handling unit, air is transported to and from the seminar room by integrated fans, and according to Swedish common practice, the supply part is entirely made up of conditioned outdoor air.

The HVAC system is controlled and observed from the control room to the left in Fig. 2 in which a BAS for the entire facility is installed. A data acquisition system is used to store measurements including ventilation flow rates, as well as temperatures and CO_2 levels at different points in the seminar room. To promote a more transparent study, the individual parts of HVAC system were automated so that their primary functions were separated as far as possible during the experiments. The first function refers to room air temperature control and was managed by heating or cooling room air using the FCU. The shifting between heating and cooling modes were managed by on/off valves while the capacity was modulated by varying the water inlet temperature via an automated by-pass, 3-way valve for mixing of return and primary

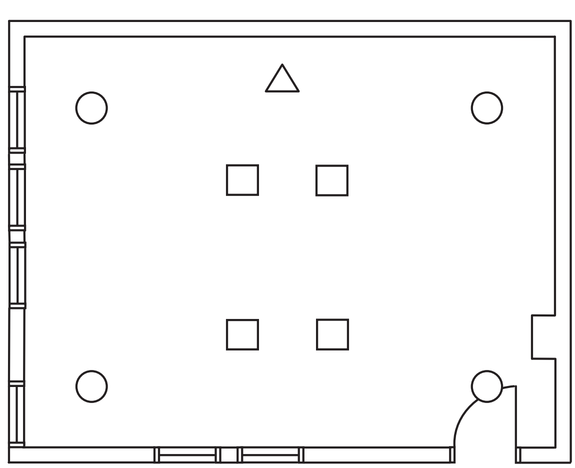

Fig. 1. Layout of the experimental site (seminar room). The walls representing left and top are external while the remaining are internal. Explanation of symbols: circles: supply air diffusers, squares: exhaust air diffusers, triangle: fan-coil unit.

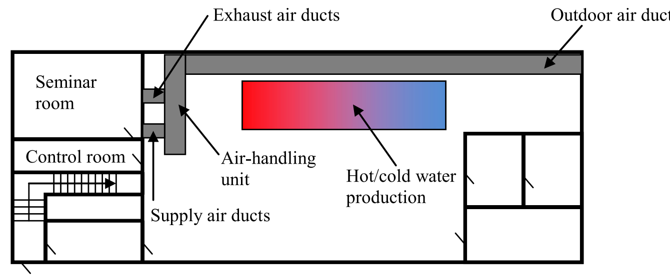

Fig. 2. Layout of the test facility, including the seminar room, a control room and an open hall.

supply water. The air-side fan was in turn operated on a constant level set to promote the propagation of heated or cooled air in the space. The second function refers to CO_2 control and was managed by fresh air supply from the ventilation system. The ventilation rate was automated by varying the speed of the central fans as well as by duct dampers and automated diffuser openings. At the same time, the thermal contribution from the ventilation system was limited by throughout the study maintaining supply air temperatures close to the level of the room.

The supply and exhaust air is transported to and from the seminar room via four ducts in each direction, and the corresponding diffusers are marked out with circles and squares in Fig. 1, respectively. Thanks to their symmetrical distribution, the room can be divided into separate modules. In this work, two variants (Fig. 3.) were considered on separate occasions by enclosing floor areas of 10 or 18 m^2 with temporary walls (filled in Fig. 3) of glued sheets of thick Styrofoam. The sizes and layouts corresponded to an office respective a meeting room, and as the FCU was incorporated in both cases, ventilation was managed by a single pair of diffusers (marked out in Fig. 3). Each module could be accessed through a built-in door, and both were built to represent spaces in modern office buildings, with tight and well-insulated envelopes.

2.2. Experimental design

The experiments consisted of a 9 h working day that was resembled by imitating and applying the following internal disturbances.

- Occupancy (referring to the number of people) with respect to heat and CO_2 emissions
- Heat emitted by lighting
- Heat emitted by equipment
- Transfer of heat and air through an open door

During the experiments, the spaces were occupied in sequences (Fig. 4.) that were constructed using statistical data from a 58 room large Swedish office building [13]. Each occupant was in turn imitated by one burning candle with defined CO_2 and heat emissions that were closely consistent to a person performing light office work. In turn, heat emissions from lighting and equipment were assumed to be dependent on occupancy, and both were imitated by modulating the output of an electrical panel radiator inside the conditioned space. Lighting corresponded to 10 W/m^2 of floor area (according to the national standard SS-EN 12464-1 [14]) and was on during occupied periods and off during vacant. Equipment corresponded to 50 W/imitated person in the meeting room, but was set to 100 W immediately as the occupancy sequence was initiated in the office room and remained constant thereafter (to represent a computer that runs all day but is turned

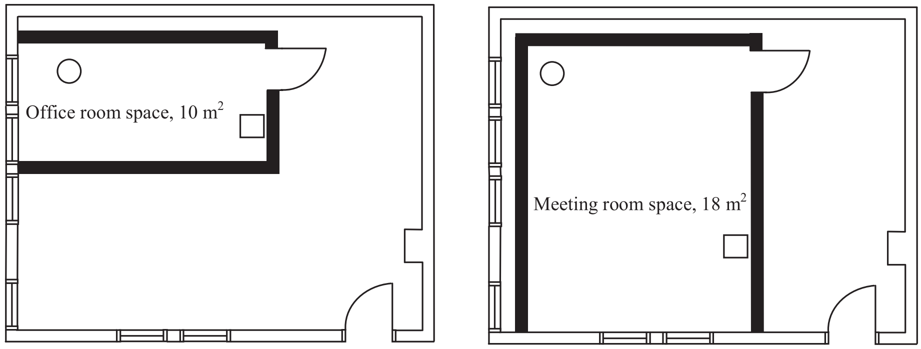

Fig. 3. The two variants of office environments that were considered in the seminar room. Left: office room space, right: meeting room space.

off outside office hours). Finally, the door was closed during the entire meeting room scenario while open for approximately one hour (14:30–15:20) during the afternoon in the office room case.

Since the meeting room was designed without any external walls (see Fig. 3), the outdoor climate had no direct influence on the indoor climate. On the other hand, the internal disturbances were occasionally large since the respective occupancy sequence exclusively contained more than one person at the same time. In the office room case, the proportions were the opposite due to the external wall in combination with a design-occupancy of one person. Hence, the meeting and office room represented its own extreme from a disturbance point of view, and this choice was made to span the results from the investigation so that most relevant office sites can be found within the range. Further, the investigation was stretched over one calendar year and in order to consider the influence of ambient climate in the investigation, the office room experiments were repeated during both the winter and the summer season. The diverse outdoor air temperatures (approximately between −10 and 20 °C) during these occasions resulted in a consistent demand for heating and cooling, respectively.

2.3. Experimental setup

In both modular spaces, the equipment used during the experiments was equivalently placed along a straight line between the coherent supply and exhaust air diffusers (see Fig. 3). To maximize the propagation of the imitated disturbances, the electrical heater and the burning candles were placed in the middle on a 1 m high table, with equal distance to the diffusers. The room air CO_2 and temperature were in turn measured by uncovered sensors with accuracies of ±50 ppm and ±0.1 °C. To avoid the measurements from being directly influenced by walls, the supply air stream or the disturbances, the sensors were mounted in the free air on a tripod between the disturbances and the exhaust air diffuser (with a minimum distance of 2 m from the disturbances, according to the national standard AFS 2009:2 [15]). The vertical placing of the sensors was based on a national standard in which a comfort zone is defined (i.e. a region in which the indoor climate constraints are valid which excludes spaces close to floor and roof) [16]. Since the considered weather seasons implied heating and cooling demand scenarios, the temperature sensor was placed in the middle of this zone to avoid regions with higher or lower temperatures than the average. The CO_2 sensor was in turn placed where the highest concentrations were expected.

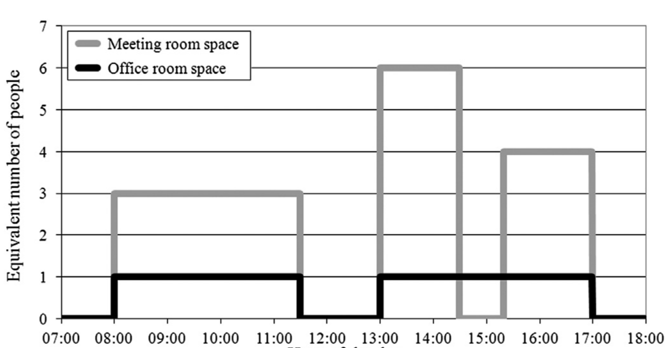

Fig. 4. Sequences of equivalent number of people (with respect to heat and CO_2 emissions) applied to the spaces during the resembled working day.

3. Controllers and control systems

In this section, it is first described how the MBC was evaluated against the BFB, which is followed by a detailed description of their structures and designs.

3.1. Evaluation method

The controllers were compared according to the method in Ref. [12] which is based on the two most important aspects of an HVAC system (including the associated control system): indoor climate is to be kept within given comfort ranges, by preferably using as little energy as possible. The indoor climate aspect was taken into account by comfort metrics (one each for IAQ and thermal climate) that both controllers were constrained to fulfill equally within feasible limits. In practice, this was achieved by first applying the MBC in a certain scenario. The same scenario was then repeated with the BFB after equivalent setpoint adjustments had been applied. In turn, their performances were measured by the associated HVAC system energy usage and these coherent experiments were performed during two consecutive days in order to avoid the influence of weather variations. The maximum allowed difference of average outdoor air temperature was set to 2 °C, and for larger variations, one of the experiments was repeated during more suitable conditions.

The IAQ was indicated by the room air CO_2 concentration (c_r) and the associated comfort constraint is presented in equation 1. It states that the level was not allowed to cross an absolute boundary of 1000 ppm, either when the MBC or the BFB was implemented. This constraint is based on several national recommendations [17] as well as the ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) standard 62-2007 [18].

$$\hat{c}_{r,\ MBC} = \hat{c}_{r,\ BFB} = 1000 \quad [\text{ppm}] \tag{1}$$

The quality of the thermal climate was indicated relative to a room air temperature (t_r) comfort region between 21 and 22 °C, which was applied throughout the study. It is based on prevailing standards and guidelines for a maintained comfort, and the first endpoint was set according to a national guideline [19] which states that lower temperatures should be avoided in occupied office rooms. The second endpoint was set 1 K higher, since according to the standard ISO 7730:2005 [20], smaller room air temperature variations do not have a negative effect on the thermal comfort, and similar recommendations are also given in ASHRAE standard 55-2004 [21]. The associated comfort constraint is presented in equation 2 and states that the deviating degree hours above and below this region should be similar when the MBC and the BFB were applied. This metric derives from the European standard EN-15251 [22] and solely applied during occupied periods while drifts were allowed during vacancy without any penalties. It is worth pointing out that a more common metric in this context is the PMV [23], but although recognized as a good estimator of thermal sensation, it was formulated during steady-state and is hence not suitable for the transient conditions studied in this work.

$$\begin{cases} \left(\sum \Delta t_{high}\Big|_{\infty,0} \times \text{time}\right)_{MBC} \approx \left(\sum \Delta t_{high}\Big|_{\infty,0} \times \text{time}\right)_{BFB} \\ \left(\sum \Delta t_{low}\big|_{\infty,0} \times \text{time}\right)_{MBC} \approx \left(\sum \Delta t_{low}\big|_{\infty,0} \times \text{time}\right)_{BFB} \end{cases} \quad [^\circ \text{Ch}] \tag{2}$$

Provided that the space is occupied
Where

$$\begin{cases} \Delta t_{high} = t_r - 22 \\ \Delta t_{low} = 21 - t_r \end{cases}$$

3.2. Benchmark feed-back controller

The structure of the BFB consists of two separate controllers, one each for CO_2 and temperature control, with identical schematics given at the top of Fig. 5. Both lacked information about disturbances and solely relied on measurements of the controlled variable as input. In each controller part, the input was compared to a fixed setpoint to form a control error, which in turn was processed by proportional (P) and integrating (I) blocks. The outcomes were the actuator signals in supply quantities: a ventilation flow rate and a fan-coil water inlet temperature in the room air CO_2 and temperature case, respectively. These were finally transformed into actuator compatible signals by a second set of cascade connected controllers. The PI-blocks were tuned using the AMIGO step response method. It is not the most common method but derives from a large number of optimization procedures and approximately returns the controller parameters that minimize the deviation from the setpoint [24].

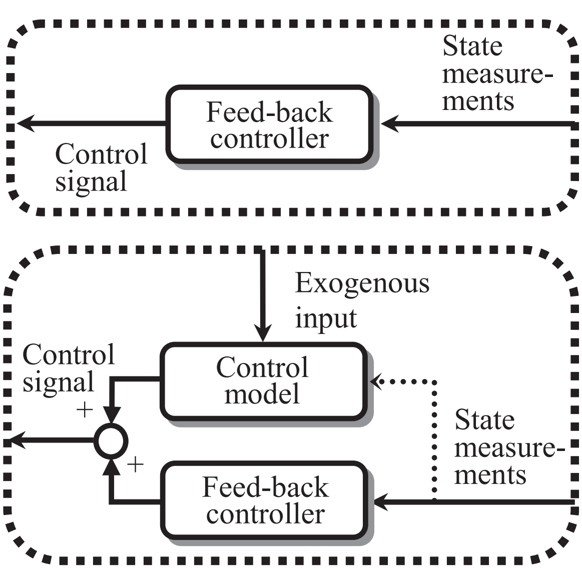

Fig. 5. General schematics of the considered controllers: top; benchmark feed-back controller, bottom; simplified model-based controller. In this work, the state measurements refer to the controlled variables, the control signal refers to actuator signals in supply quantities and the exogenous input refers to the imitated internal disturbances.

3.3. Model-based controller

The investigated MBC consists of two separate parts, one each for CO_2 and temperature control, with identical schematics given at the bottom of Fig. 5. Compared to the designs considered in most previous publications, the complexities of both control model and inputs are lower, and these aspects are described in the following text.

3.3.1. Exogenous inputs

While the MBCs in most previous publications had information about the entire set of disturbances (including external), the exogenous inputs were in this work limited to the imitated internal disturbances presented in section 2.2. As all of these were utilized for temperature control, the inputs to the control model for CO_2 were limited to the number of people and door opening (the remaining ones were irrelevant in that case). Since the aim of the study was to evaluate the performance of the simplified MBC, an ideal disturbance sensing system was assumed by directly utilizing the predetermined sequences as exogenous inputs. This is primary a simplification from an occupancy point of view due to the lack straight forward measurement methods. For further information about the connection between uncertainties in the exogenous input and control performance [25], can be considered.

The control model was designed to process exogenous inputs expressed in units of CO_2 flow rate and/or thermal power. These quantities were known for all considered disturbances after applying a two-step processing to the door opening in the office room scenarios. In the first step, the infiltration flow rate through the open door was described by the empirical equation 3 [26] which contain three parameters: the height (H [m]) and the area (A [m^2]) of the door as well as a constant (K) which is dependent on the geometries of the controlled space and the adjacent (adj) room. K was in this work determined experimentally but standard values given in Ref. [26] can also be used. Secondly, the CO_2 and temperature on the other side of the door were measured and used in equations 4a and 4b together with the estimated infiltration flow rate.

$$\dot{V}_{door} = K_{door} \cdot A_{door} \cdot \left(H_{door} \cdot \left|t_{adj} - t_r\right|\right)^{0.5} \quad \left[\text{m}^3/\text{s}\right] \tag{3}$$

$$\dot{Q}_{door} = \dot{V}_{door} \cdot \rho_{air} \cdot c_{p,\ air} \cdot \left(t_{adj} - t_r\right) \quad [W] \tag{4a}$$

$$\dot{M}_{CO_2,\ door} = \dot{V}_{door} \cdot \left(c_{adj} - c_r\right) \quad [\text{ml/s}] \tag{4b}$$

3.3.2. Control model

The complexity of the control model was heavily reduced by replacing complete process representations with a non-linear filter for temperature control and a static mass-balance for CO_2 control. Each control model part was further supported by a feed-back controller identical to the BFB. The individual parts were designed to return supply quantities (i.e. ventilation flow rates or thermal power) and the outputs were summed up and transformed into actuator compatible signals (by a cascade connected controller) before passed on. As the FBs were used to compensate for errors (such as unmeasured or faulty measured disturbances) and thereby managed the base supply, the purpose of the control model was to act fast and accurate to changes in the exogenous inputs.

The non-linear filter for temperature control is of closed-loop character and consists of equations 5a and 5b. The exogenous input (u) was the total heat emitted by the available disturbances, and a registered increase was in first hand met by a negative heat supply (i.e. to partly overcome the output of the supporting feed-back) from equation 5a. If the system initially was in cooling mode or if an initial heat supply was insufficient to balance a registered heat emission increase, equation 5b was in turn used to increase the cooling supply. As a decrease of exogenous input was registered, the procedure was reversed which means that the filter has the ability to modulate the cooling supply freely (up to the magnitude of the exogenous inputs), but only to scale the heating output from the supporting feed-back.

The filter parts (i.e. equation 5a for heating modes and 5b for cooling modes) were featured to modulate the control model output (y) by scaling the exogenous inputs with respect to the current room air temperature (t_r). The scaling property of each filter part was in turn determined by a pair of parameters, including one of the comfort interval boundaries (t_{low}: 21 °C and t_{high}:22 °C), and an associated activation temperature (t_{act}). As the activation temperatures were assigned values inside the comfort interval close to the coherent boundary, each parameter-pair formed a region. For room air temperatures inside any of these regions, the exogenous inputs were scaled down between 1 and 99%. For room air temperatures above the comfort interval, the entire registered heat emission was utilized as cooling supply, and for room air temperatures below, the filter output was zero.

$$y_{\text{cooling mode}} = \left(\left(\frac{t_r - t_{\text{act, high}}}{t_{\text{act, high}} - t_{\text{high}}} \right) \Big|_{0,1} \cdot u \right) \tag{5a}$$

$$y_{\text{heating mode}} = -\left(\left(1 - \frac{t_{\text{act, low}} - t_r}{t_{\text{act, low}} - t_{\text{low}}} \right) \Big|_{0,1} \cdot u \right) \tag{5b}$$

Remark: The activation temperatures are essentially design parameters that can be determined in a similar way as the static gain of a conventional feed-back controller. Tuning the activation temperatures is to find a trade-off between stability and speed; activation temperatures close/far from the associated boundaries are associated to large/small static gains.

The static mass-balance for CO_2 control is presented in equation 6a. It is of open-loop character with exogenous inputs of CO_2 emission from burning candles ($\dot{M}_{CO_2,\ \text{candles}}$) and CO_2 flow rate through the door (eq. 4b). These were processed together with measurements of the CO_2 level in the supply air (c_s), while the room air CO_2 variable (c_r) was replaced by the comfort boundary (1000 ppm) to solve the corresponding supply air flow rate. For each change in number of people or external CO_2 flow rate, the procedure was repeated and a new actuator signal was returned.

The complexity of 6a as control model is considerable lower than the more conventional dynamic version in equation 6b. Mainly, 6b has a variable time-constant ($V_r/\dot{V}_s$) that typically is estimated with rate-of-change room CO_2 measurements. This means that control instability is imminent due to enhancement of measurement noise and that complementary signal processing normally is required. Further, the room air volume (V_r [m^3]) is also required in 6b, but this parameter has a smaller influence on the complexity since an accurate value normally can be determined from spatial measurements or a blueprint.

$$0 = \dot{V}_s \cdot \left(c_s - c_r \right) + \dot{M}_{CO_2,\ \text{door}} + \dot{M}_{CO_2,\ \text{candles}} \tag{6a}$$

$$\frac{dc_r}{d\tau} \cdot V_r = \dot{V}_s \cdot (c_s - c_r) + \dot{M}_{CO_2,\ \text{door}} + \dot{M}_{CO_2,\ \text{candles}} \tag{6b}$$

4. Results

In the following section, the results from the investigation are presented as two indicators for HVAC system energy usage associated to the MBC and the BFB. The energy usage of the FCU was indicated by the supplied or extracted heat on the waterside, calculated by equation 7. The water temperatures and flow rate in this equation were measured with an accuracy of ±0.1 °C and 1% respectively, which approximately resulted in a total uncertainty of 2%. In turn, the energy usage of the ventilation system was indicated by the supply air flow rate, measured with an accuracy of ±2 l/s.

Altogether, these two indicators represent the main bulk of HVAC system energy usage accounts. In the FCU indicator, only site dependent parts, such as distribution losses and efficiencies regarding the production of heating and cooling carriers, were neglected. Further, since equal and constant supply air temperature setpoints were used during all coherent experiments, the ventilation indicator is directly proportional to the air-handling energy. At the same time, the indicators prevented the results from being influenced by outdoor climate dependent air-handling energy and by operational dependent efficiencies due to unequal controller setpoints (for fulfilling the comfort constraints).

$$\dot{Q}_{FCU} = \left| \dot{V}_w \cdot \rho_w \cdot c_{p,\ w} \cdot (t_{in} - t_{out}) \right| \quad [\text{W}] \tag{7}$$

Two actions were applied in this chapter to facilitate for the reader. First, the temperature and CO_2 control tasks are presented separately in the following text, even though they occurred simultaneously during the experiments. Such division was possible since the ventilation system and FCU were considered for one task each and intersections were minimized by choosing supply air temperature setpoints close to the level in the room. Second, the energy indicators were graphically presented as cumulative distribution functions (CDF) (i.e. sorted values from low to high on an increasing x-scale). Hence, for most scenarios, the left part of these figures is associated to vacant periods, and the right part to periods with high internal disturbances (since the demand for cooling and ventilation increases with occupancy). The FCU power for the winter office scenario is the only exception (part of Fig. 7), and then the complete opposite applies due to the consistent heating demand.

4.1. Temperature control

In this section, the controlled room air temperatures as well as the associate FCU thermal powers are presented for the considered scenarios. The offsets in the temperature figures are due to the comfort constraint (the setpoint of the BFB was adjusted to achieve similar degree hours outside the comfort interval as the MBC) and the corresponding influence on the energy indicator can be visualized in the CDF as an associated offset during vacant periods.

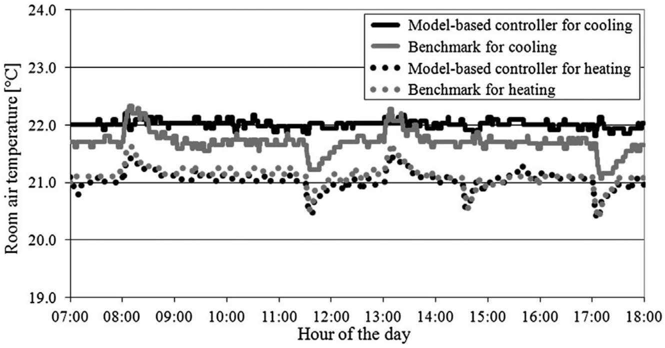

Fig. 6. Variations of controlled room air temperature, measured in the office room during the resembled working day. The figure includes both the winter (heating demand) and the summer (cooling demand) season scenarios.

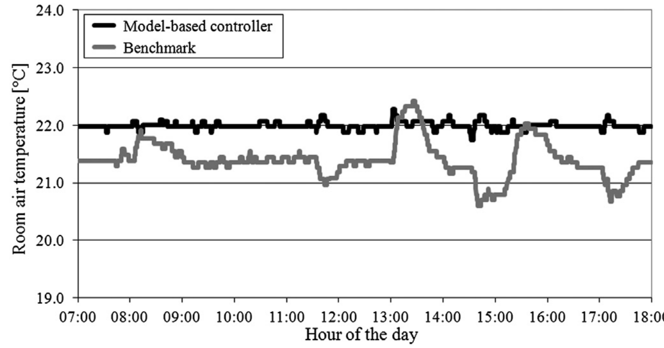

Fig. 8. Variations of controlled room air temperature, measured in the meeting room during the resembled working day.

In Figs. 6 and 7, the results from the two office room scenarios are presented. During the cooling demand scenario, the largest strain on the thermal climate occurred at 08:00. Then, all internal disturbances were initiated at the same time and thereafter, the equipment part was active throughout the rest of the day which means that the event that occurred at 13:00 had less influence. In the heating demand scenario, the largest strain on the thermal climate was instead due to the opening of the door at 14:20, which was the only heat sink that occurred during an occupied period. For both scenarios, only marginal setpoint offsets were needed to achieve similar comfort, and no corresponding influence on the energy usage can be seen in Fig. 7 (i.e. the energy usages during vacant periods coincide).

In Figs. 8 and 9, the results from the meeting room scenario are presented. The largest strain on the thermal climate was associated to the largest heat gain at 13:00. Similar comfort was achieved by reducing the setpoint of the BFB with 0.6 °C, which according to Fig. 9, only has a marginal influence on the energy usage. An important remark to Fig. 8 is that the temperature drops below 21 °C occurred during vacant periods and had therefore no negative influencing on the thermal climate according to the comfort constraint.

4.2. CO_2 control

In this section, the controlled room air CO_2 concentrations as well as the associate supply air flow rates are presented for the considered scenarios. The offsets in the CO_2 figures are due to the comfort constraint: none of the controllers were allowed to pass an absolute boundary of 1000 ppm (not including measurement noise). To facilitate for further discussions, the flow rates were presented relative to the allowed range which stretches from 0 l/s to (0.35 l/s × floor area +7 l/s × maximum number of occupants) according to a national guideline [19].

In Figs. 10 and 11, the results from the office room are presented, and as the winter and summer scenarios were identical from a CO_2 point of view, the figures applies to both cases. The occupancy steps at 08:00 and 13:00 were of equal size and strain on the indoor climate, and the setpoint of the BFB was reduced to 740 ppm to achieve similar IAQ (even though the maximum supply air flow rate only was sufficient to maintain a level of about 810 ppm during occupied periods). The opened door between 14:30 and 15:20 composed instead an immediate emission sink since air with a lower level of CO_2 flowed into the room. However, this effect was diminishing as the external space gradually became diluted by CO_2 from the burning candles.

In Figs. 12 and 13, the results from the meeting room scenario are presented. The occupancy steps occurred at 08:00, 13:00 and 15:20, whereof the intermediate constituted the largest strain on the air quality. To maintain similar IAQ during that period, the setpoint of the BFB was reduced to 680 ppm.

5. Conclusions

It can be concluded that the advantages of the investigated MBC over the BFB were highly dependent on the considered scenarios. In the temperature control case, the variations inside the space were decreased considerable during the two cooling demand scenarios (especially in the meeting room case) but insignificantly during the heating demand scenario. Further, the coherent influences on the FCU energy usage were negligible in

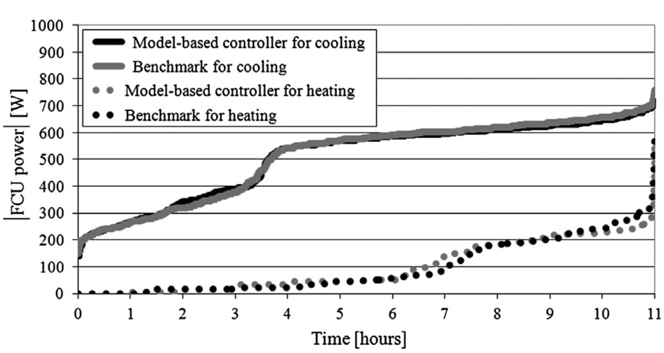

Fig. 7. Cumulative distribution function of FCU power supplied to the office room during the resembled working day. The figure includes both the winter (heating demand) and the summer (cooling demand) season scenarios.

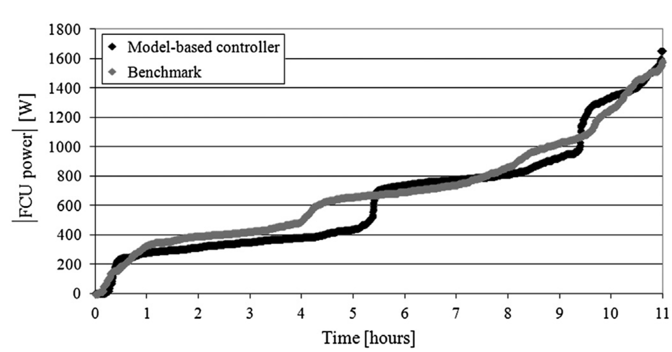

Fig. 9. Cumulative distribution function of FCU power supplied to the meeting room during the resembled working day.

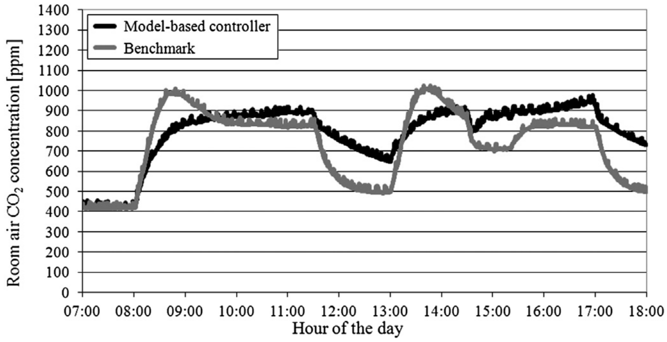

Fig. 10. Variations of controlled room air CO_2 concentration, measured in the office room during the resembled working day.

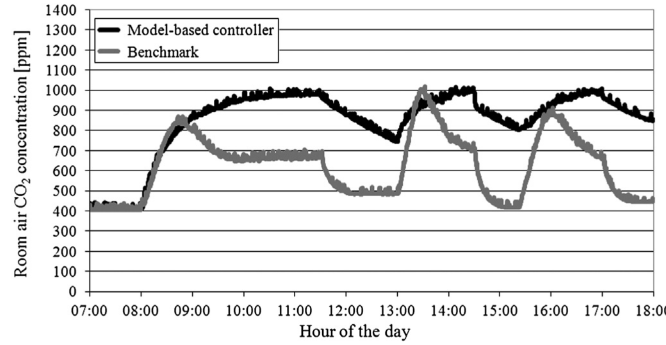

Fig. 12. Variations of controlled room air CO_2 concentration, measured in the meeting room during the resembled working day.

the two office scenarios while a reduction of 7% was indicated in the meeting room. In the CO_2 control case, the benefits were more widespread and considerable higher: the total supplied air was reduced by 35% and 55% in the office and meeting scenario respectively, at the same time as the variations of CO_2 in the spaces were decreased substantially. From an energy point of view, these reductions correspond to a major share of the total energy used by the HVAC system.

From these findings, two more conclusions can be stated. First, the potential of the MBC is dependent on the extensiveness of internal disturbances and is slightly larger during cooling demands than during heating demands. Second, the benefits are much larger when implemented to control HVAC systems with long time delays while the advantage over a common feed-back controller, such as the BFB, is decreased when applied to control faster systems. The reason is that the parameter settings of a feed-back are highly dependent on transport delays in the process (a slow control is necessary to avoid instabilities in a slow process) while the parameters of the MBC are unaffected by this aspect. In this study, the FCU in the office room represents a fast system, followed by the FCU in the meeting room on second place (i.e. the FCU is the same but a larger room increases the sensor transport delay) while the ventilation system represents a slow system.

5.1. Sources of energy savings

Figs. 9, 11 and 13 can be used to illustrate where the indicated energy savings derive from. Fig. 9 is associated to the FCU power during the meeting room scenario, and it can be seen that both the lowest and the highest values associated to each controller coincides, which means that the peaks as well as the supply during vacant periods were more or less unaffected when the MBC was introduced. Instead, the main savings derive from a reduction in the intermediate power range. Further, Figs. 11 and 13 are associated to CO_2 control in the office and meeting room respectively, and in these cases, the peaks as well as the intermediate supply air flow rates were drastically reduced as MBC was applied. All of these savings can be explained by two properties. First, the main part is due to a fast response when a reduction of internal disturbances was registered. Then, the output of the control model directly went from the initial state to a relatively accurate terminal state while the BFB modulated between all intermediate states with an increased energy usage as consequence. This is visualized as the step-shaped and smooth curves in the CDFs associated to MBC and the BFB, respectively. The second part of the energy savings derives from a fast response when an increase of internal disturbances was registered. The main benefit was then a limited deviation from the setpoint, and in turn that the setpoint of the BFB was adjusted for similar comfort. In the temperature case, the associated influence on the energy usage was negligible but in the CO_2 case, this feature stands for the largest part of the peak reduction.

6. Discussion

Even though the comfort criterions were based on current indoor climate standards and guidelines, their role in this study can be argued. Their purpose was to provide a comparison of the controllers on equal grounds, i.e. what energy usage can be expected if the primary function of a desirable indoor climate already has been fulfilled. But in real life situations, such comparison is somewhat insufficient since a desirable indoor climate as base-line cannot be guaranteed. Hence, even if it is obvious that the indoor climate can be improved if a conventional feed-back controller is

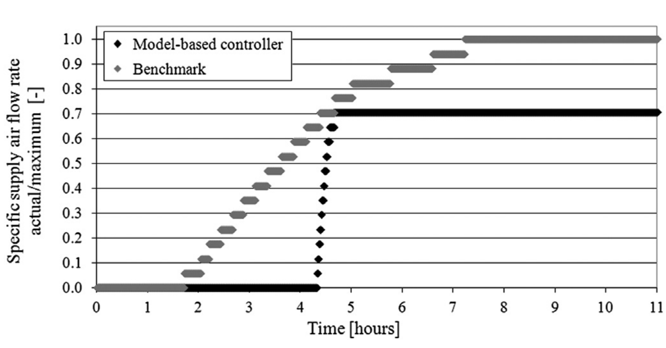

Fig. 11. Cumulative distribution function of supply air flow rate, measured during the resembled working day in the office room.

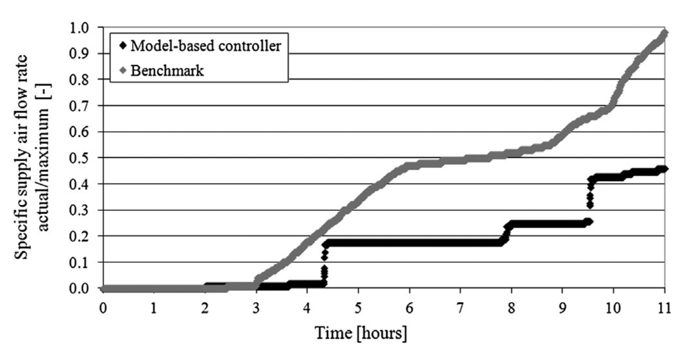

Fig. 13. Cumulative distribution function of supply air flow rate, measured during the resembled working day in the meeting room.

replaced by the investigated MBC, it is uncertain if the energy usage at the same time will be reduced. This aspect is of course dependent on the conditions provided by the controller that is replaced, but to give a hint, the CO_2 part of the experiments were repeated for two alternative comfort criterions. In the first case, equal setpoints (1000 ppm) were applied to the MBC and the BFB. The prior energy savings was then almost diminished, but as the MBC avoided concentrations above the setpoint, the peaks associated to BFB stretched to about 1300–1400 ppm. In the second case, the two controllers were constrained to achieve equal average CO_2 concentration during the working day. The prior energy savings were then only partly decreased (to about 20–30%), and while the MBC could sustain concentrations below 1000 ppm, the peaks associated to the BFB stretched to about 1200–1250 ppm.

6.1. Reflections regarding the set of exogenous input

The MBC had no information about disturbances outside the controlled spaces (such as transmission, air leakage and solar radiation). Most of these unmeasured disturbances had only a marginal influence on the CO_2 control task which is visualized in the CDFs as step-shaped supply air flow rate curves. Each level is associated to the controller response for a specific number of people and only small adjustments from the terminal states were required. The largest CO_2 control error was due to omitting the infiltration flow rate in the office room scenario and the terminal state then ended up about 100 ppm below the setpoint. The situation was on the other hand a bit different in the temperature control case. Less information about the prevailing disturbances was available and the output errors from the control model hence became larger. The corrections were primary managed by the filter and somewhat by the supporting feed-back, and these adjustments are visible as the smoothly shaped power curves in the CDFs.

7. Summary

In this work, a model-based controller with a simplified control model and a limited number of inputs was evaluated for indoor climate control in office environments. The investigation was performed through experiments by resemble a working day in a test facility and a feed-back controller was used as benchmark. Further, two spaces, representing a meeting and an office room, as well as two weather seasons, were considered. The indoor climate was indicated by measured room air temperature and CO_2 concentration, and both controllers were constrained to maintain the same comfort level by controlling the thermal power output of a fan-coil unit as well as the ventilation flow rate. From the investigation, it could be concluded that the simplified model-based controller primary had the possibility of reducing the energy usage associated to the ventilation system. The air flow supplied during the experiments was reduced by 35 and 55% in the office and meeting room respectively, at the same time as the variations of the CO_2 concentration was reduced. Also the power of the fan-coil unit was reduced by 7% in the meeting room, while unaffected in the office room space, even though the temperature variations were decreased.

Acknowledgment

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Paper VI

Motion sensors for ventilation system control in office buildings

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Nomenclature

c	CO_2 concentration [ppm]
c_p	specific heat capacity [J/(kg K)]
h	time [hour]
$\dot{Q}$	thermal power [W]
t	celsius temperature [°C]
u	general input signal
$\dot{V}$	volume flow rate [m^3/s]
y	general output signal

Greek letters

ρ	density [kg/m^3]

Subscripts

r	room
s	supply
vent	ventilation

Abstract

A model-based building automation system with information about indoor climate disturbances is a promising technology for increasing energy efficiency in offices. But, since the associated level of complexity typically is high, installation and commissioning have the tendency of becoming extensive processes that obstructs a widespread utilization. This work contributes in resolving such issues by providing an experimental evaluation of an alternative model-based controller for ventilation system control in office building. An overall low complexity was achieved by: (1) limiting the inputs to the most common internal disturbances, (2) replacing occupancy information with motion sensor responses, (3) to process the information by two separate static control models with only one parameter in total. Further, a feed-back controller was used as benchmark, and both temperature and CO_2 control tasks were evaluated. The main finding was the possibility of drastically reducing the complexity and still end up with a high potential for saving energy and improving the indoor climate compared to systems of common practice. However, these benefits were somewhat dependent on the considered scenarios, which is important to consider in practice.

Keywords

Heating, ventilation and air-conditioning; Office buildings; Indoor climate control; Ventilation system; Motion sensor; Energy efficiency; Model-based control; Temperature control; CO_2 control

1. Introduction

The purpose of a model-based building automation system (BAS) is to increase the adaptation between HVAC (heating, ventilation and air-conditioning) system and building. Typically, a sensing system gathers information about indoor climate disturbances as exogenous input to an integrated control model. Based on some process representation, the corresponding impacts on the controlled variables are predicted and the control signals are subsequently adjusted to achieve a predetermine behavior of the process. A common approach is to combine these features with disturbance predictions and objective functions so that the entire operation of the HVAC system can be optimized over a long but finite horizon. Several previous works have evaluated the technique and found that substantial energy reductions can be combined with a maintained indoor climate [1-5]. However, a major drawback is that the associated level of complexity typically is high which means that a widespread utilization is prevented by time-consuming and costly employment and commissioning.

There are several reasons to why the complexity of model-based controllers for indoor climate control usually is high. In order to accurately predict the future indoor climate and desirable control signal, information about most relevant disturbances is required as well as an accurate model about the building and HVAC system. But, (1) several indoor climate disturbances are hard to measure, estimate or predict, and (2) the building and HVAC system are in many senses unknown processes with non-linear and complicated structures and features. More relevant information and a more accurate control model leads to a potentially higher control performances, but also to a higher level of complexity in terms of increased costs, extensive tuning and programming as well as continuous maintenance to update for changes in the process. Thus, the main challenge of finding more easily implementable alternative BASs is to provide complexity reducing measures with as little impact on control performance as possible.

1.1. Background

This work is dedicated to the search for energy efficient and easy implementable BAS, and belongs to a larger research project in which different applications were investigated through a similar methodology. In a previous publication [6], a simplified model-based controller design for indoor climate control in office buildings was derived by evaluating a large number of complexity reducing measures through simulations. In the process, several alternative control models were proposed and evaluated, and a systematic search for the disturbances with the largest potential as exogenous inputs was conducted. It was shown that a high control performance could be maintained by providing the most common internal disturbances as exogenous input to a static non-linear filter with only one parameter. The function of the controller was thereby limited to achieving a desirable indoor climate using as little energy as possible by anticipating the short-term and current effects of the considered disturbances. The design primary aimed to facilitate implementability in typical office sites while achieving a considerable higher performance than systems of common practice. For that reason, conventional feed-back controllers have been considered as benchmarks in the common methodology.

In two following publications, the derived controller design was experimentally evaluated in office environments with hydronic or air-based heating and cooling. The results showed that the most beneficial application was associated to automating HVAC parts with slow dynamics; which in this context refers to the mechanical ventilation system. A common feature of these two publications was the exogenous inputs and the corresponding disturbances were assumed to be equal. In practice, perfect information about occupancy is especially problematic to obtain since the available measurement or estimation methods are either associated to high uncertainties or complexities. On the other hand, occupancy is an important disturbance to account for indoor climate control in office building (due to its large influence on thermal climate and indoor air quality), and cannot be omitted without major reduction of performance [7].

1.2. Purpose and procedure

As the previous works assumed perfect disturbance information as exogenous inputs, the present paper takes the implementability aspect one step further by only considering standard HVAC sensor technologies in the disturbance sensing system. In correspondence to [6], the exogenous inputs were limited to the most common, internal disturbances consisting of lighting, equipment and occupancy. Information about heat emissions from lighting and equipment were provided as by power sensors, and were processed using the non-linear filter from [6]. However, to maintain a low complexity of the disturbance sensor system, occupancy information was provided as by a motion sensor, and an addition memory function was added for processing this signal. Moreover, the non-linear filter was evaluated separately as well as in combination with the memory function to determine the value of incorporating motion sensor responses in the control.

Experiments were conducted during a typical working day that was re-created in a meeting room by imitating lighting, equipment and occupancy in 9 hour sequences. The same conditions were then repeated as indoor climate control was managed by the model-based controllers and a conventional feed-back controller as benchmark. To span the investigation over different HVAC systems, separate experiments were conducted for CO_2 and temperature control, and both tasks were managed through ventilation flow rate automation in accordance to the results from [8,9]. Moreover, to maintain a high level of generality, the results were prevented from being influenced by any subjective elements in a supply air temperature algorithm. Instead, ideal levels were set to minimize the required flow rate during each experiment, and the same level was furthermore kept for the model-based controller and the benchmark to increase comparability. Finally, as the experiments stretched over one working day, the focus was on periods when a desirable indoor climate is of utmost importance and this aspect was accounted for by applying fixed comfort constraints while the performances of the controllers were measured by the associated HVAC energy usages.

2. Investigation

The investigation was conducted in a university test facility located in Gothenburg, Sweden. It consists of a two floors detached building commonly used for education and research within the area of building services engineering. An experimental HVAC system stretches through the majority of the building and multiple sites and subsystems are specialized for studying indoor climate control aspects. In this section, the test facility and the technical installations used in this work are first described which is followed by a presentation of the experimental design.

2.1. Experimental framework

The experiments were conducted in a seminar room (fig.*1*) which is located on the entrance floor in the north-west corner of the facility (fig.*2*). It has a floor area of 5.6 × 6.2 m, a height of 2.4 m, a concrete and steel frame and an envelope of mineral wool and gypsum. Two of the walls (left and top in fig.*2*) are external, whereof one has a section of outside solar shaded windows over most of its length.

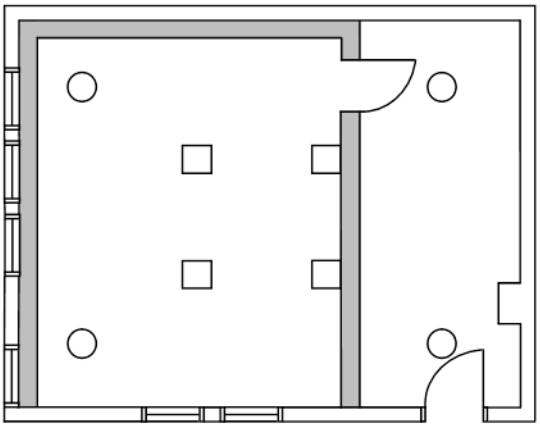

Figure 1. Layout of the seminar room, moreover the experimental site. The walls representing left and up are external while the remaining are internal. Explanation of symbols: circles: supply air diffusers, squares: exhaust air diffusers. The temporary walls and the diffusers used during the experiments are marked as filled.

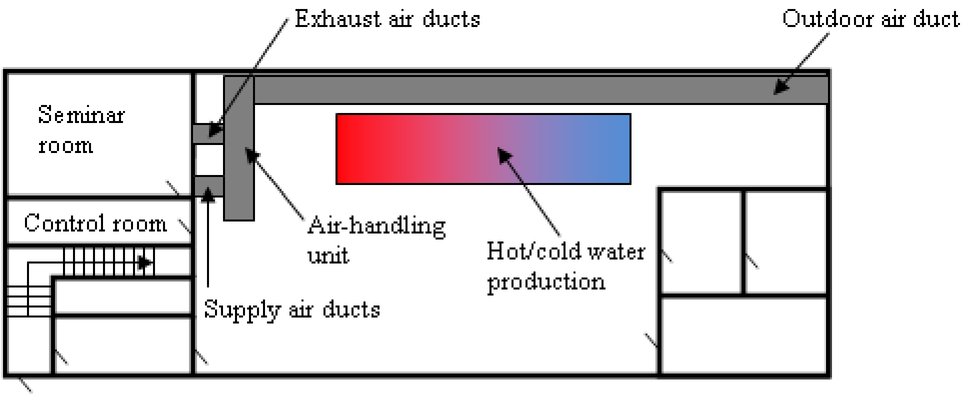

Figure 2. Layout of the test facility, including the seminar room, a control room and an open hall.

Indoor climate control is managed by a VAV system for mixed and balanced ventilation. A set of ceiling-mounted diffusers provide heating, cooling and air renewal from a central air-handling unit (AHU) consisting of two fans and two air-coils. In the coils, hot and cold water from a set of production units are used for supply side conditioning, while the fans transport air to and from the room via four ducts in each direction. According to Swedish common practice, the supply side is entirely made up of outdoor air, while the exhaust is discharged to the ambience. Further, the entire system is controlled and observed from the control room (left in fig.*2*) via a building automation system. The ventilation flow rate can be adjusted by varying the speed of the AHU fans as well as by duct dampers and automated diffuser openings. The supply air temperature is in turn controlled by varying the water inlet temperature to the coils via automated shunt connections.

The air diffusers are marked out as circles (supply air) and squares (exhaust air) in figure *1*, and thanks to their symmetrical distribution, the room can be divided into separate modules. In this work, a cross-aligned diffuser pair (marked as filled) was selected for ventilating a space with a floor area of 18 m^2. The size, layout and construction of this module were chosen to represent a meeting room in a modern office building with tight and well insulated envelope. The main part was built with temporary walls of glued sheets of thick Styrofoam (also marked as filled) whereof one contained a built-in wooden door. Besides of the Styrofoam, the floor and ceiling of the seminar room, as well as the wall adjacent to the control room, were also incorporated in the construction.

2.2. Experimental design

In accordance to the common methodology in the research project, the experiments consisted of a 9 hour working day that was resembled in the meeting room by imitating the following internal disturbances.

- Occupancy (referring to the number of people)
- Lighting
- Equipment

The occupancy sequence in figure *3* was constructed in accordance to annual statistical data from a 58 room large Swedish office building [10]. The meeting room was occupied during the majority of an experiment, with the exceptions of resembled lunch and participants shift in the afternoon. The highest load occurs at 13:00 hours, and as the floor area corresponds to a design number of nine people [11], the resulting occupancy factor was then about 70 %. The occupants were in turn imitated by burning candles of a type that corresponded to one person with low activity from both a heat and CO_2 emission point of view. Further, lighting and equipment were imitated by an electrical panel radiator, and both were assumed to be dependent on occupancy. Lighting corresponded to 10 W/m^2 of floor area (according to the national standard SS-EN 12464-1) and was on during occupied periods and off during vacant, while equipment corresponded to 50 W/imitated person.

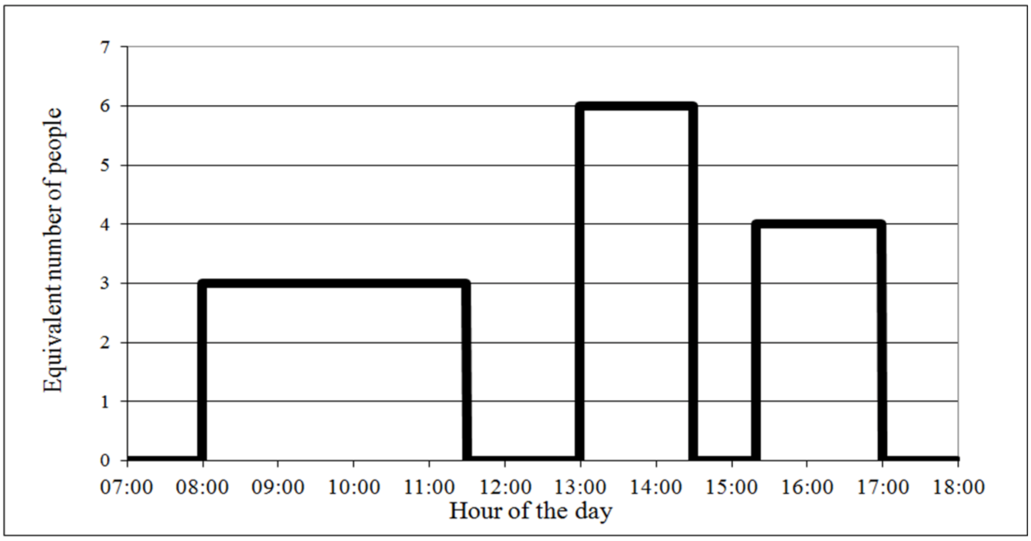

Figure 3. Sequence of equivalent number of people (with respect to heat and CO_2 emission) applied to the meeting room space during the resembled working day.

As the meeting room lacked external walls, the ambient conditions had no direct influence on the indoor climate. At the same time, the internal disturbances were occasionally large since the governing sequence exclusively contained more than one person at the same time. These choices were made to provide experimental conditions that coincided with the focus of the investigation, and three aspects were primary considered. Firstly, to resemble the expected load distribution of a modern office building with tight and well insulated envelope (i.e. a small/large proportion of external/internal disturbances). Secondly, to emphasis the difference between the two considered types of exogenous inputs (heat emissions/motion sensor responses) by limit the influence of omitted disturbances (i.e. external). Thirdly, to promote comparability between coherent experiments involving different controllers by limiting the influence of external climate variations.

2.3. Experimental setup

The equipment used during the experiments was placed along a straight line between the coherent supply and exhaust air diffusers in figure *1*. To maximize the propagation of the imitated disturbances, the electrical radiator and the burning candles were placed in the middle (with equal distance to the diffusers) on a 1 m high table. The room air CO_2 and temperature were in turn measured by uncovered sensors with accuracies of ±50 ppm and ±0.1 °C. To avoid the measurements from being directly influenced by walls, the supply air stream or the remaining equipment, the sensors were mounted in the free air on a tripod between the disturbances and the exhaust air diffuser (with a minimum distance of 2 m from the disturbances, according to the national standard AFS 2009:2). The vertical placing of the sensors on the tripod was based on a national standard in which a comfort zone is defined (i.e. a region in which indoor climate constraints are valid, excluding spaces close to floor and ceiling)

[11]. The temperature sensor was placed in the middle of this zone and the CO_2 sensor where the highest concentrations were expected.

3. Controllers and control tasks

The model-based controller and the benchmark were evaluated for IAQ and thermal climate control by applying measured room air CO_2 and temperature as indicators, respectively. To increase transparency, these two control tasks were considered separately and the controllers were constrained to fulfill equal comfort (within feasible limits) while their performances were measured by the associated HVAC system energy usage. In this section, the evaluation method is first presented, and then, a detailed description of the controller designs is provided.

3.1. Evaluation method

The model-based controller and the benchmark were compared according to the method in [6] which is based on the two most important aspects of an HVAC system (including the associated control system): indoor climate is to be kept within given comfort ranges, by preferably using as little energy as possible. The indoor climate aspect was taken into account by comfort metrics (one each for IAQ and thermal climate) that both controllers were constrained to fulfill equally within feasible limits. In practice, this was achieved by first applying the model-based controller in a certain scenario. The same scenario was then repeated with the benchmark after equivalent setpoint adjustments had been applied. In turn, the performances of the controllers were measured by the associated HVAC system energy usage and these coherent experiments were performed during two consecutive days in order to avoid the influence of weather variations. The maximum allowed difference of average outdoor air temperature was set to 2 °C, and for larger variations, one of the experiments was repeated during more suitable conditions.

During the IAQ control task, the indoor climate was indicated by the room air CO_2 level (c) and the associated comfort constraint is presented in equation *1*. It states that the maximum CO_2 level is not allowed to cross an absolute boundary of 1000 ppm, either when the model-based controller MBC or the benchmark controller BFB is used. This level is based on several national recommendations [12] as well as the ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) standard 62-2007.

$$\hat{c}_{r,MBC} = \hat{c}_{r,BFB} = 1000 \quad \text{[ppm]} \qquad (1)$$

During the thermal climate control task, the indoor climate was indicated relative to a neutral room air temperature (t_r) comfort interval between 21 and 22 °C. The first endpoint was set in accordance to a national guideline [13] which states that lower temperatures should be avoided in occupied office rooms. The second endpoint was set 1 K higher, since according to the standard ISO 7730:2005, smaller room air temperature variations do not have a negative effect on the thermal comfort, and similar recommendations are also given in ASHRAE standard 55-2004. The associated comfort constraint is presented in equation *2* and states that the deviating degree hours above and below this region should be similar when the MBC and the BFB were applied. This metric derives from the European standard EN-15251 and solely applied during occupied periods while drifts were allowed during vacancy without any penalties.

$$\begin{cases} \left(\sum \Delta t_{high} \Big|_{\infty,0} \times time \right)_{MBC} \approx \left(\sum \Delta t_{high} \Big|_{\infty,0} \times time \right)_{BFB} \\ \left(\sum \Delta t_{low} \Big|_{\infty,0} \times time \right)_{MBC} \approx \left(\sum \Delta t_{low} \Big|_{\infty,0} \times time \right)_{BFB} \end{cases} \quad [°Ch] \qquad (2)$$

$$\textit{Provided that the space is occupied}$$

$$\textit{Where} \quad \begin{cases} \Delta t_{high} = t_r - 22 \\ \Delta t_{low} = 21 - t_r \end{cases}$$

3.2. Benchmark feed-back controller

The benchmark feed-back (FB) lacked information about disturbances and solely relied on measurements of the controlled variable as input (i.e. room air temperature or CO_2). Its general structure is presented in figure *4* (top), and internally, proportional (P) and integrating (I) blocks were used to process a control error which was formed by comparing the input to a fixed setpoint. The outcome was in ventilation flow rate quantities and a final transformation into actuator compatible signals was done by a second cascade connected controller. The PI-blocks were tuned using the AMIGO step response method. It is not the most common method but derives from a large number of optimization procedures and approximately returns the controller parameters that minimize the deviation from the setpoint [14].

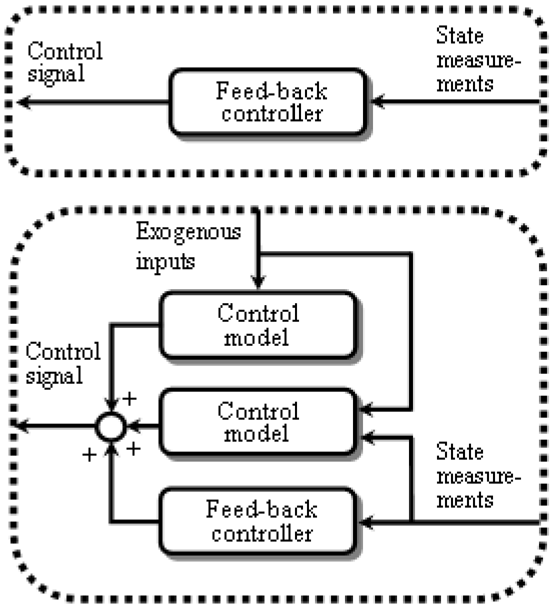

Figure 4. General schematics of the considered controllers: top; benchmark feed-back controller, bottom; simplified model-based controller. In this work, the state measurements refer to measurements of the controlled variable, the control signal refers to supply air quantities and the exogenous inputs refer to the imitated internal disturbances.

3.3. Model-based controller

The structure of the investigated model-based controller is presented in the bottom of figure *4* and consists of three blocks connected in parallel: from top to bottom, one control model for disturbances represented by discrete events (referring to occupancy provided by a motion sensor), one control model for disturbances with known quantities (referring to lighting and equipment) and one feed-back (FB) controller identical to the benchmark. The three outputs were summed up and transformed into an actuator compatible signal by an additional cascade connected controller. Compared to a conventional model-based controller, simplifications were made from both a control model and an input point of view, and these aspects are described in the following text.

3.3.1. Exogenous inputs

While model-based controllers in most previous works had perfect information about the entire set of disturbances (including external), the investigated controller was in [6] simplified by reducing the number to the imitated internal disturbances. However, the concept was extended in this work by only considering exogenous inputs that in practice are associated to low sensor complexities. That is, lighting and equipment heat gains as provided by power sensors, and occupancy as provided by a motion sensor. As all of these signals were utilized for temperature control, CO_2 control only involved the motion sensor (since the corresponding number of people is the only relevant disturbance in that case).

Since the aim of the study was to evaluate the performance of the simplified model-based controller, an ideal disturbances sensor system was assumed. The predetermined sequences of lighting and equipment were directly used as exogenous inputs and the motion sensor response was considered without any delay. These choices were made to delimit the work and an estimation of how the results are influenced by this assumption can be retrieved from [9], in which the connection between uncertainties in the exogenous input and control performance is studied.

3.3.2. Control model

The complexity of the control model was heavily reduced by replacing the common dynamic balance equations to: (1) the non-linear filter from [6] for lighting and equipment, and (2), a memory function for motion sensor responses. As the purpose of the control model was to act fast and accurate to changes in the exogenous inputs, a FB controller was furthermore integrated to compensate for any error in the exogenous inputs (such as incomplete, unmeasured or faulty measured disturbances).

The non-linear filter (eq.*3*) is of closed loop character and was specifically used for temperature control. While the exogenous input (u) is made up of the total heat emitted by lighting and equipment, the output (y) corresponds to a cooling supply which was transformed into a ventilation flow rate using the current room- and supply air temperatures (t_s) through equation *4*. The filter has the ability to modulate the output by scaling the additive inverse of the exogenous input with respect to the current room air temperature (t_r). The scaling property was in turn determined by a temperature region stretching from the upper boundary of the comfort interval (t_{high}) to a point within (t_{low}). For room air temperatures…

- …inside this region, the additive inverse of the exogenous input was scaled down between 1 and 99 %.
- …above this region, the entire magnitude of the exogenous input was utilized as cooling supply.
- …below this region, the filter output was zero.

$$y = -\left(\left.\left(\frac{t_r - t_{low}}{t_{high} - t_{low}}\right)\right|_{0,1} \times u\right) \quad \text{[W]} \qquad (3)$$

$$\dot{V}_{vent} = \frac{y}{\rho_{air} \times c_{p,air} \times (t_s - t_r)} \quad [m^3/s] \quad (4)$$

Remark: Finding an appropriate parameter for the lower end-point of the temperature region (t_{low}) is much like finding the static gain of a feed-back controller. That is, it's a trade-off between stability and speed, and a narrow/broad region corresponds to large/small static gains.

The motion sensor output was in turn utilized during both control tasks (room air temperature and CO_2) through a memory function whose main features are illustrated in figure *5*. The control procedure is best explained by dividing the operation between occupied and vacant periods, denoted with 1 respective 0 in the figure. First of all, the memory function requires one occupied learning period (marked in gray) before contributing to the control. As that period ends (1→0), the current control signal value from the supporting FB is save, and as the next occupied period begins (0→1), this value is immediately send to the actuator. This procedure is then repeated for the upcoming events, by passing on the previous FB control signal plus its own output to the next occupied period and so on. By saving the output from the FB (and not the part from the non-linear filter), only control signals associated to unmeasured disturbances are passed on, and as the influence of the external climate was limited by omitting external walls, this part is primary dependent to occupancy. The experiments were conducted by assuming the sequence of imitated occupancy (see figure *3*) as symmetrical. This means that each experiment involving the memory function begun with the final part of the sequence (15:20-17:00) as a learning period, the FB output at 17:00 was saved, an vacant period was applied until the system reached steady-state, and finally, the sequence starting at 07:00 was initialized.

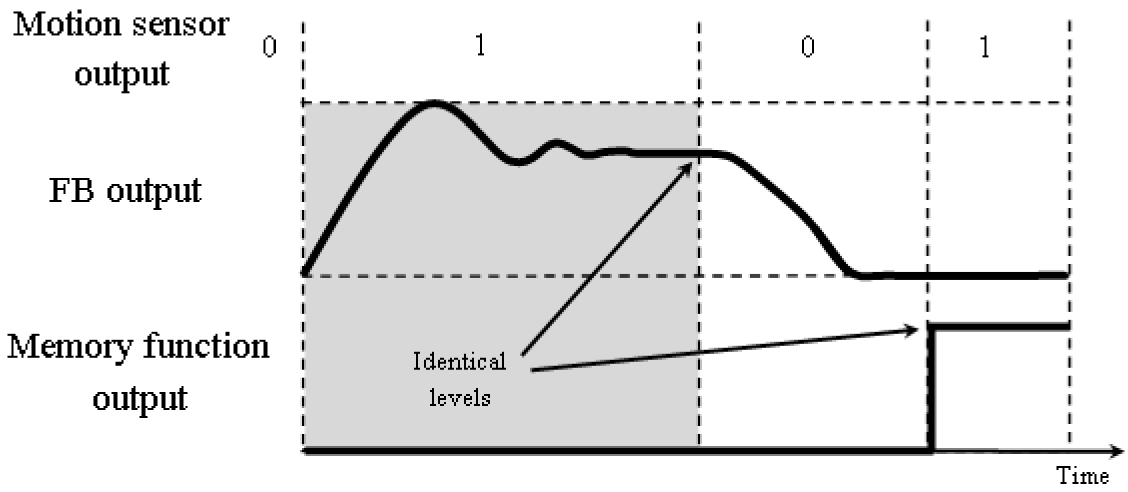

Figure 5. Illustrated learning period (gray) and features of the memory function used to process motion sensor outputs.

4. Results

In this work, a low complexity model-based controller was evaluated for ventilation system control in office buildings by considering a conventional feed-back controller as benchmark. The controllers were implemented in a meeting room space and a working day was resembled by imitating the most common office related disturbances in sequences. These disturbances were also considered as exogenous inputs in two versions to find their combinatorial and individual contribution to the control. Further, two control tasks including temperature and CO_2 control were studied separately, and while the controllers were constrained to achieve equal indoor climate, their performances were measured by the associated HVAC system energy usage.

The HVAC system energy usage was indicated by the supplied air volume and the results are in turn presented as the ratio between the actual value and the maximum allowed to the space (set according to the national guideline BBR19). This indicator was chosen to represent the main bulk of energy usage accounts with the following benefits. First, the results were only influence by uncertainties from one sensor, calibrated and adjusted to a maximum error of ± 2 l/s. Second, the supply air flow rate is a transparent unit in this context, and moreover directly proportional to the energy for air-handling since equal and constant supply air temperature setpoints were used during coherent experiments. Third, the results were prevented from being influenced by operational dependent efficiencies due to unequal controller setpoints (for fulfilling the comfort constraints).

Finally, to facilitate for the reader, the energy indicator for each control task and controller is presented graphically in cumulative distribution functions (CDF) (i.e. sorted values from low to high on an increasing x-scale). Since the demand for cooling or air renewal increases with occupancy, the left part of these figures is associated to vacant periods, which is followed by periods associated to higher and higher loads.

4.1. Temperature control task

In this section, the results from the temperature control task are presented in figure *6* and *7* as room measurements and the associated ventilation flow rate. Each curve in the figures is associated to one of the considered controllers, and as both versions of the model-based controller (MBC) utilized the heat emitted by equipment and lighting in the control, only version (v.) 2 had information about occupancy as provided by an ideal motion sensor (i.e. occupied or vacant room without delay-time). This means that the non-linear filter is active in both cases, while the memory function only was used by version 2.

The largest strain on the thermal climate coincides with the largest heat gain at 13:00 hours. According to the comfort constraint (similar degree hours outside the comfort interval during occupied periods) equal thermal climate was automatically achieved by the two versions of the model-based controller (when the sensor uncertainty of 0.1 °C was used as resolution), and by the benchmark after a setpoint offset of -0.5 °C had been applied. Although this constraint didn't apply during vacant periods, the offset was maintained throughout the working day, and by doing so, an appropriate temperature level was ensured at the beginning of each occupied period. According to figure *7*, the associate influence on the ventilation flow rate corresponds to an increase of about 5-7 % which is seen as an offset during vacant periods.

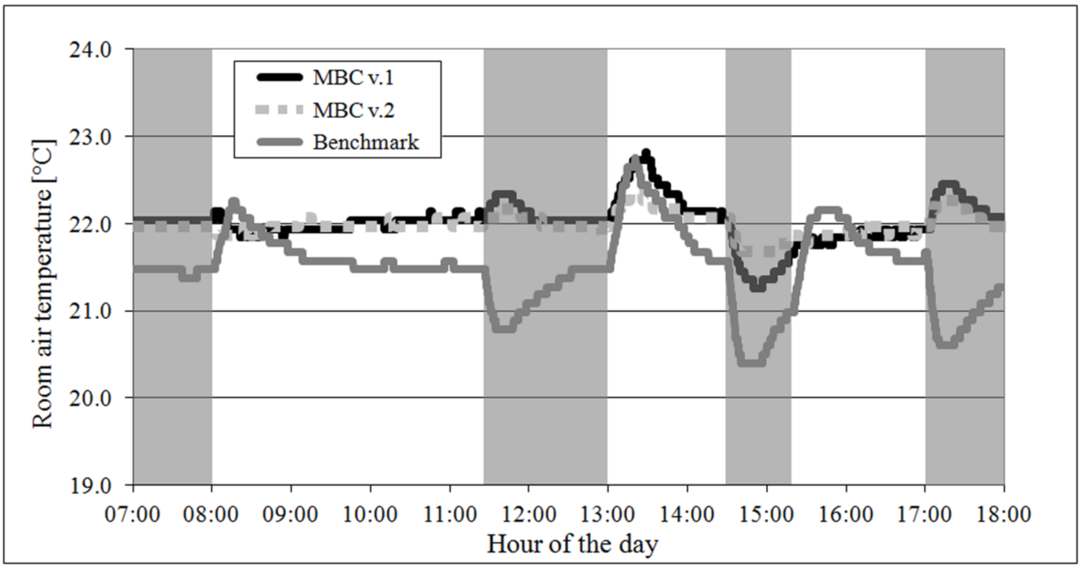

Figure 6. Variations of controlled room air temperature during the resembled working day. Vacant periods are marked in gray (MBC = Model-based controller).

Remark to figure *6*: the temperature drops below 21 °C occurred during vacancy (gray areas) and were therefore not influencing the thermal climate negatively according to the comfort constraint.

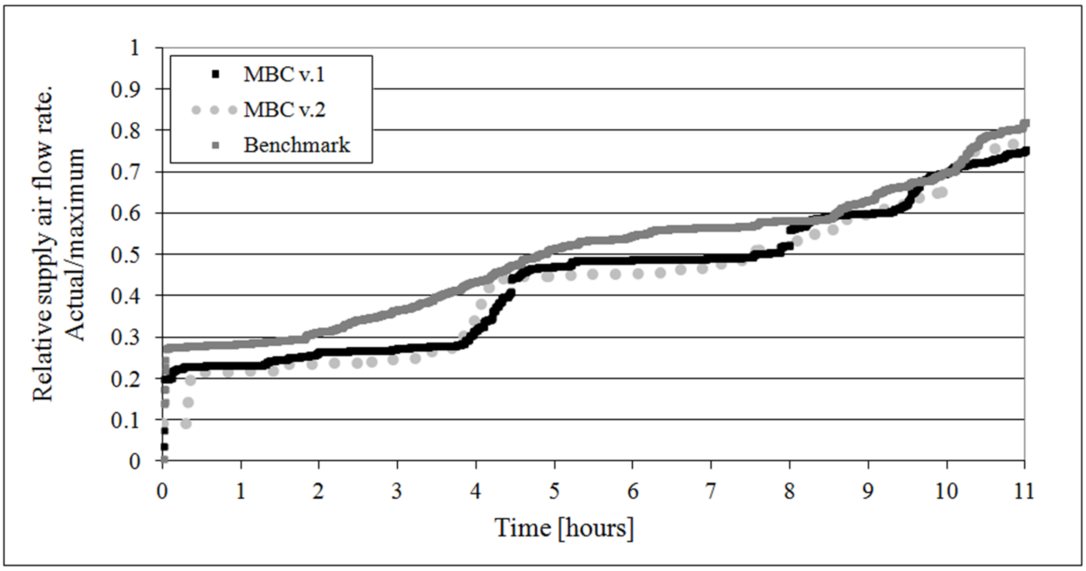

Figure 7. Cumulative distribution function of ventilation flow rate during the temperature control task (MBC = Model-based controller).

4.2. CO_2 control

In this section, the results from the CO_2 control task are presented in figure *8* and *9* as room measurements and the associated ventilation flow rate. Each curve is either associated to the benchmark or to the model-based controller with information about occupancy as provided by an ideal motion sensor. As imitated people was the only source for CO_2, the ventilation system was partly off during vacant periods, which is seen in figure *9* as the set of zeros stretching from about 0-3 and 0-4 hours on the x-scale depending on the type of controller.

The largest strain on IAQ coincides with the largest increase of occupancy at 13:00 hours. The IAQ constraint (none of the controllers were allowed to pass an absolute boundary of 1000 ppm, but for practical reasons, not including measurement noise) was fulfilled by reducing the setpoint of the benchmark to 680 ppm. Figure *9* indicates that the corresponding influence on the supply air flow rate is dependent on the magnitude of the IAQ strain, and that the setpoint offset led to a 20-40 % increase during periods with a small respectively large number of imitated people.

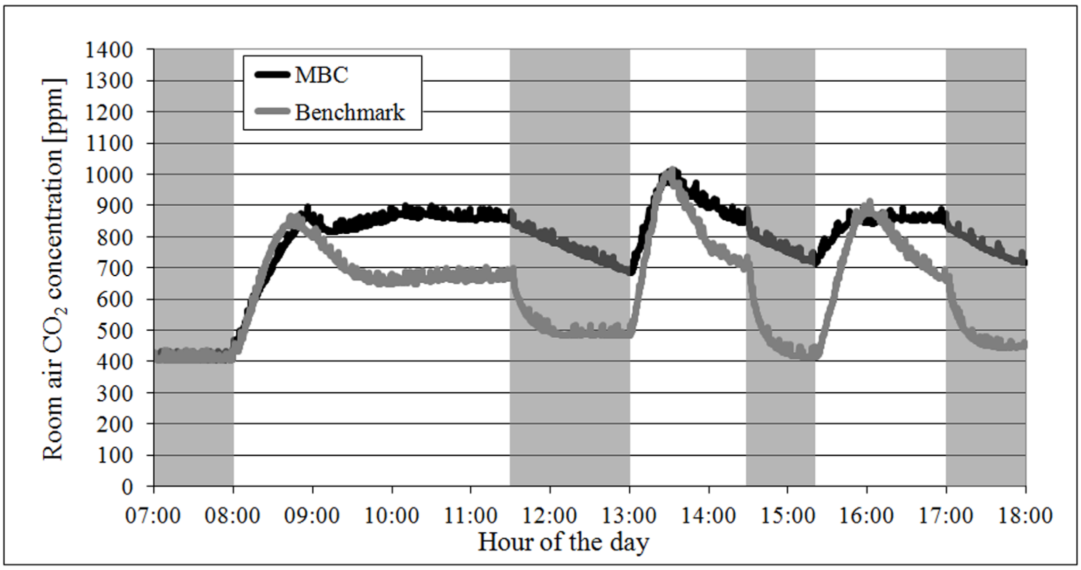

Figure 8. Variations of controlled room air CO_2 concentration during the resembled working day. Vacant periods are marked in gray (MBC = Model-based controller).

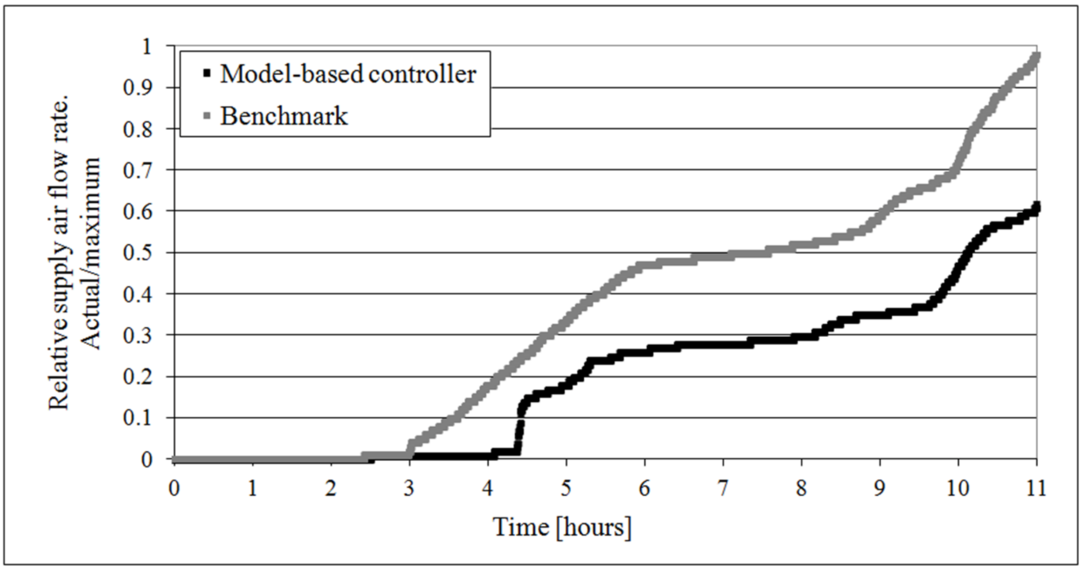

Figure 9. Cumulative distribution function of ventilation flow rate during the CO_2 control task.

5. Conclusions

It can be concluded that the simplified model-based controller has the ability of reducing the HVAC energy usage and improving the indoor climate considerably compared to the benchmark. But, it was also shown that these benefits were somewhat depended on the considered variants and control tasks. During the temperature control task, two versions of the model-based controller with respect to exogenous inputs were considered: both with information about lighting and equipment, and the second with additional information about occupancy as provided by an ideal motion sensor. Both resulted in equal thermal comfort, and compared to the benchmark, the variations of the room air temperature was decreased considerable at the same time as the supplied air was reduced by 11 and 15 % respectively. Hence, by only considering lighting and equipment as exogenous inputs, the potential energy savings were fairly high, and if also a motion sensor is added, an addition of 4 % can be expected. During the CO_2 control scenario, the disturbances sensor system of the model-based controller was solely made up by the motion sensor, and compared to the benchmark, the CO_2 variations in the spaces were decreased substantially at the same time as the total supplied air was reduce with 45 %. From an energy point of view, this reduction corresponds to a major share of the total energy used by the HVAC-system. To sum up, if the current model-based controller is to be implemented in an office building were the ventilation system is used for thermal climate control, a disturbance sensors system made up of power sensors for lighting and equipment is sufficient. If the ventilation system instead is designed for air quality control, a motion sensor is a sufficient and much simpler option compared to systems designed to estimate the actual number of people.

5.1. Sources of energy savings

As equal comfort was obliged throughout the study, the considered controllers were only differentiated by the associate energy usages. The ability of the model-based controller to use less energy for maintaining a desirable indoor climate derives from two features that can be illustrated in the associated CDFs (figure *7* and *9*). First, the main part of the savings is due to a fast response when a reduction of internal disturbances was registered. Then, the output of the control model directly went from the initial state to a relatively accurate terminal state while the benchmark modulated between all intermediate states with an increased energy usage as consequence. This feature is visualized as step-shaped curves in the CDFs and lead to major savings in the intermediate ventilation flow range (between 2-8 hours on the x-axis). The second feature is a fast response when a rise in internal disturbances was registered, and the main benefit was an increased comfort due to a limited deviation from the associated interval. But energy was also saved because the setpoint of the benchmark was adjusted for similar comfort, and this part stands for the entire savings potential during vacancy and long-lasting occupied periods (i.e. during static conditions).

Summary

A low complexity model-based controller was evaluated for ventilation system control in office buildings by considering a conventional feed-back controller as benchmark. The controllers were implemented in a meeting room space of a test facility and a working day was resembled by imitating the most common office related disturbances in sequences. An overall low complexity was achieved by separately considering motion sensor responses, as well as information about lighting and equipment, as exogenous inputs to a static control model with only one parameter in total. Further, two control tasks including temperature and CO_2 control were studied separately, and while the controllers were constrained to achieve equal indoor climate, their performances were measured by the associated HVAC system energy usage. Compared to the benchmark, the air supplied during the working day was reduced between 11 and 45 %, dependent on the considered scenarios. Therefore it could be concluded that the potential of the model-based controller for saving energy and improving the indoor climate was large, and especially during the CO_2 control scenario. It could also be concluded that the contribution of the motion sensor was rather low during temperature control, but crucial for CO_2 control.

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