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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
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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]

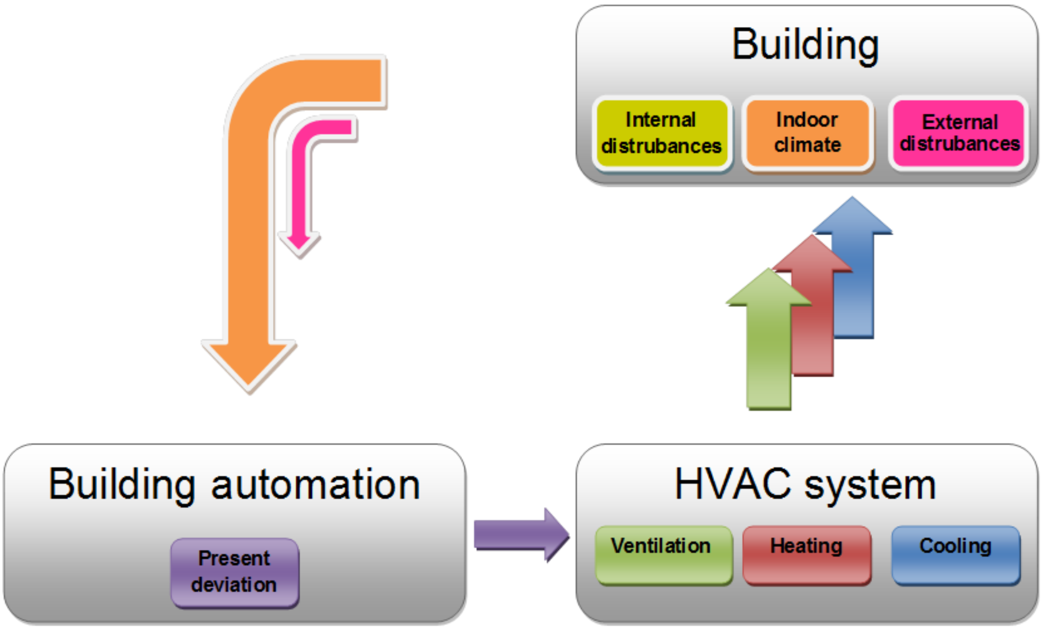

Figure 1. Typical working principle of a conventional building automation system. The main source of information comes from present indoor climate variables and the controller acts upon deviations from predetermined comfort regions. The controller offset is further commonly determined by a single external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

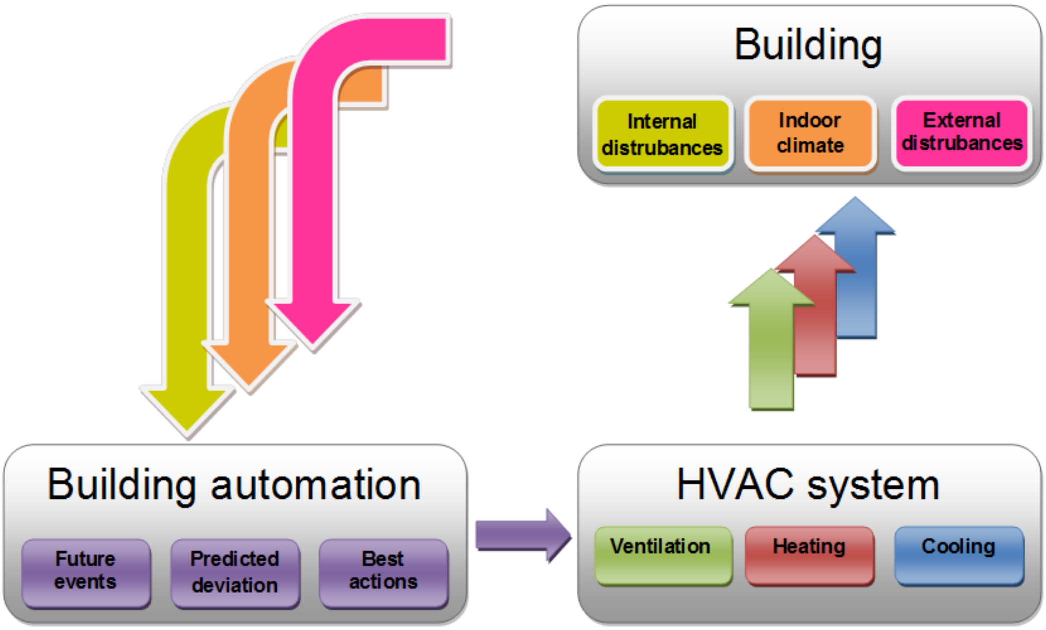

Figure 2. Typical working principle of a model-based building automation system. A relevant set of indoor climate disturbances is used to predict future consequences and to decide on the best actions. Further, several future events such as vacant periods, energy prices, changed operational modes etc.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

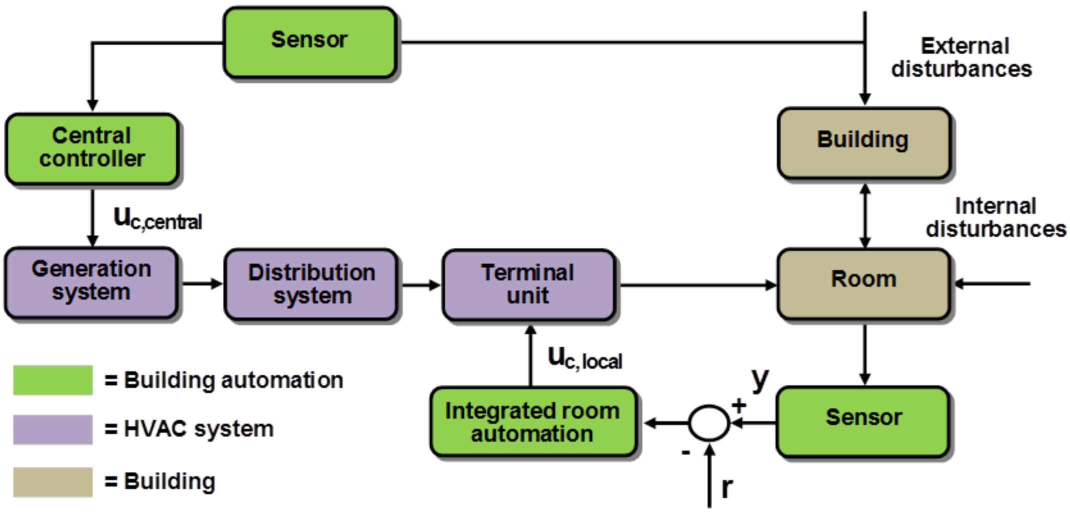

Figure 3. Principal characterisation of a building HVAC system: u_c = control signal(s), r = setpoint(s), y = measured controlled variable(s).

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.

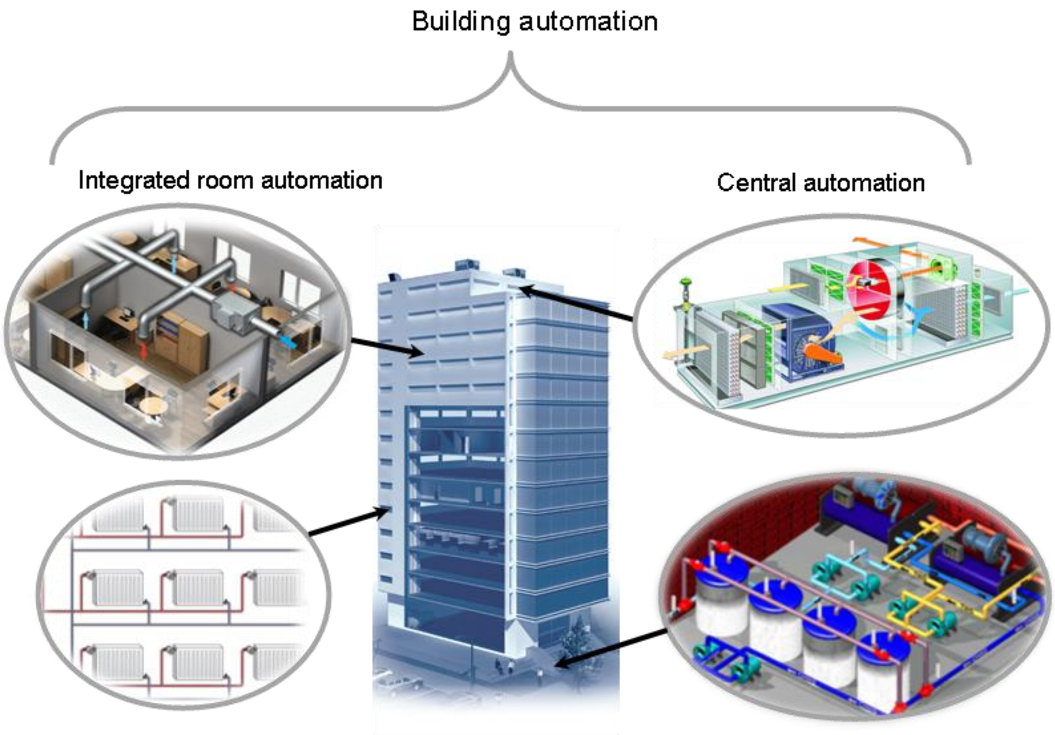

Figure 4. Examples of integrated room and central automation tasks; together referred to as building automation (figures from various internet sources).

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.

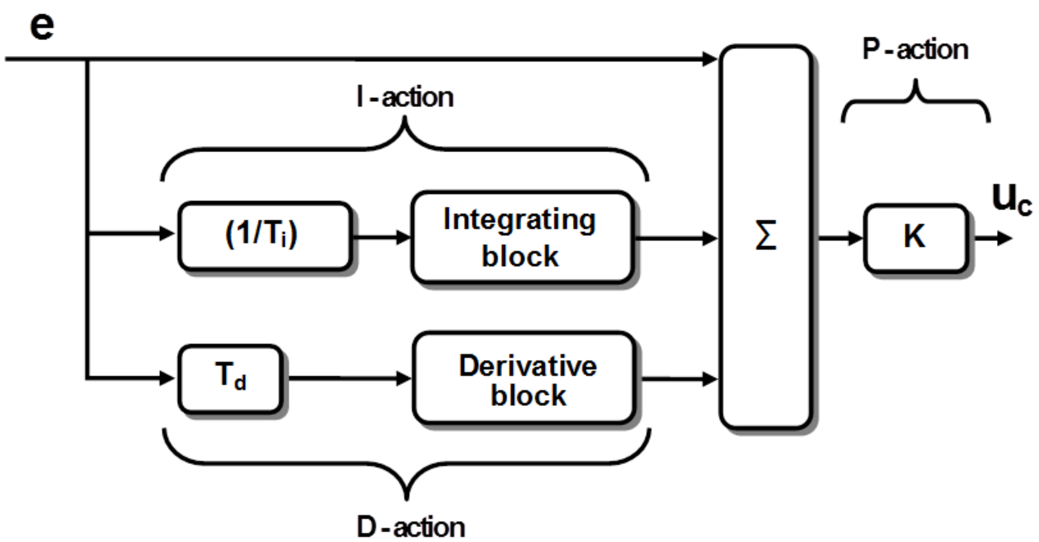

Figure 5. Schematics of a feed-back controller.

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.

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

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.

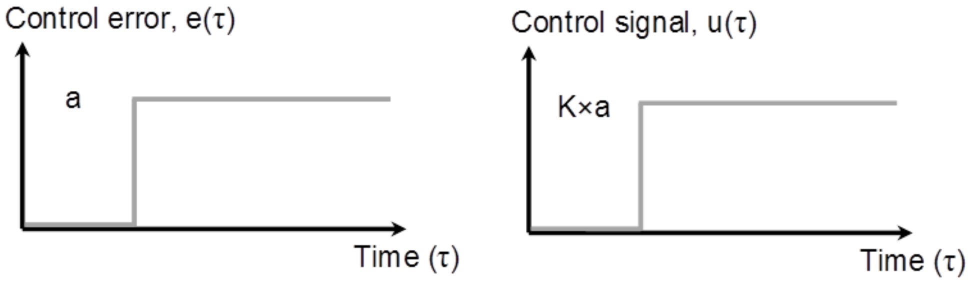

Figure 6. The response of a P-module (right) to a control error step of quantity a (left).

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.

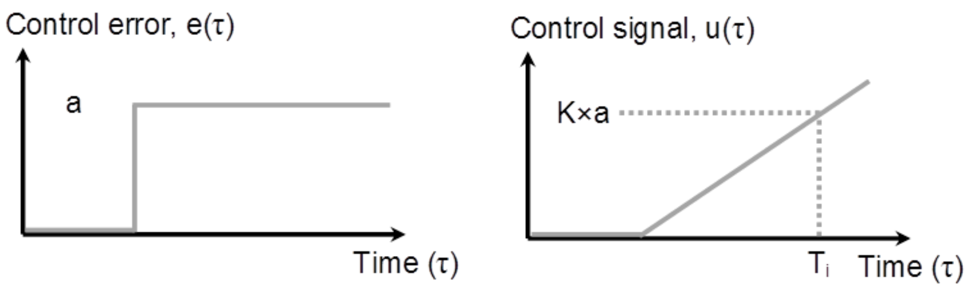

Figure 7. The response of an I-module (right) to a control error step of quantity a (left).

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.

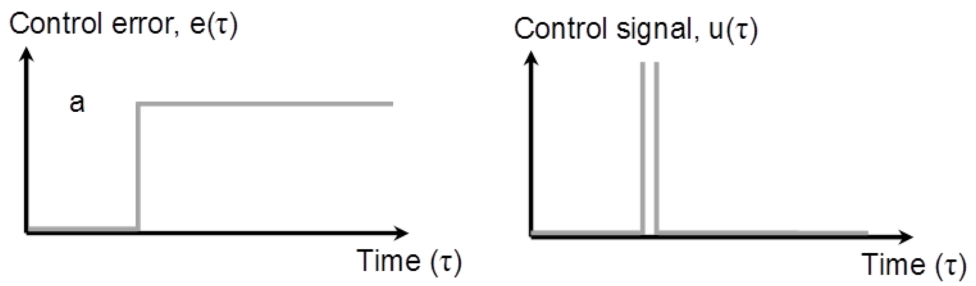

Figure 8. The response of a D-module (right) to a control error step of quantity a (left).

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.

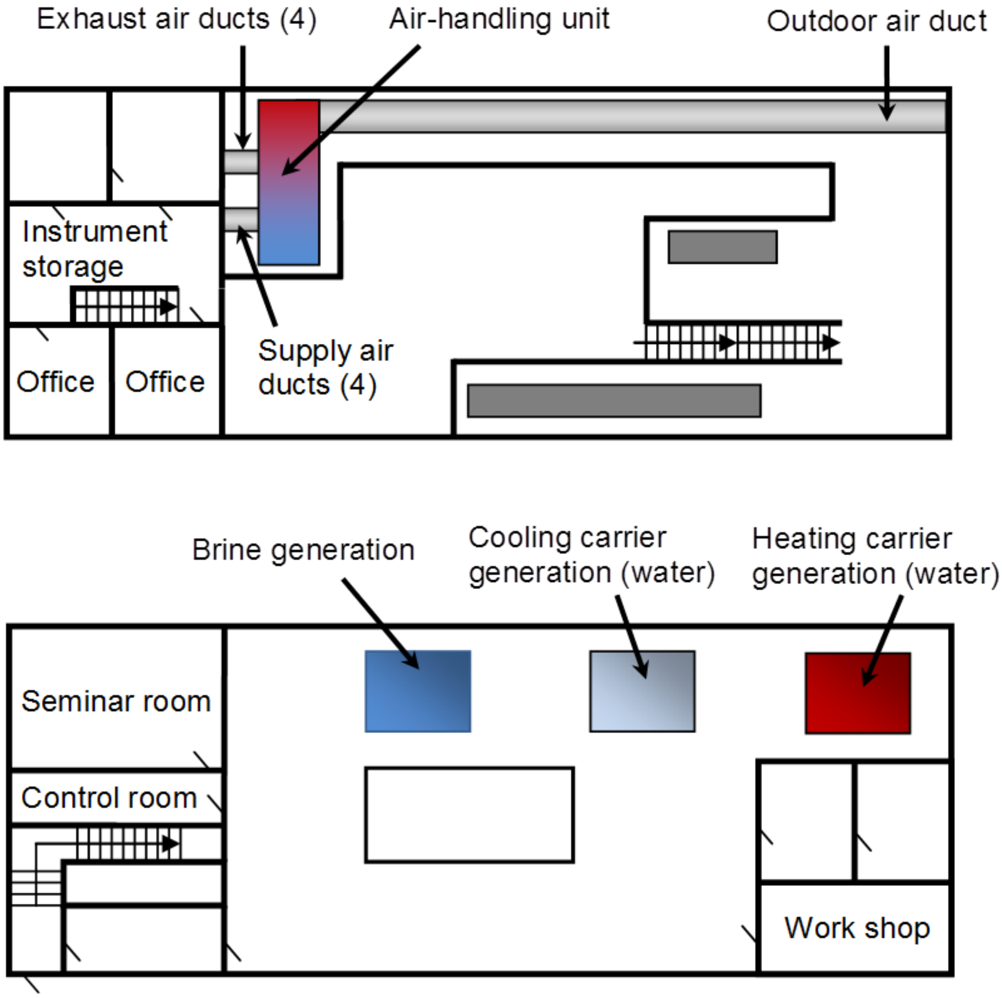

Figure 9. Schematic layout of the laboratory building. Bottom: entrance floor, top: 2nd level and entresol.

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.

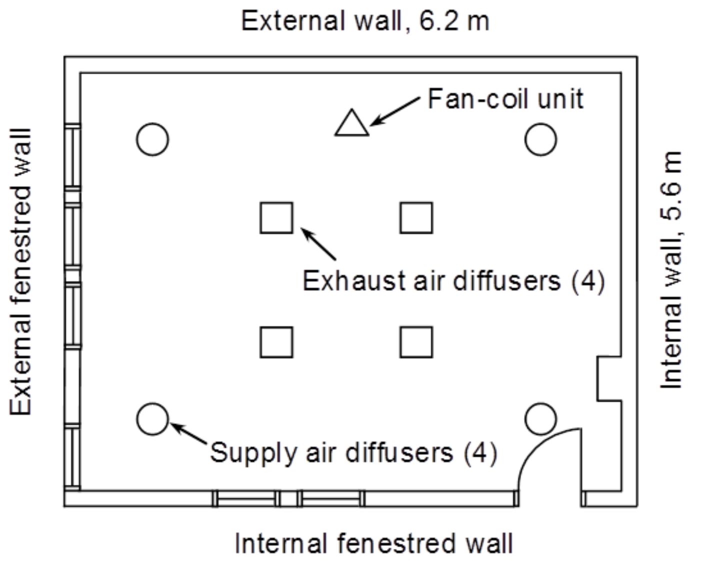

Figure 10. Schematic layout of the seminar room and some of the associated technical installations.

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)*.

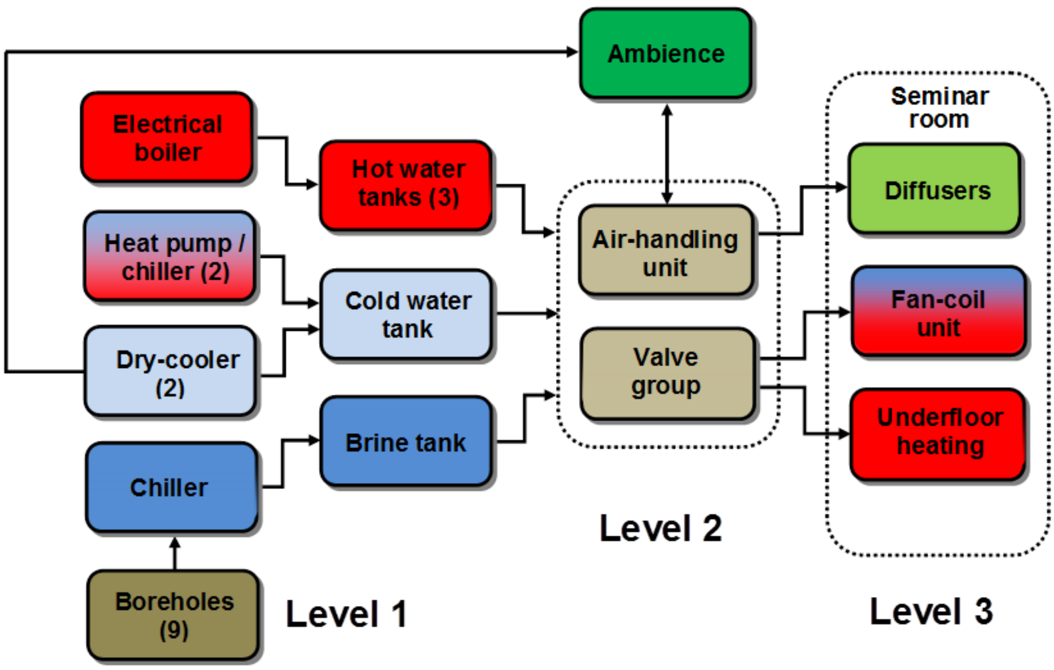

Figure 11. Flow sheet of technical installation in the experimental site. The level division is associated to functions that were provided during the experiments.

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.

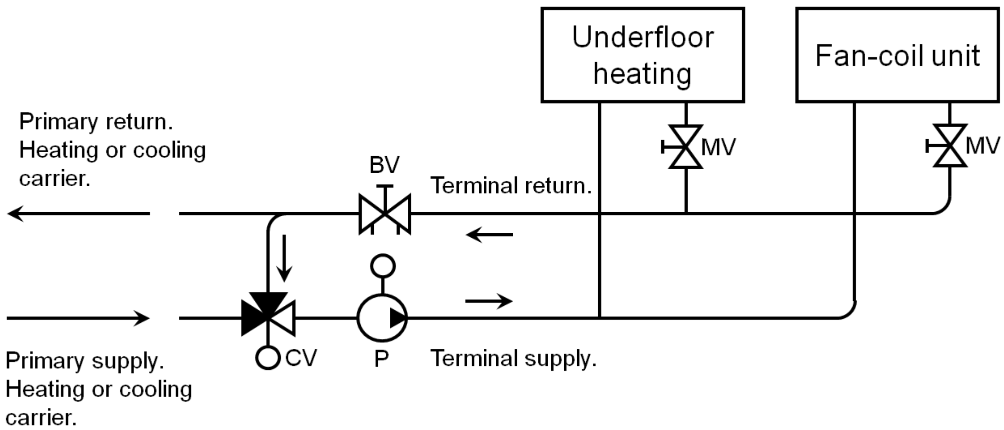

Figure 12. A simplified sketch of the valve group that was used to automate the hydronic terminal units for heating/cooling in the seminar room.

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.

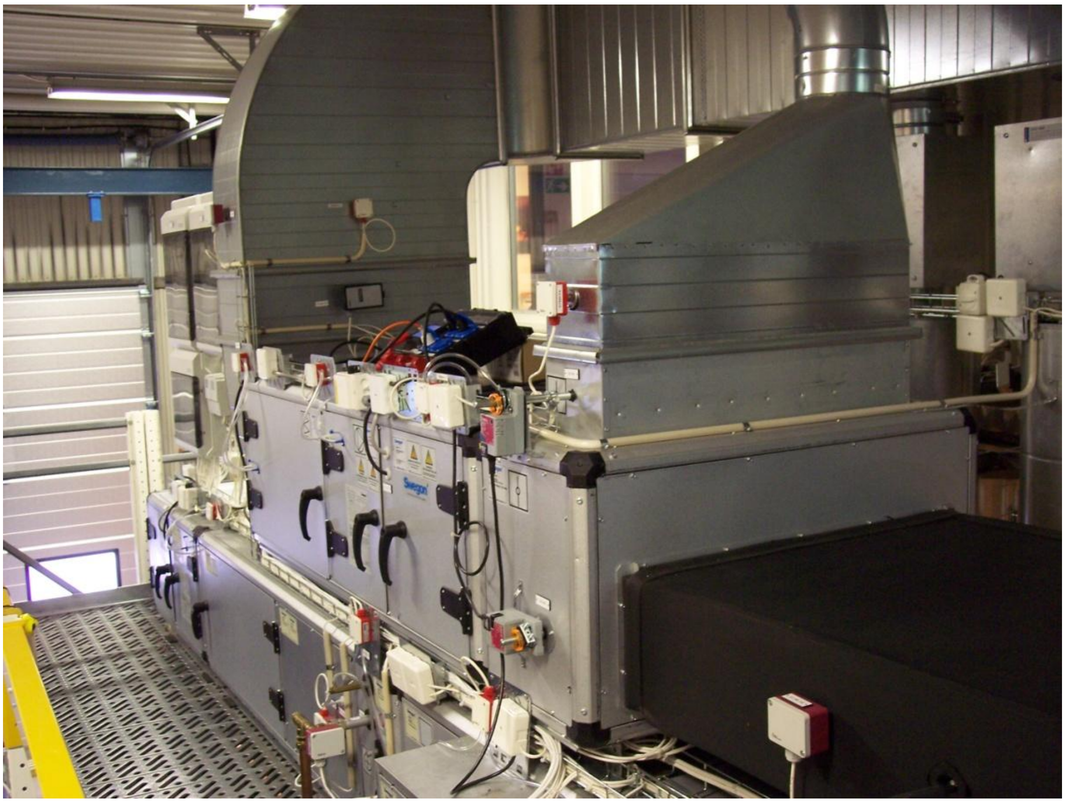

Figure 14. Photograph of the experimental air-handling unit which is located on the entresol in the facility.

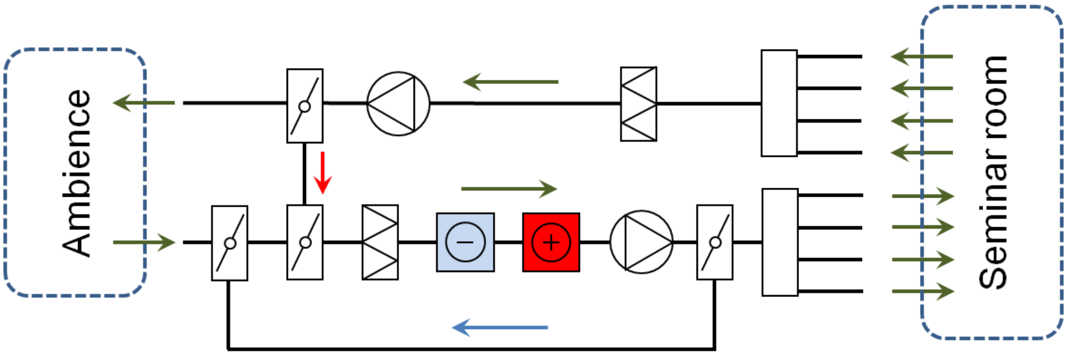

Figure 15. Schematics of the experimental air-handling unit. Green arrows indicate the normal pathways; the blue arrow indicates the auxiliary circulation pathway for an accurate control; the red arrow indicates the available but ignored re-circulation pathway.

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*.

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

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

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

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

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.

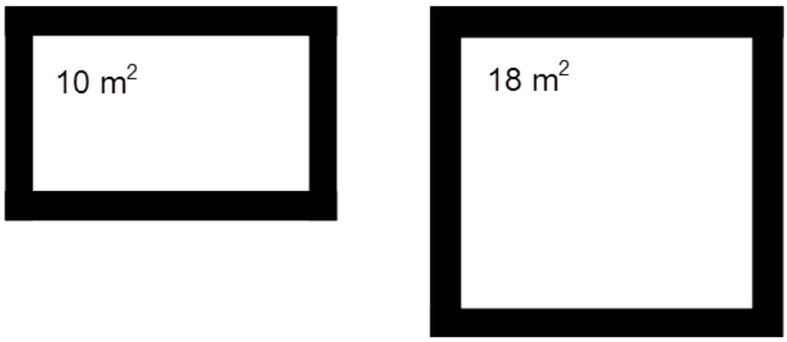

Figure 16. Schematics of the sites that were considered in the mutual methodology; office cell to the left and meeting room to the right.

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/m³]	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.

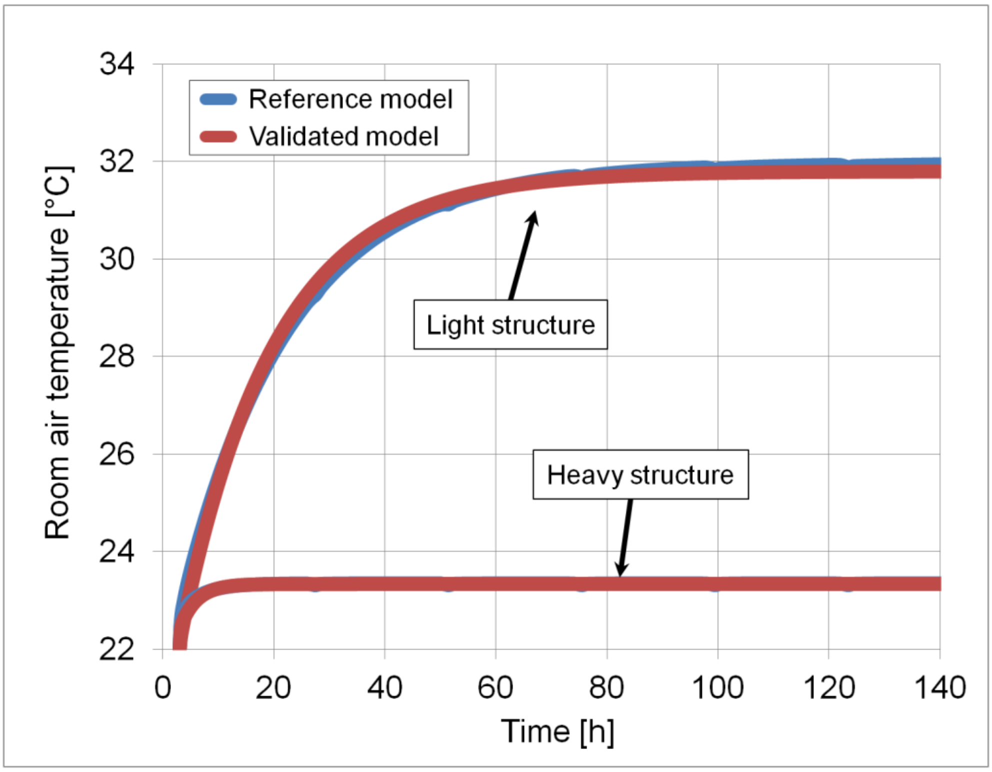

Figure 17. Room air temperature responses to a step in internal heat gain (0-280 W).

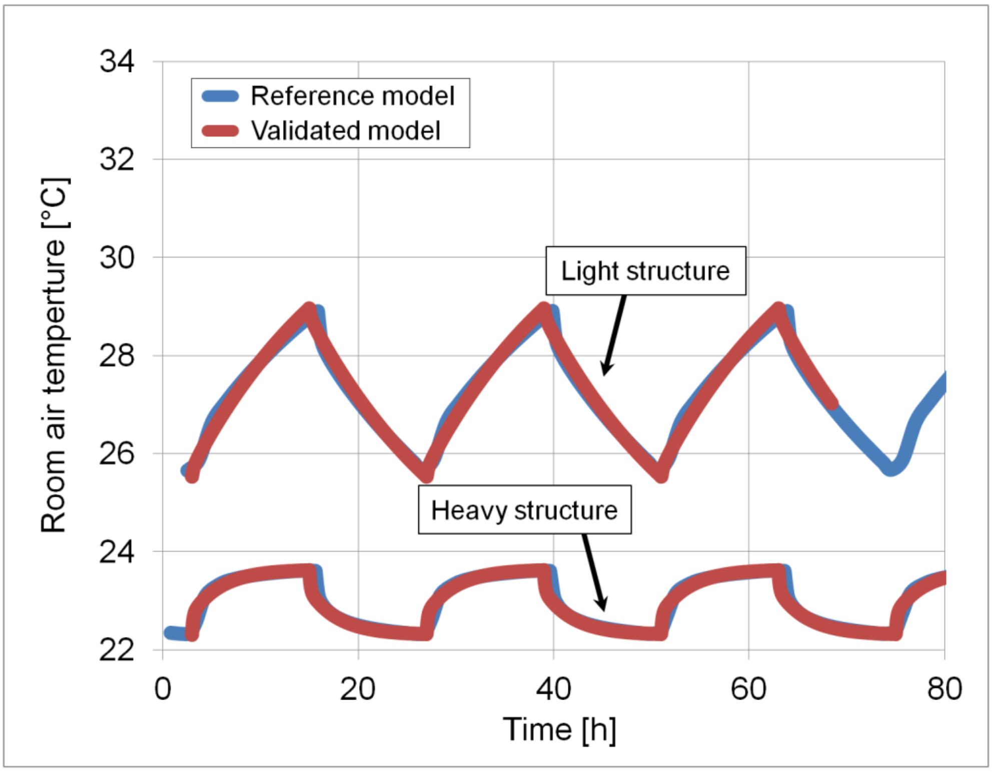

Figure 18. Room air temperature responses to internal heat gain pulses (shifting between 0 and 280 W every 12th hour).

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.

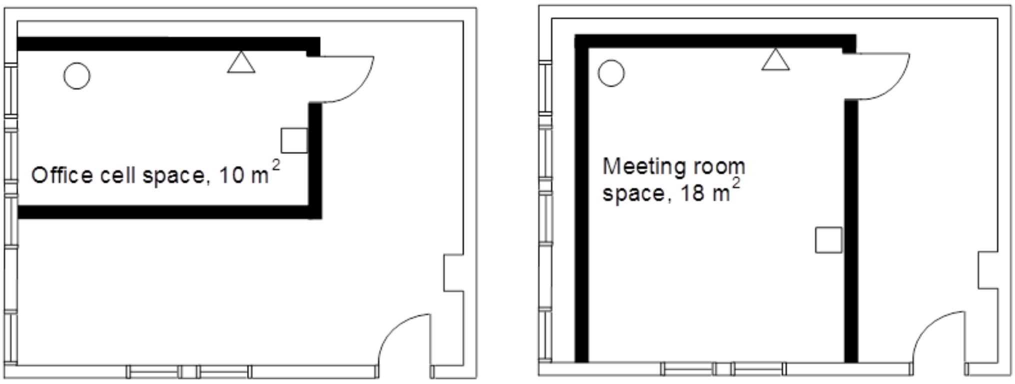

Figure 19. Alignment of the office cell and the meeting room in the seminar room during the experimental studies, respectively.

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.

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

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

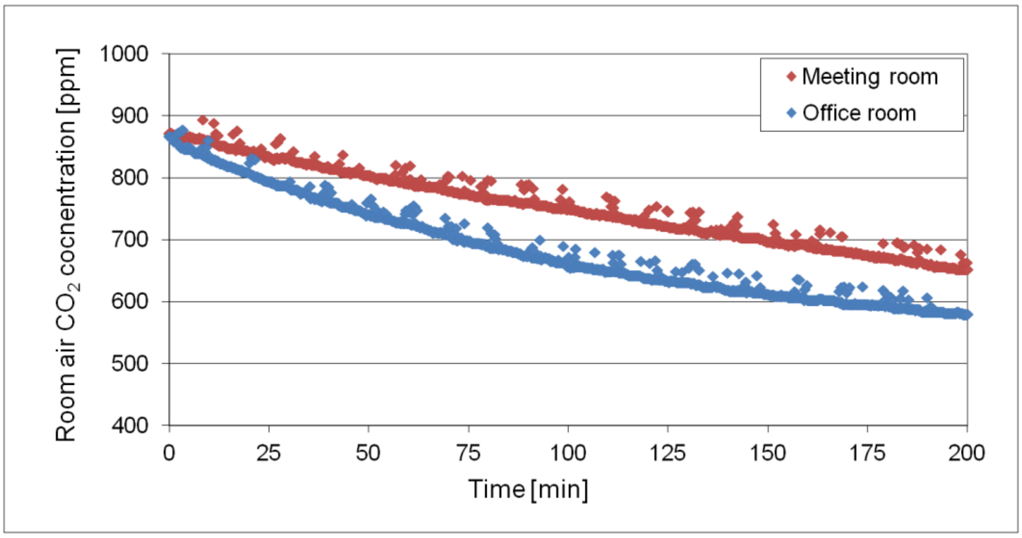

Figure 21. Transient CO_2 decrease in the respective site during periods without any sources or ventilation.

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.

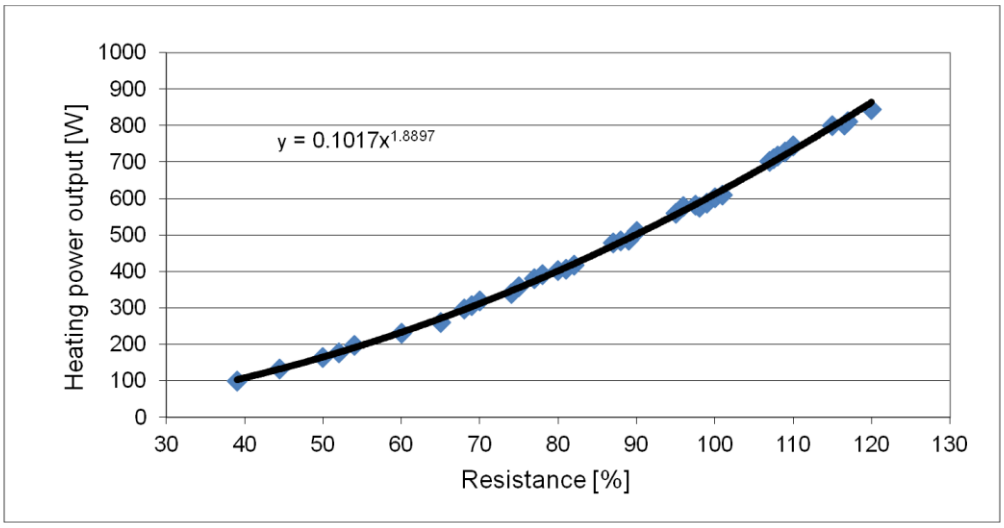

Figure 23. Measured relation between variable resistance setting and heating power output from the electrical panel radiator.

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.

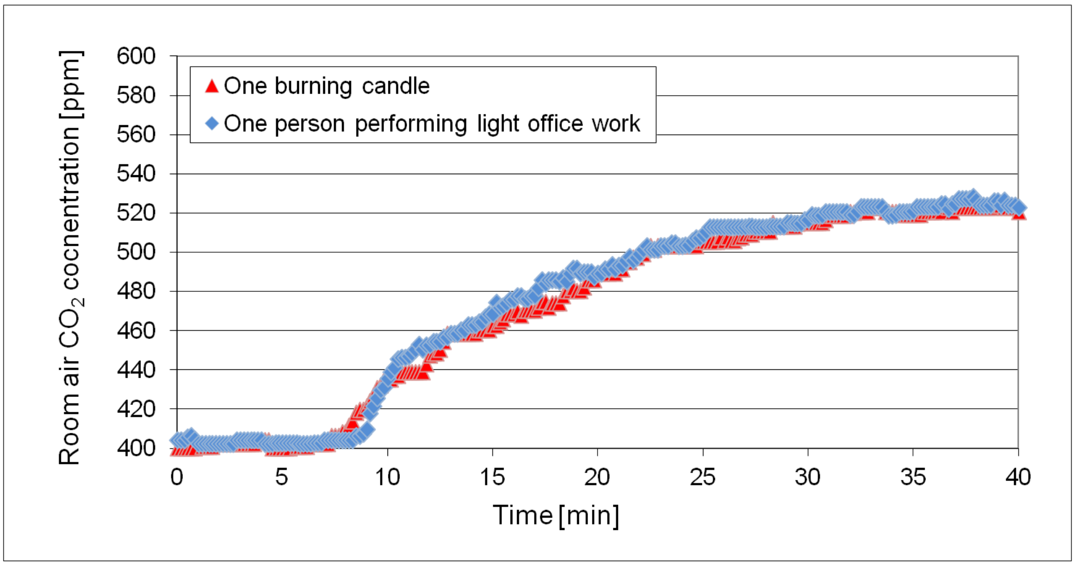

Figure 25. Correspondence between heat emission from one burning candle and one office worker indicated by comparing measurements of the respective temperature rise in a confined space.

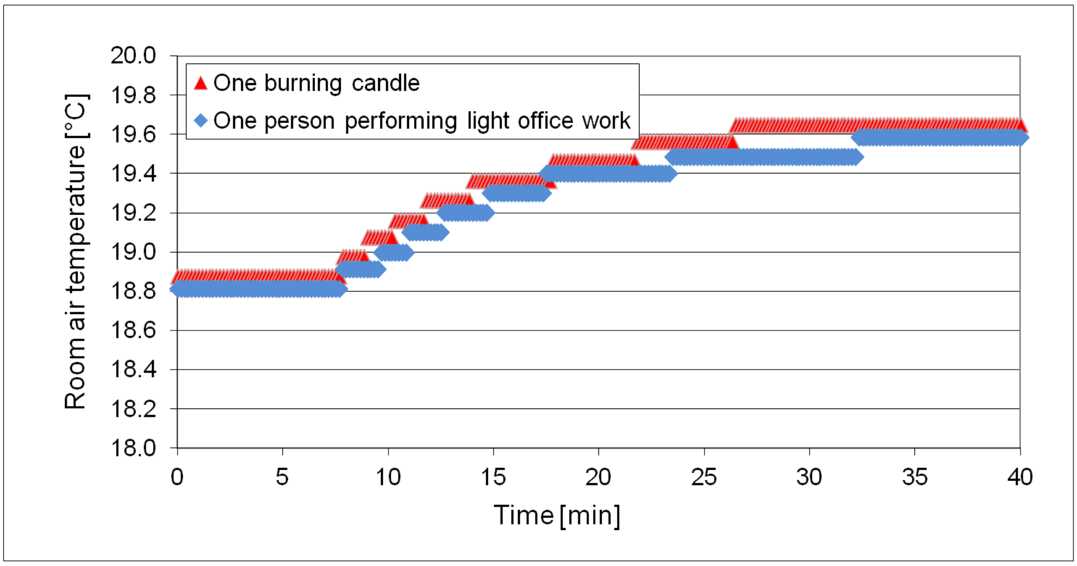

Figure 24. Correspondence between CO_2 emission from one burning candle and one office worker indicated by comparing measurements of the respective concentration rise in a confined space.

[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.

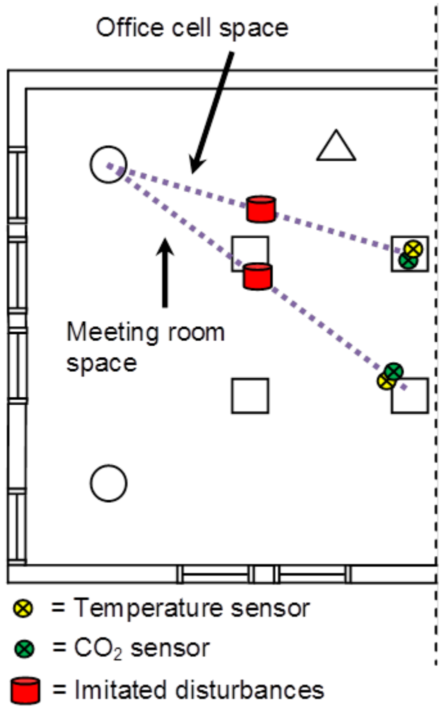

Figure 26. Outline of experimental setup. In each space, the sensors and equipment for imitating disturbances were equivalently placed along a straight hypothetical line between the active pair of air diffuser.

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.

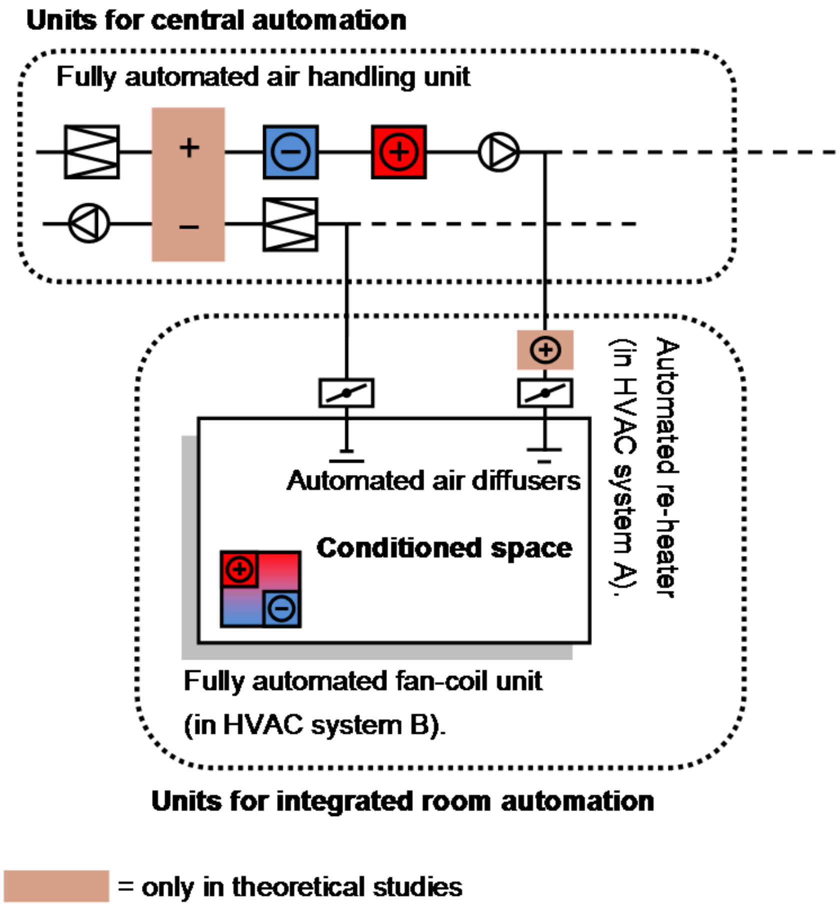

Figure 27. Schematics of the two HVAC systems A and B that were considered in the investigation.

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.

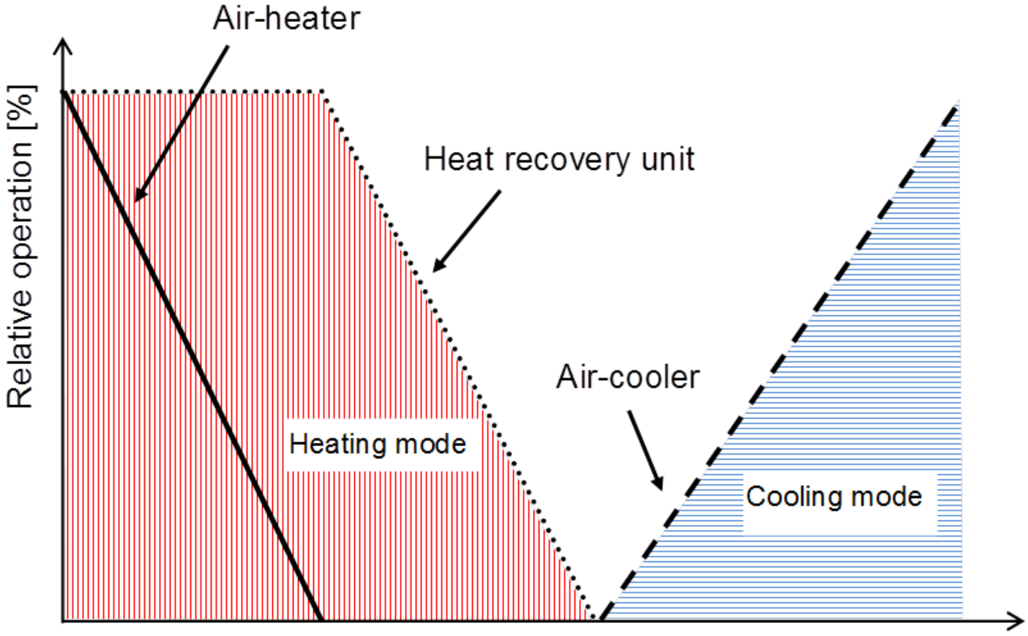

Figure 28. Considered control sequence for central air-conditioning. The heat recovery unit was only considered in theoretical studies.

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.

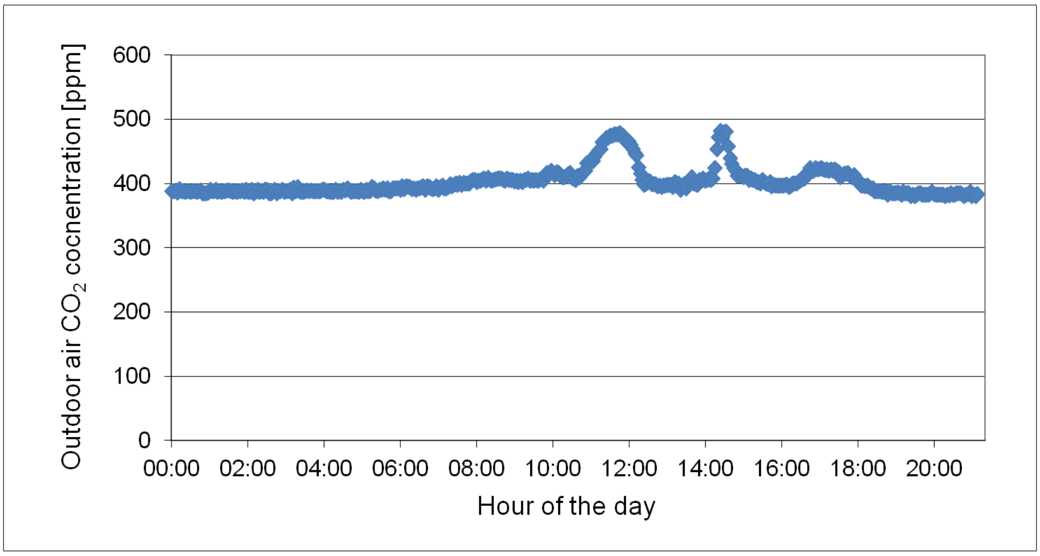

Figure 29. Typical variations in outdoor air CO_2 concentration as observed during the experiments: fairly constant levels during night and evening, but momentary traffic induced rises during morning and afternoon.

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.

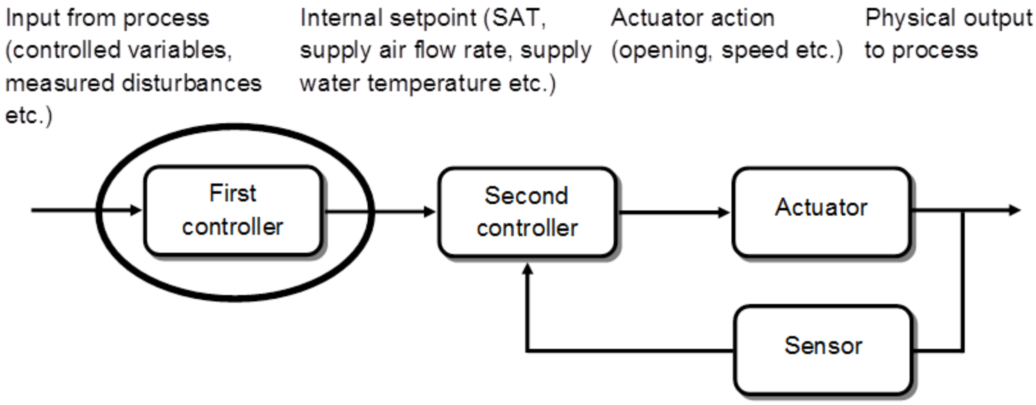

Figure 30. Schematic picture of the addressed control function. All suggested and benchmark strategies were applied to the first controller in a cascade alignment. The second controller was throughout made up of conventional feed-back controller.

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*.

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

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

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

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

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

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.

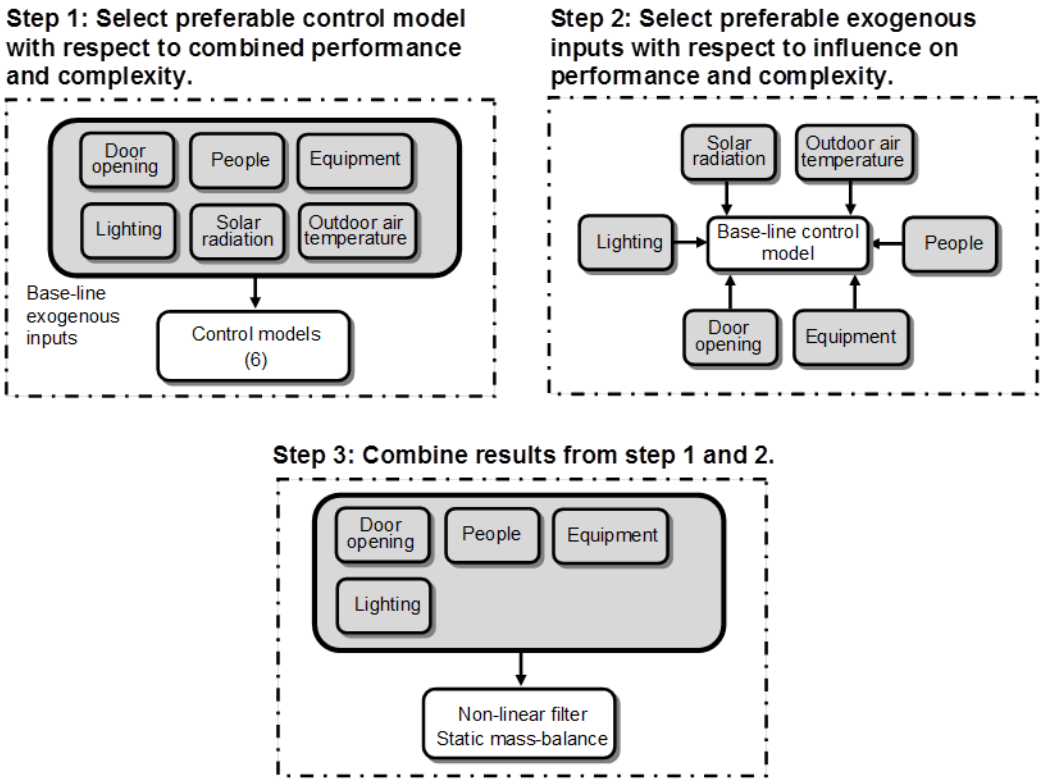

Figure 31. Illustrated procedure of paper I.

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.

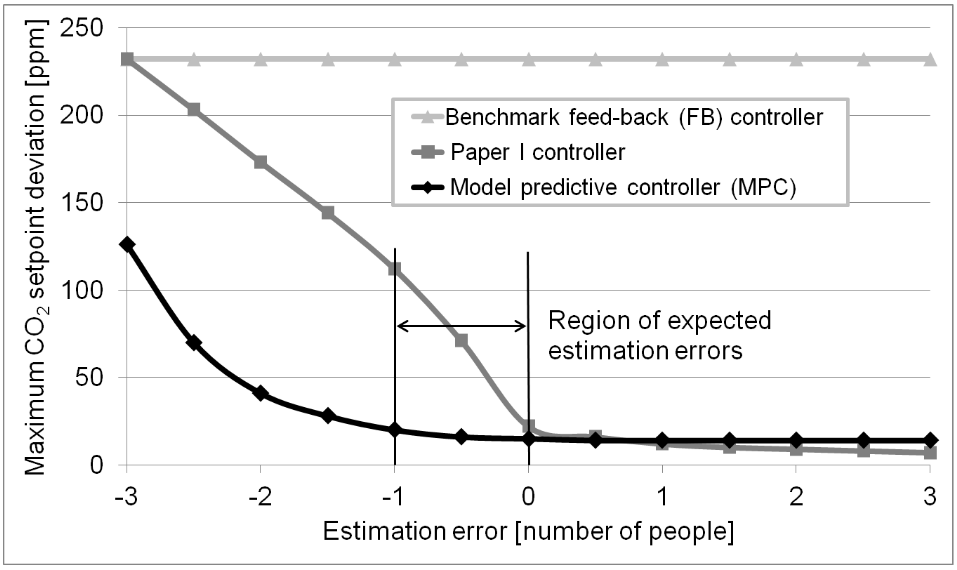

Figure 32. Influence of occupancy estimation error when the information is used by various model-based controllers for CO_2 control. The expected quantity which was derived in the experimental part is marked out.

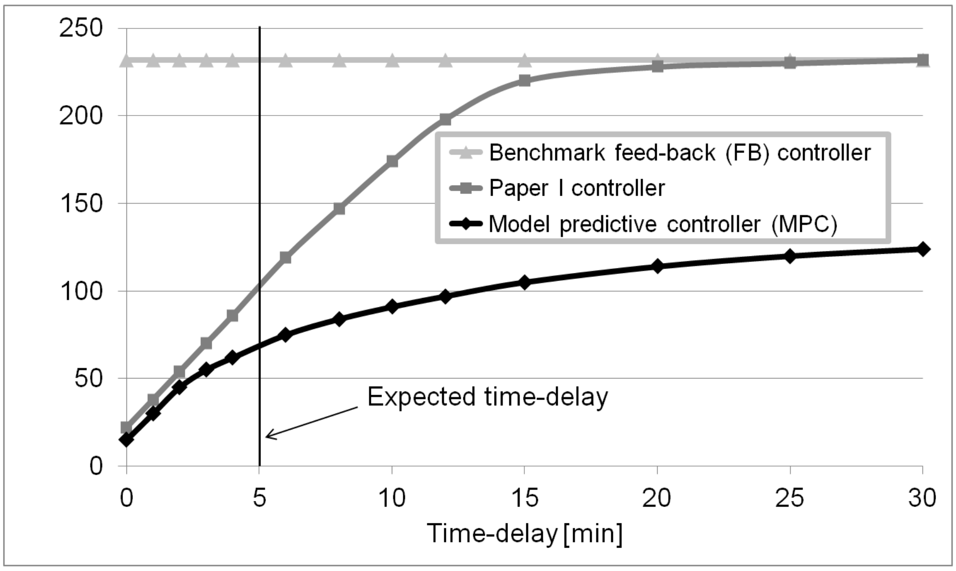

Figure 33. Influence of time-delay associated to occupancy estimations when the information is used by various model-based controllers for CO_2 control. The expected quantity which was derived in the experimental part is marked out.

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.

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

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.

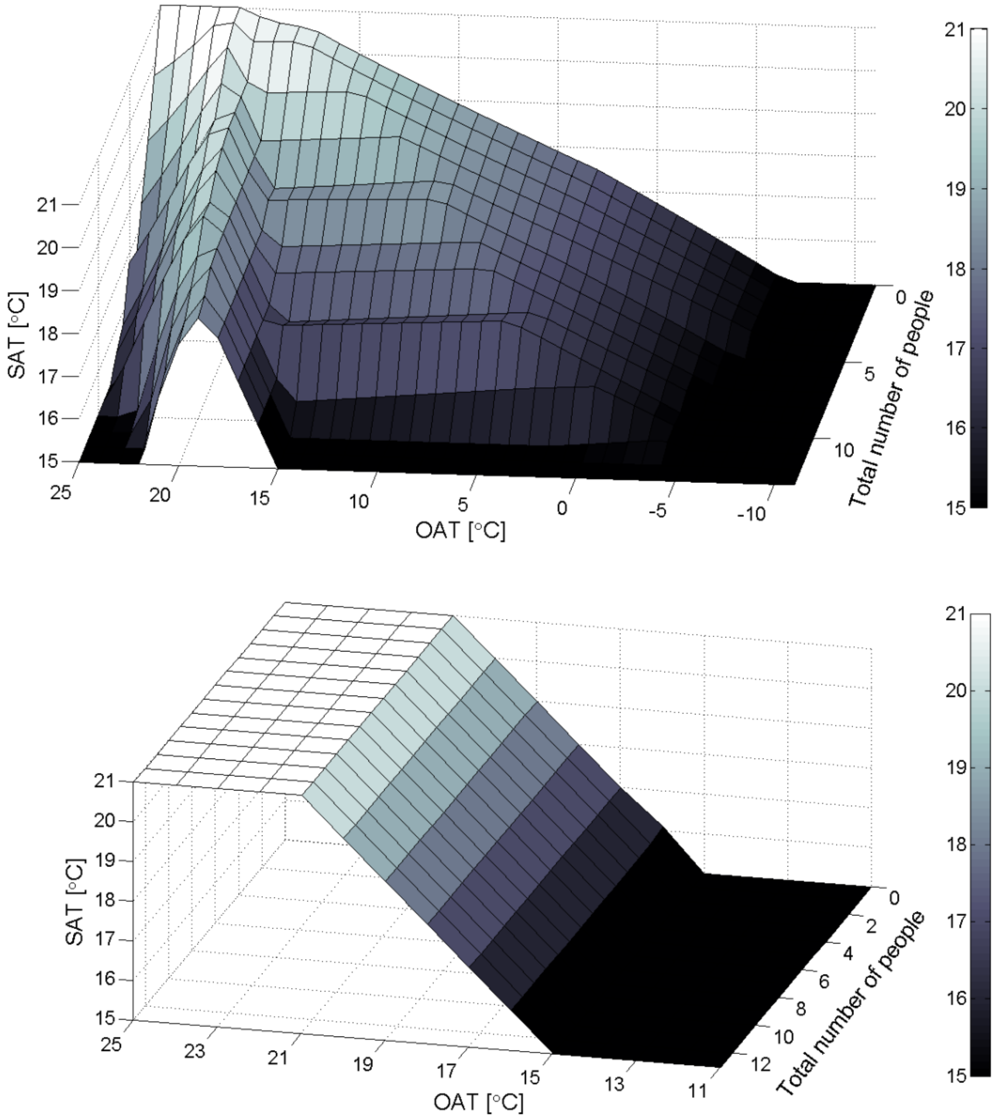

Figure 34. Optimal supply air temperature (SAT) setpoint as a function of external and internal disturbances. The upper part is for HVAC system A (all-air), and the lower is for HVAC system B (hydronic heating/cooling and hygienic ventilation).

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.

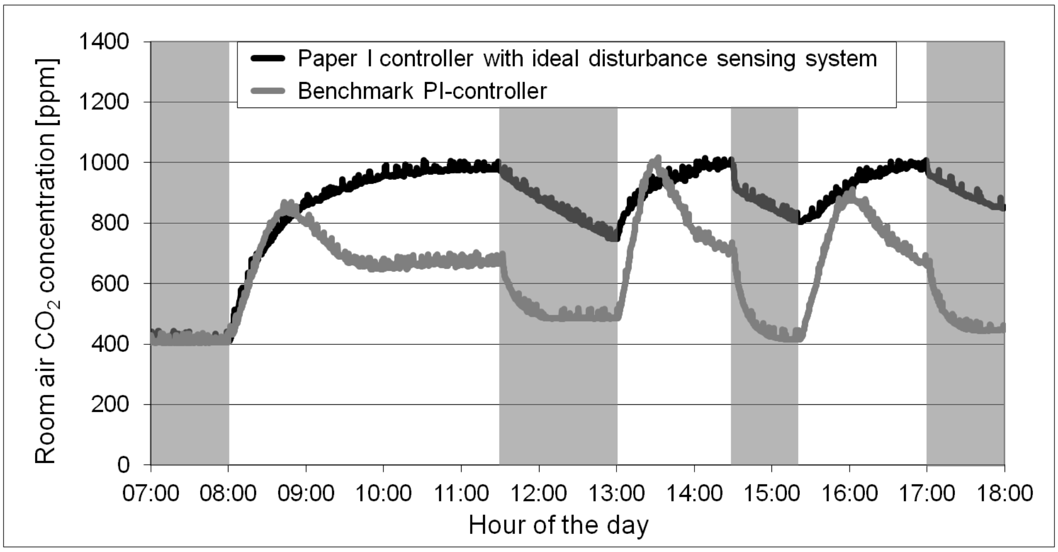

Figure 35. Example of the CO_2 control task during the re-created working day in the meeting room space (comfort constraint of concentration below 1000 ppm). The controller from paper I has perfect information about internal disturbances and the benchmark is a feed-back. Vacant periods are marked in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

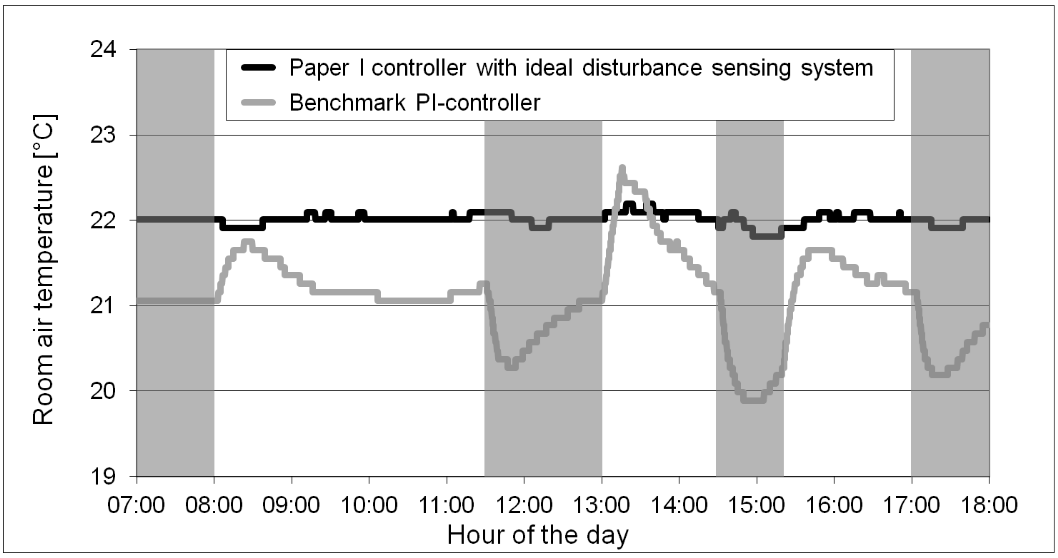

Figure 36. Example of the temperature control task during the re-created working day in the meeting room space (comfort constraint of equal degree hours outside a neutral region between 21-22 °C). The controller from paper I has perfect information about internal disturbances and the benchmark is a feed-back.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

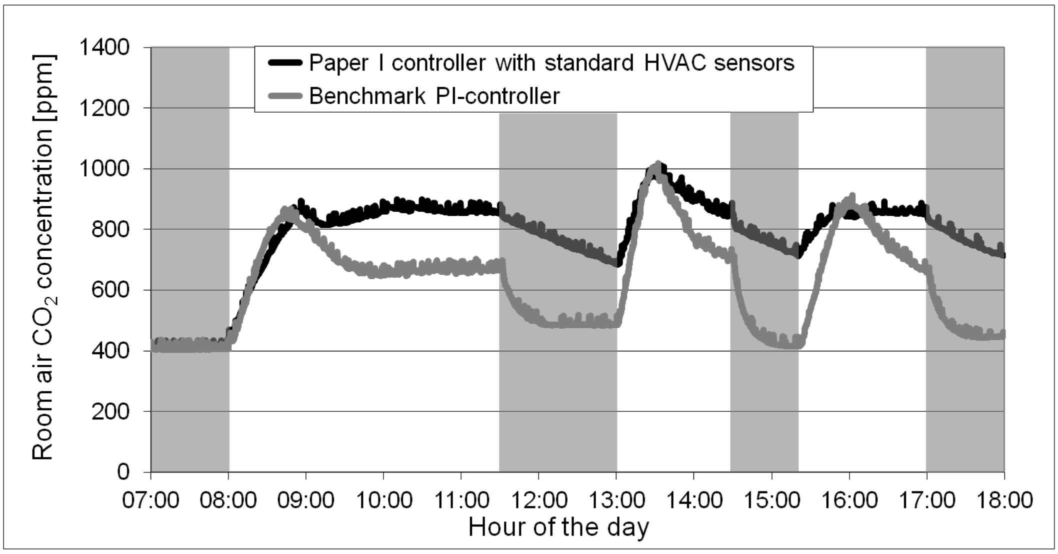

Figure 37. Example of the CO_2 control task during the re-created working day in the meeting room space (comfort constraint of concentration below 1000 ppm). The controller from paper I rely on information from standard HVAC sensors and the benchmark is a feed-back. Vacant periods are marked in grey.

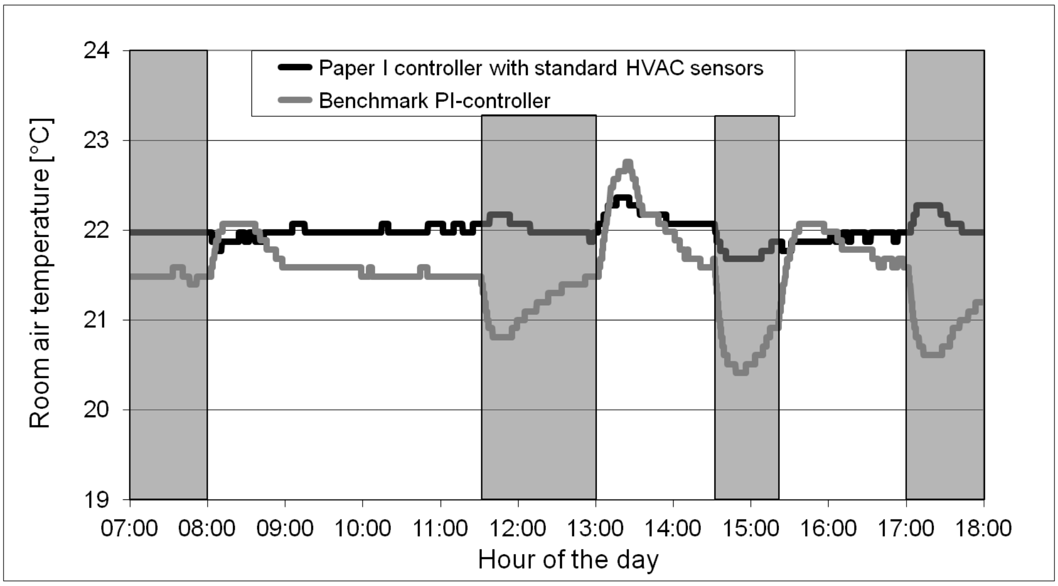

Figure 38. Example of the temperature control task during the re-created working day in the meeting room space (comfort constraint of equal degree hours outside a neutral region between 21-22 °C). The controller from paper I rely on information from standard HVAC sensors and the benchmark is a feed-back.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

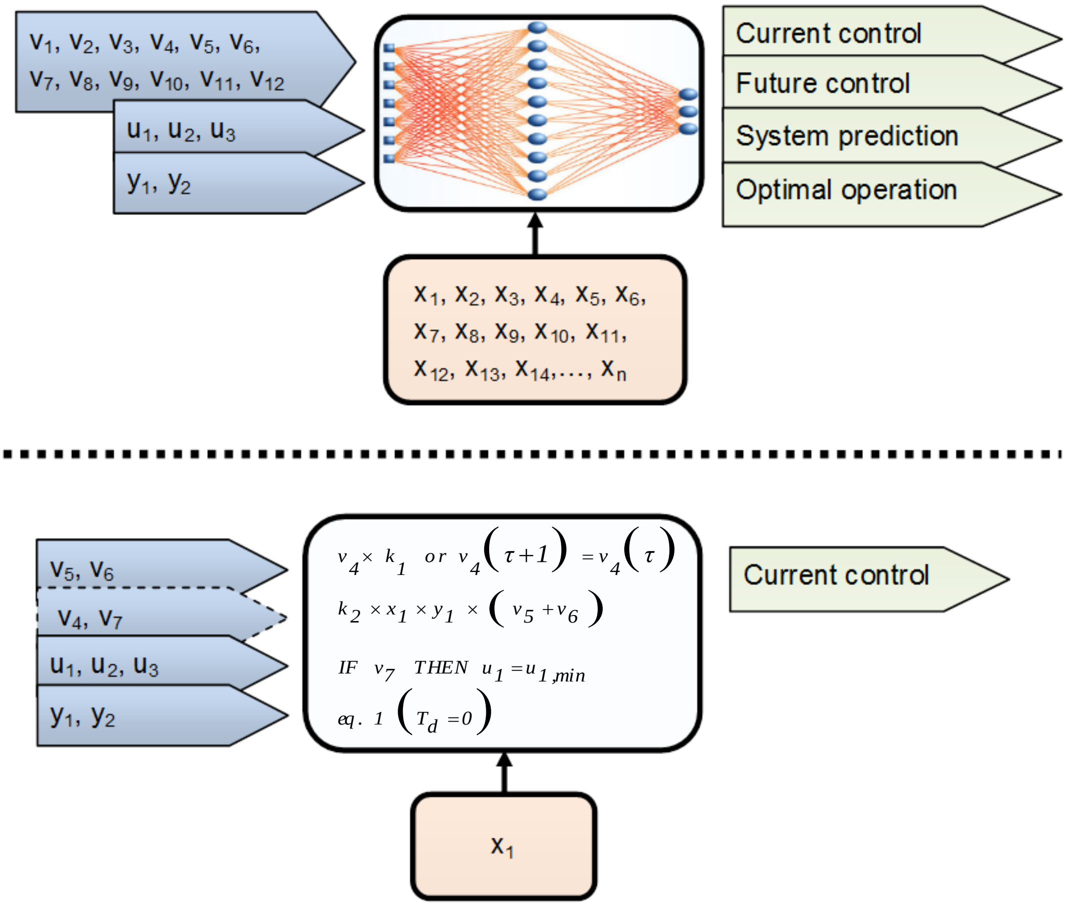

Figure 39. General structures of a typical MPC for building automation (top) and the suggested controller for integrated room automation (bottom). Signal designations according to table 9. k_1 and k_2 are constants.

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.

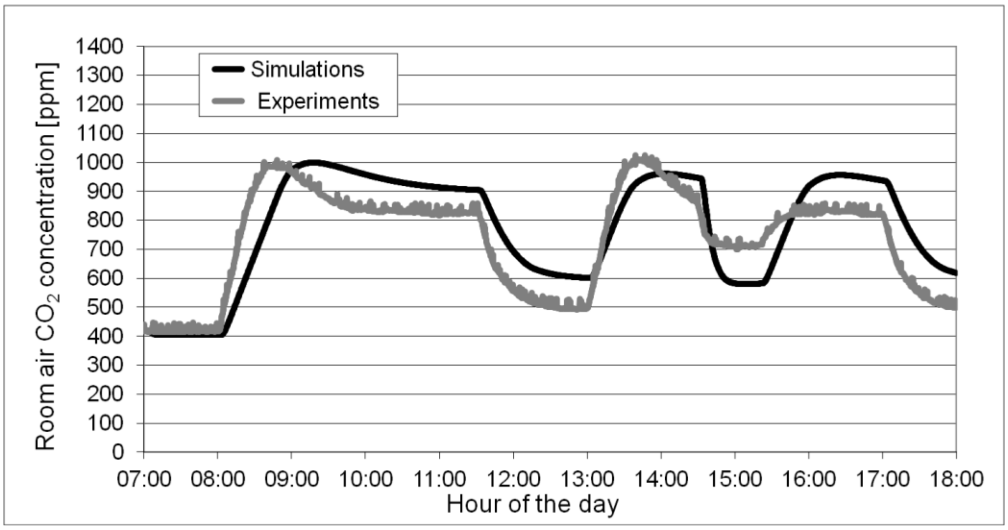

Figure 40. Experimental and simulated results of the benchmark for CO_2 control via HVAC system B in the office cell. Note that the duration of the simulated working day was adjusted to agree with the experimental.

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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