Final Report: Use of Weather And Occupancy Forecasts For Optimal Building Climate Control – Part II: Demonstration (OptiControl-II)

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Summary

The overall goal of the OptiControl project (2007-2013) was to develop and test tools, methods and novel strategies for improved building control, and in particular for predictive control that integrates weather forecasts. In a first project part, OptiControl-I (2007-2010), among other things novel control strategies compatible with state-of-the-art industry practice were elaborated. Here we report the work executed in the second part of the project, OptiControl-II (2011-2013). The objective was to extend, implement and rigorously test the newly developed, integrated (multiple control disciplines), whole-building control strategies in a representative, fully functional Swiss office building.

The OptiControl-II project was co-sponsored by swiss*electric* research, Siemens Switzerland Ltd., Building Technologies Division, Zug, Automatic Control Laboratory ETH Zurich, Gruner AG, Basel, and Actelion Pharmaceuticals Ltd., Allschwil. The target building was generously made available by Actelion Pharmaceuticals Ltd. Further information and a list of all persons that have participated in the project can be retrieved from www.opticontrol.ethz.ch.

In summary, the OptiControl-II project successfully developed the OptiControl-I strategies further for practical application, implemented them and proved their feasibility under real-world conditions in a concrete, challenging case study, tested them during a period of one and a half years using detailed measurements, user feedbacks and simulations, contributed new methods and tools for advanced building control, communicated the obtained results by means of numerous publications, reports, presentations and a successful on-site event, and provided a comprehensive benefit-cost assessment. Next to reaching all specific project goals, the project can be said to have pioneered research and development in the area of integrated whole building control.

Approach. The overall approach taken was based on an iterative process that combined computer based modeling, model validation, controller development and simulation with stepwise controller deployment, carefully designed measuring campaigns and feedback from users. The project focused on the offices part of the target building. The newly developed control strategies applied to, and were optimized for, the heating, cooling, ventilation, blinds operation and lighting of the five office levels.

Target building. The target building, located in Allschwil close to Basel, Switzerland, was a carefully selected, well-functioning 6-storey office building representative for Swiss conditions. It was put into service in 2007. It has a conditioned floor area of ~6'000 m^2, a typical thermal insulation level, insulation glazing, and a window area fraction of 50%. Heating and cooling is accomplished primarily by means of a thermally activated building system (TABS), i.e. pipes buried in the concrete slabs of the floors carrying hot/cold water. The building further features a central air handling unit (AHU), radiators in the corner offices and the lounge, and centrally controlled external blinds. A gas boiler generates the hot water for the TABS, the AHU heater and the radiators. The cold water for the TABS is provided by free cooling only using a cooling tower.

Preparation of building. The target building was prepared such as (i) to flexibly support the implementation of different high-level (supervisory) control strategies; (ii) to allow for a conclusive evaluation of the control experiments; and (iii) to support the validation of detailed building models. The instrumentation effort focused on the assessment of energy usage and occupant comfort in the five upper office floors of the building. Particularly detailed measurements were taken on the entire second floor. The existing low-level control software was adapted to accommodate all new sensors and actuators, and to provide a suitable interface for the newly introduced high-level control. Shortcomings of the existing system related to unnecessary cooling and erroneous energy recovery operation by the AHU, erroneous outside air temperature measurements, and one-pipe water circulation in the

TABS heating mixing circuit were fixed. The bulk of the work could be completed in September 2011, before testing of the novel control strategies started.

Modeling. Computer models were used for the simulation-based development, testing, tuning, and long-term performance and sensitivity assessment of the newly developed control strategies. Two main types of models were developed: (i) Comprehensive energy simulation models of the target building's entire second floor. They were based on the EnergyPlus (EP) software and simulation engine and included detailed representations of all relevant building physical processes. Validation and tuning of these models proved very challenging. Measurements of net energy usage depended on several highly uncertain disturbances and processes, and were not well reproduced. Room temperatures and their dynamics were, however, realistically simulated. The model's limited predictive accurracy proved not too critical since the developed control solutions were robust and general enough not to depend on the details of the target building. (ii) Simplified, physically based thermal resistance-capacitance (RC) models for use in Model Predictive Control (MPC). These were implemented within the MATLAB scientific computing environment using a modular, flexible modeling approach. Validation studies showed that the models reproduced both, EP simulated, as well as measured office room temperature dynamics very well. To simplify RC modeling specifically for MPC a method for the measurement-based estimation of solar heat fluxes through windows and an open source MATLAB toolbox were developed.

Development of control strategies. Controller development was based on a carefully designed interface between high- and low-level control, and a software development environment that made it possible to apply all developed high-level control programs without any changes either to the real building, or to a model of the building, respectively. Developed were four novel Rule Based Control (RBC) strategies of increasing complexity, and one novel MPC strategy. Three of the RBC strategies and the MPC strategy consider the building's thermal dynamics in combination with weather forecasts (predictive control) and handle multiple actuators and their interactions (integrated control).

Assessment of controller performance. Five different high-level control strategies – including the state-of-the-art, non-integrated reference strategy that was used on the target building prior to the start of the project – were operated under fully realistic conditions during fourteen different experimental subperiods in the timespan October 2011–April 2013. Without any exceptions, all novel control strategies were found to function reliably and correctly on the target building. Repeated feedback from the building owner and the facility manager showed that they were fully satisfied by the performance of all applied new control strategies. Measured Non-Renewable Primary Energy (NRPE) usage suggested a comparable energy efficiency for all novel strategies, and indicated an improvement compared to the reference strategy. Measured office room temperatures showed that all novel strategies provided a good thermal comfort and that they produced less overheating cases as compared to the (already well performing) reference control. This result was also confirmed by two web-based occupant surveys that were conducted in Autumn 2011 and Spring 2012, respectively. Both surveys showed that the general satisfaction with the building was high already prior to the start of the project, and that it remained so after novel RBC had been operating for three months. The novel strategies' control performance was further assessed by means of whole-year dynamic simulations. The found total NRPE savings for heating, ventilation, cooling, lighting and equipment, valid for buildings similar to the target building, were for the novel RBC between 10% and 15%, and for MPC around 17% of the value simulated under reference control (243 kWh m^{-2} a^{-1}) while providing a similar level of occupant comfort. Relative savings for monetary cost were in a similar range and corresponded to 1.4–1.8 CHF m^{-2} a^{-1} for RBC and 2.1 CHF m^{-2} a^{-1} for MPC using 2012 energy prices. When considering only heating, ventilation and cooling the NRPE savings amounted to 13%–20% for RBC and over 25% for MPC (reference value: 86 kWh m^{-2} a^{-1}). All simulated strategies (including the reference strategy) yielded similarly high levels of thermal comfort, but widely differing room temperature frequency distributions.

Load Shifting. Adaptation of control strategy RBC-2 based on a Pulse Width Modulation procedure made it possible to restrict TABS heating to an assumed low-tariff phase from 21:00 until 06:00 of the following day. Simulations assuming presence of a heat pump for heat production showed that for buildings similar to our target building and under a relatively modest high/low tariff rate ratio of 1.5 the monetary cost for TABS heating can be lowered by 24% and for electrical peak power by 4% (>10% for winter months), with practically no change in annual NRPE usage. The load shifting capabilities of the MPC strategy were tested directly on the building, by adjusting the MPC cost function such as to assume, again, heat production by a heat pump, and a diurnally varying price signal for electricity that featured two arbitrarily chosen low-price windows (04:00–06.30 and 21:00–01:30, respectively). MPC was found to successfully shift heating power demand as much as possible to the low-price windows while fully respecting thermal comfort constraints.

Integrated blind control. The importance of coordinating the blind operation with the actuation of all other HVAC system components (so-called integrated blind control) was investigated by means of annual simulations using the RBC-2 strategy and eight variations thereof. It was found that the novel integrated blind control strategies can be expected to save around 5%–10% NRPE and monetary cost for heating, cooling and lighting compared to non-integrated strategies while providing improved thermal comfort. The integrated blind control strategies can moreover be expected to increase acceptance by the office room users as compared to non-integrated strategies, because they support heating and cooling in a manner that can be much more easily understood by the occupants.

Benefit-cost analyses. The benefit of the novel RBC strategies lies in their better control performance and user acceptance, as well as their higher robustness with respect to control parameter settings, building system variations, and disturbances as compared to state-of-the-art solutions. However, they have somewhat higher investment cost, and they are more demanding in terms of engineering, commissioning and service. Their acceptance in practice will depend on the extent the additional complexity can be hidden behind easy understandable concepts, automated procedures and user-friendly interfaces, but also on the education level of control solution developers, planners, project and service engineers and facility managers. The MPC approach can be expected to modestly outperform the most advanced RBC strategies for buildings similar to the target building. Larger gains in performance can be expected on more complex buildings. The required initial investment in model development is however currently too high to justify deployment in everyday building projects on the basis of energy savings alone. Robustness of MPC with regard to modeling and other errors must and can be substantially improved by means of relatively simple extensions to the MPC formulation, but further research is needed in this area. The ease and flexibility with which cost functions, thermal comfort requirements, and other constraints can be modified in MPC opens up entire new possibilities for the adjustment of the trade-off between energy usage, monetary cost and thermal comfort in building control, and for the integration of buildings as responsive elements in future energy systems.

Outlook. Thanks to the compatibility of our results with state-of-the-art building automation systems and products we are confident that some of the newly developed RBC strategies will be incorporated in Siemens control products within the next one or two years. Future work in the field of advanced building control should focus on the following areas: (1) Development of advanced monitoring functionality for buildings and their automation systems; (2) Development of simpler tuning methods, or even of auto-tuning methods, for the control parameter settings of the novel RBC strategies with the goal to lower the required effort in the commissioning and service phases; (3) Adaptation of the novel RBC strategies to a range of additional HVAC/blinds/light applications based on implementation in real buildings and/or simulation studies; (4) Development of general methods and simple-to-use tools for setting up a robust MPC for any given building.

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1 Introduction

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The overall goal of the OptiControl project (2007-2013) was to develop and test tools, methods and novel strategies for improved building control, and in particular for predictive control that integrates weather forecasts. The project was carried out under the guideline that the resulting control concepts and prototype software can later be easily incorporated in commercial workflows and building automation systems.

The project brought together specialists from the ETH Zurich, Siemens Switzerland, Gruner AG, EMPA Materials Science & Technology, the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss), and Actelion Pharmaceuticals Ltd. A list of all participating persons can be found in [1].

After an initial evaluation of applications potentially suitable for weather-dependent predictive building control it was decided to focus the project on so-called Integrated Room Automation, a very general application that deals with the automated and integrated control of blinds, electric lighting, heating, cooling, and ventilation in office buildings.

The project was executed in two phases. The results of the first phase (OptiControl-I, 2007-2010) were, among other things, novel rule-based (RBC) and model predictive (MPC) control strategies, plus a general methodology for the simulation-assisted development and assessment of building controls. Extensive simulation studies suggested that the newly developed control approaches can significantly reduce energy usage and/or peak power demand while at the same time maintaining high occupant comfort ([2], [3]).

Here we report the results from the second phase (OptiControl-II, 2011-2013). While Phase I was entirely based on simulation studies the overall goal of Phase II was to implement and rigorously test control strategies similar to those developed in Phase I in a representative, fully functional Swiss office building. The demonstrator building was generously made available by the Swiss company Actelion Pharmaceuticals Ltd.

1.1 Overview of the OptiControl-II Project

The project's objectives were as follows:

1. Preparation and modeling of a representative Swiss office building for rigorous assessment of predictive control algorithms.
2. Demonstration of the feasibility of predictive control algorithms incorporating weather forecasts (proof that the algorithms can be successfully run on a representative building).
3. Performance assessment of the novel control algorithms in terms of total energy usage, energy costs, occupant comfort, reliability in operation, and peak power demand in practical operation.
4. Assessment of the novel control strategies' acceptance by the occupants, the facility manager and the building owner.
5. Benefit-cost analyses for building owners.

The overall approach taken was based on an iterative process that combined computer based modeling, model validation, controller development and simulation with stepwise controller deployment, carefully designed measuring campaigns and feedback from users.

The work was divided into the following packages: coordination and communication; preparation of the target building; modeling, simulation and control; design, execution and analysis of the field experiments; synthesis and reporting. A professional communication was established right from the beginning to ensure that the project gets appropriate visibility and that the interests of all stakeholders are respected [4].

1.2 Target Building

1.2.1 Description

The target building is a 6-storey office building (Figure 1-1, Table 1-1) that is owned and operated by Actelion Pharmaceuticals Ltd. It is located in Allschwil, close to Basle, Switzerland. During the research project it remained fully operational and was occupied by Actelion staff.

Figure 1-1: View of the target building from the south

The building was put into service in 2007. It has a simple rectangular groundplan with a total floor area of around 6'000 m^2. The ground floor hosts an entrance area, a kitchen and a personnel restaurant. Cellular offices for up to 3 people are located next to the facade of the upper floors. Meeting and facility rooms can be found in the core of the building.

The building is of heavy construction type. The glazing fraction of the façade is approximately 50%. Exterior venetian blinds are available that are controlled centrally. Their position can be overriden by the occupants.

Heating and cooling is mainly accomplished by means of Thermally Activated Building Systems (TABS), i.e. pipes buried in the concrete slabs of the floors carrying hot/cold water. The entire building is served by one single TABS-zone; the TABS massflow rate and supply water temperature are determined globally for the entire building. In corner offices and the lounges radiators are additionally available. For the radiators thermostatic control is used.

A central air handling unit (AHU) is available in order to guarantee hygienic minimal air change rates in all office rooms. It is operated during working hours only with a constant outdoor air flow rate. The AHU has a heat exchanger for return air heat/cold recovery, a heating coil in the supply air, and an evaporative cooler in the return air. Supply air temperature is determined globally for the entire building. There are no local reheating coils.

Table 1-1: Key characteristics of the OptiControl-II target building.

Building Characteristic	Value
Year of construction	2007
Number of levels	6
Conditioned floor area	6'035 m^2
Construction type	Heavy
Window area fraction	50%
Thermal insulation level (U-value)	0.32 $Wm^{-2}K^{-1}$
Insulation glazing (U-value)	1.34 $Wm^{-2}K^{-1}$
Solar heat gain coefficient windows (g-value)	0.6
Gas boiler maximum power	480 kW
Mechanical chiller maximum power	109 kW
Hybrid cooling tower maximum power	100 kW
Offices Air Handling Unit volumetric flow rate	18'400 m^3h^{-1}
Building total energy usage by gas boiler (Ø 2008-2012)[1]	46 kWh m^{-2} a^{-1}
Building total electricity usage (Ø 2009-2011)[2]	83 kWh m^{-2} a^{-1}

Occupancy dependent ventilation is available in the meeting rooms. Natural ventilation by manual opening of windows is possible in all office rooms.

A condensing gas boiler provides all heating energy for the TABS, the AHU heater and the radiators. The office cooling by TABS is based solely on night-cooling through a hybrid cooling tower. To reduce maintenance effort the tower was however operated prior to and throughout the project in the dry mode only.

1.2.2 Suitability

The building was chosen as a demonstrator building for the OptiControl project for several reasons:

- It was representative for many modern office buildings in Switzerland (see below).
- The owner and operator fully supported the implementation and testing of the new control strategies.
- At the beginning of the project the building was overall functioning correctly, and there was a good user acceptance of the original control strategy. This gave a valid baseline in order to assess possible energy savings and comfort improvements.

[1] Of which 68% are used for the ventilation and heating of offices and auxiliary spaces, 22% for the kitchen and personnel restaurant, and 10% for hot water production.

[2] Of which 65% are used for equipment, lighting and elevators, 20% by the kitchen, and 11% for air conditioning.

- The building's technical systems matched well the systems studied in the OptiControl-I project. Thus, in OptiControl-II the developed software tools and models could be reused, validated and further improved.
- A building automation system was in place.
- Last but not least, initial simulation studies had suggested a substantial potential for energy savings thanks to predictive control.

1.2.3 Representativity

The building can be considered as representative for Swiss conditions for several reasons:

- Location in a typical suburban industrial zone.
- Medium size, unpretentious architecture (compact design, typical number of floors, not a high-rise building, homogeneous façade, no overhangs or wings, flat roof).
- Typical floor layout (offices located at the façade, infrastructure rooms at the core).
- Typical wall to window area ratio (not a highly glazed office tower).
- Swiss average thermal insulation and glazing.
- No attached or detached shading.
- Representative building systems (usage of TABS for heating and cooling becomes more and more standard for Swiss and German office buildings).
- Uniform usage of upper floors.
- Typical occupancy and internal gains levels (close to SIA Standard 2024).
- Typical occupancy schedules (normal working hours, non-occupied at weekends).
- Typical combination of energy sources (natural gas plus electricity).
- Typical, state-of-the-art building automation system (limited number of sensors, basic automation functions present).

Perhaps the only atypical building characteristics are that there are a kitchen and a restaurant on the ground floor, and that there is only one TABS zone for the entire building.

1.2.4 Project Scope

The OptiContol-II project focused on the offices part of the building. The newly developed control strategies applied to, and were optimized for, the heating, cooling, ventilation, blinds operation and lighting of the five office levels.

In particular, the following energy consumers were outside the scope of the project: The heating, cooling and ventilation of the personnel restaurant and the kitchen, the hot water production, the ventilation of the auxiliary spaces, the exhaust fans, and general electricity consumers such as servers, office equipment, outside lighting and elevators.

1.3 Overview of the Report

This report synthesizes the results of the different work packages. It covers all main results of the OptiControl-II project. Partially, it references work that has already been or is about to be published. The report is structured as follows:

In Chapter 2 we present the preparation of the target building, as needed for the implementation and assessment of the novel control strategies.

Chapter 3 presents the adopted modeling strategy and the implementation and testing of the various computer models used in the project.

Chapter 4 reports the used development framework for building control, and presents the developed rule-based (RBC) and model predictive (MPC) control strategies and their implementation in the building.

Chapter 5 deals with the controller assessment: it addresses the performance assessment methodology, the measured and simulated performances of the novel control strategies, and the results from the user and occupant surveys.

In Chapter 6 we report further relevant results, in particular also results on the load shifting capabilities of the novel control strategies, and on the importance of integrating the blinds control into an overall control system.

Chapter 7 provides a benefit-cost analysis of the novel control strategies for the target building.

In Chapter 8 we give an overview of the publication and dissemination activities carried out in the course of the project.

Chapter 9 finally provides a summary and an overall assessment of the project's results.

1.4 References

[1] http://www.opticontrol.ethz.ch/06E-Participants.html

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[4] Treier, H., Meister, L. & Gut, A. (2011). Kommunikationskonzept OptiControl-II. Reflecta AG, Bern, Switzerland, 13 pp. http://www.opticontrol.ethz.ch/Lit/Trei_11_Rep-ReflectaAG_KKOptiControl.pdf

2 Preparation of Building

M. GWERDER & D. GYALISTRAS

At project start the control instrumentation of the building was analyzed and a concept on building preparation was elaborated. Since the building's original control instrumentation was not sufficient for the project's purposes substantial additional equipment – in particular sensors and meters – had to be installed. The preparation of the building was completed in September 2011.

2.1 Instrumentation

The instrumentation concept was set up with the following goals in mind: (i) to support the implementation of different high-level control strategies[3]; (ii) to allow for a conclusive evaluation of the control experiments; (iii) to support the validation of detailed building models.

The instrumentation effort focused on the detailed assessment of energy usage and occupant comfort in the five upper office floors of the building (OG1 to OG5). The ground floor, the basement floors and the core rooms (such as archives, WCs, stairways, IT rooms or interior meeting rooms) were not considered further.

Below follows the list of requirements from the original instrumentation concept, followed in each case by a brief description and discussion on how the requirement was satisfied:

Control

- *There is a clearly defined interface between high-level and low-level control.* This interface was very first defined at the conceptual level. This allowed us to implement the high-level algorithms in the high-level language MATLAB and to profit from the extensive development work already done in the forerunner project OptiControl-I. At the technical implementation level, the high-level and the low-level control were separated by running the former on an industry PC. Communication between control levels was accomplished through a BACnet-OPC server using MATLAB as an OPC client. Figure 2-1 shows the implemented control system topology with the industry PC and two newly introduced automation stations that were needed to integrate various new sensors and energy meters, as described later. The chosen, hierarchical control approach allowed us to leave the original low-level control essentially unchanged.
- *There is a robust fallback scenario.* High-level control was implemented such that switching back to the original control solution (that runs totally independent from the industry PC) should be possible at all times. Conditions considered for triggering an automated switch back to the original control solution included communication failure between control levels, or the failure of high-level control (e.g., problems with the high-level control algorithm, the underlying software, or the input data acquisition).

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[3] So-called high-level (supervisory) control takes care of major control decisions, e.g. "start heating up the building by maximizing solar gains". Low-level control takes care of subordinate tasks, such as starting up and shutting down of plants, fast closed loop control of given setpoints, plant protection functions (such as frost protection or wind protection), alarming etc.

- *Control is restricted to the one existing TABS zone in the building.* I.e. no additional zones or subzones were created. The main reasons for this were cost considerations and the fact that most TABS buildings typically have only one to a few zones. The presence of only one TABS zone has the advantage that experimentation with high-level control affects all offices within the building, such that feedback can be obtained from a large number of rooms and occupants. However, it has also disadvantages: precision of the actuation was limited, and we were not able to test the control strategies' ability to handle the extra complexity and cross coupling the would have arisen from multiple TABS.
- *Blind control is integrated in the building's automation system.* This was accomplished. However, integration of the blind control was limited by the facts that (i) the existing blind automation system supports integration of only a limited number of commands from the building automation system, and (ii) that it does not provide any feedback on current blind position, i.e. there is no means to signal user blind interactions to the control system.
- *The estimation of external and internal heat gains is supported.* To this end were installed, firstly, solar radiation sensors (one sensor per façade orientation, plus one measuring radiation on a horizontal pane), as well as illuminance sensors (one sensor per façade orientation). Secondly, occupant presence and electricity consumption by equipment and lighting were measured in a range of offices (see below).

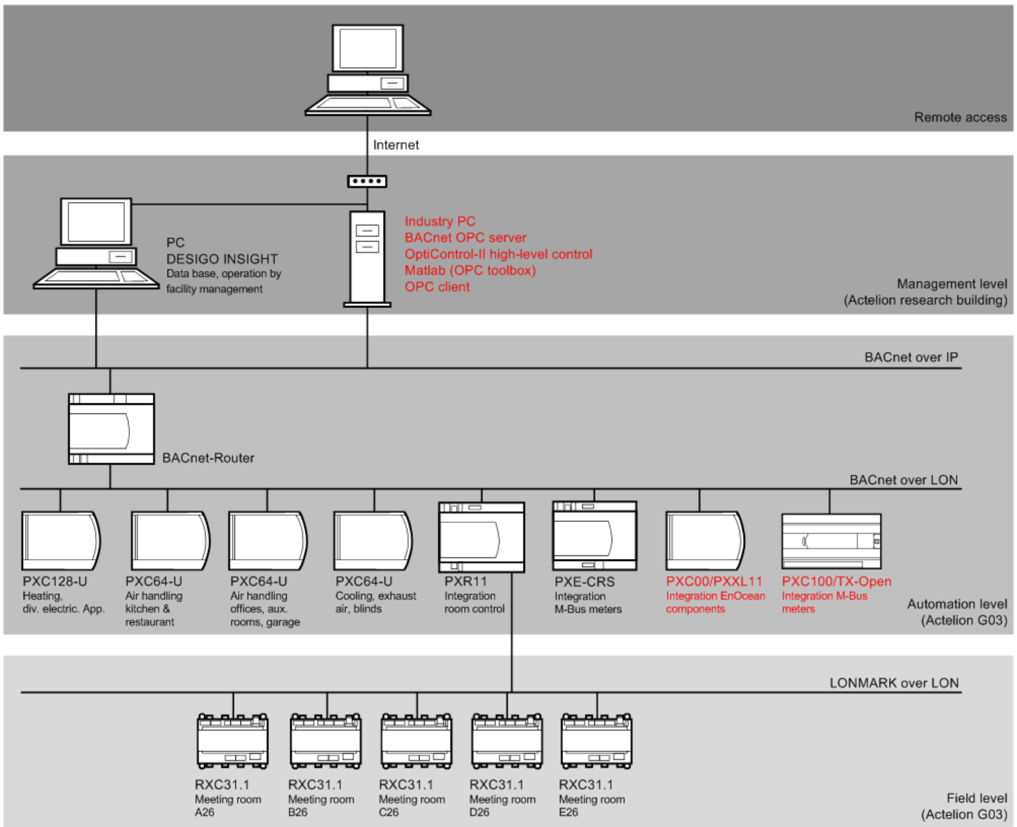

Figure 2-1: System topology (hardware, no actuators and sensors) of the Siemens building automation system in the Actelion G03 demonstrator building (new components in red).

Energy Usage

- *Overall heating and cooling energy consumption is measured.* All relevant heat and cold circuits were equipped with heat/cold meters: TABS heating, TABS cooling, static heating, and ventilation heating.

- *Overall electric energy consumption is measured.* Electrical energy meters were installed to measure electricity consumption per floor in all five upper floors. In addition, in the second floor electrical consumption by lighting and equipment was measured in each office individually, see Figure 2-2 (bottom right). The electricity consumptions of the fans, of the cooling tower and of the adiabatic cooler were also metered.

Figure 2-2: Additional equipment installed in offices: wireless room temperature sensor (left, next to the office door), wireless presence and illuminance sensor (top middle, at ceiling), wireless window contacts (top right, above the window), electrical energy meter for measuring consumption of electrical lighting (bottom right, within the media channel).

Comfort

- *Comfort measurements are done wirelessly and are limited to selected parts of the building.* This was decided in order to limit installation effort, costs, and impact on the occupants. We decided to focus on all offices of the second floor and selected offices on the first and fifth floors. All installed sensors were based on the EnOcean wireless technology. The standard configuration per office room consisted in measuring room temperature, presence, illuminance and window opening state (see Figure 2-2 for photographs taken in the building).
- *Indoor air quality is assessed mainly on the whole-building level.* Additional instrumentation related to the mechanical ventilation was thus installed to measure volumetric flow of supply and extract air, as well as CO_2 and VOC concentrations and relative humidity of extract air. At the single office level CO_2 concentration and relative humidity was measured only in three selected offices of the second floor using wireless EnOcean sensors.
- *The variation in average temperature across floors is assessed.* In all five upper floors two temperature sensors per floor were installed in the hallways. The temperature measurements in the hallways can be considered roughly representative for average floor temperature due to the mechanical ventilation induced air flow from the offices into the core zones of the building.

In summary, our approach allowed for an accurate assessment of energy consumption and comfort at two different levels of detail: at the whole building level, and in more detail at the floor level for the second floor. The second floor measurements can be considered representative because of very similar usage patterns across all five office floors.

2.2 Execution of Instrumentation Work

Execution of instrumentation work was done by Siemens Switzerland (lead, extension and adaption of building automation) and the subcontractor companies Griesser AG (blind control integration), Etavis AG (electrical installations) and Klima AG (sanitary installations). Actelion Pharmaceuticals Ltd granted and set-up remote access to the building automation system for the OptiControl-II project participants.

The bulk of the work was completed in September 2011. Subsequent testing revealed some problems with the integration of the energy meters. These problems were finally solved by January 2012.

Table 2-1 gives a list of the main additionally installed hardware components.

Table 2-1: List of main additionally installed hardware components.

Description	Hardware type	Hardware name	Count
Room temperature sensors	Sensor (wireless)	Siemens QAX95.4	29
Room temperature, rel. humidity and CO2 concentration sensors	Sensor (wireless)	Thermokon SR04 CO2	3
Presence and indoor illuminance sensors	Sensor (wireless)	Thermokon SR-MDS	19
Outdoor illuminance sensors	Sensor (wireless)	Thermokon SR65 LI	4
Window contacts	Sensor (wireless)	Thermokon SRW01	31
Electrical energy meters to measure consumption for illuminance	Sensor	Elko MIZ	18
Other electrical energy meters	Sensor	Elko KIZ	13
Solar radiation sensors	Sensor	Siemens QLS60	5
Heat/cold meters	Sensor	Siemens WSM	4
Differential pressure sensors to measure volumetric flow	Sensor	Siemens QBM65-10 (dP)	2
Air duct temperature sensor	Sensor	Siemens QAM2120.040	1
Air duct humidity sensor	Sensor	Siemens QFM2100	1
Air duct CO2/VOC concentration sensor	Sensor	Siemens QPM2102	1
Griesser I/O modules for blind control integration	I/O module	Griesser FS-4I Flexmodul Slave	6
Automation station for wireless sensors integration	Control device	Siemens PXC00	1
Automation station for meter integration	Control device	Siemens PXC100	1
Industry PC	PC	Fujitsu Server TX100	1

Additional sensors for control and monitoring included wireless room sensors (room temperature, CO_2 concentration, humidity, luminance, presence detection, window opening detection), outside condition sensors (solar radiation, illuminance), electricity meters (meters to measure consumption for artificial lighting, meters to measure consumption of electrical consumers in the offices and of cold generation), heat and cold meters, as well as additional sensors for the Air Handling Unit (AHU) supplying the offices.

Additional actuators were installed to integrate blind control and cooling tower control into the building automation control system.

Besides the sensors and actuators, additional control hardware was installed to integrate the new sensors and actuators. Moreover, the industry PC for the high-level control was installed in the Facility Management center. The PC was coupled to the building automation network and software for control and communication was installed (cf. Figure 2-1).

2.3 Adaptation and Correction of Original Control Software

The existing low-level control software had to be adapted, first, to integrate all new sensors and to monitor and log the corresponding data points; second, to integrate all new actuators; and third, to provide a suitable interface for the high-level control.

The high-level control interface was specified and implemented from scratch. It provides functions for the setting of operating modes, setpoints and blind commands which are further processed in the low-level control.

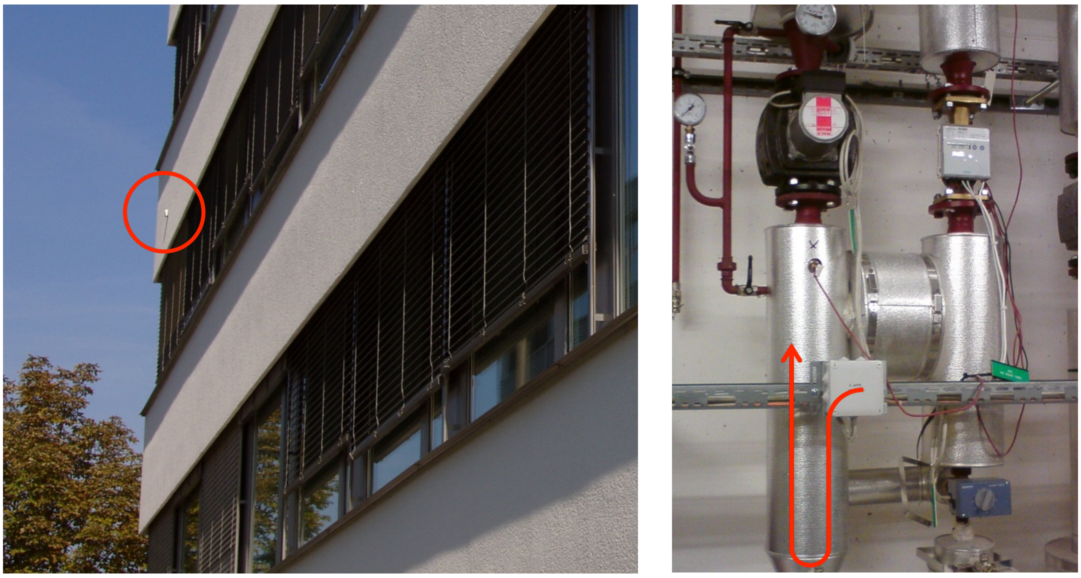

Figure 2-3: Outside air temperature sensor affected by direct solar radiation (left), TABS heating distribution with one-pipe water circulation (right, arrow indicates water flow in the concerned pipe).

The following shortcomings were detected in the process of analyzing the original plant behavior and control software:

- *Unnecessary cooling with the adiabatic cooler in mechanical ventilation*: Return air was cooled even in cases where cooling could have been accomplished at no additional cost by using outside air.
- *Inefficient cooling due to erroneous energy recovery operation*: Cold recovery was not always fully activated when the return air adiabatic cooler in mechanical ventilation was running.
- *Outside air temperature measurement error*: It was found that the outside air temperature sensors were occasionally exposed to direct solar radiation, see Figure 2-3 (left). This resulted in an overestimation of outside air temperature and may have ultimately caused insufficient heating and/or wrong energy recovery operation in mechanical ventilation.

  We found that the outside air temperature can be estimated much more accurately by using the minimal measured value from the following four temperature sensors: the two sensors located at the target building (Actelion building G03), plus two further sensors located at a neighboring building (Actelion building H91).

- *One-pipe water circulation in TABS heating mixing circuit*. After installing a heat meter in the TABS heating distribution, heat power input to TABS of up to 20 kW was detected even when the mixing valve was completely closed (purge operation). It turned out that this was due to the occurrence of one-pipe water circulation in the distribution system, see Figure 2-3 (right).

We decided to correct the first three of these shortcomings as a first measure to improve the building automation. This was done before high-level control was activated for the first time.

To minimize impact of the fourth shortcoming, we extended the building automation software by implementing a pulse width modulation (PWM) procedure for the TABS heating operation. PWM helps to reduce the undesired heat input into the TABS because during periods where the circulation is switched off (most frequently during spring and autumn) heat transfer is interrupted. The undesired heat input was also further reduced by usage of room temperature feedback for controlling the TABS, since the latter switched off the heating more frequently by lowering the heating limit (highest outside air temperature under which heating is enabled) when room temperatures are high.

3 Modeling

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Modeling of the target building was central to the OptiControl project for several reasons. Firstly, the models were indispensible tools for the simulation-based development, testing and tuning of the newly developed control strategies. Secondly they were used for "what-if" analyses and sensitivity tests that could not have been readily performed with the real building without compromising occupant comfort, or due to constraints in the available time and money. Finally, they were used to study the building's behavior over sufficiently long periods (typically a whole year) in order to derive robust estimates of (differences in) energy usage and occupant comfort for different controllers.

In the following Section 3.1 we first introduce the two main types of models used in the project and comment on their scope. Sections 3.2 and 3.3 give more detailed descriptions of these models. During the course of the project it became clear that the needed modeling effort presents a major obstacle for the routine application of Model Predictive Control (MPC) to buildings. Section 3.4 describes some methods developed in order to reduce this effort.

3.1 Model Types and Scope

The two types of models considered were:

1. Whole building energy simulation models. These models included detailed representations of all relevant building physical processes. They were based on the EnergyPlus (EP) software and simulation engine that is developed and maintained by the US Departement of Energy. Further information can be obtained from [1].
2. Thermal resistance-capacitance (RC) models. These models implement various simplifications as compared to the EP models, such as the pooling of radiative and convective energy fluxes and simplified heat transfer and transmission calculations. A description and evaluation of the adopted RC modeling approach is given in [1].

The detailed building energy simulation models allowed for extensive testing and initial tuning of the newly developed control strategies in a virtual reality before applying them to the real building. In addition, they served as a starting point and as a reference for deriving the much simpler RC models that are at the core of the Model Predictive Control (MPC) procedure.

Two kinds of RC models were developed: a fully detailed Resistance-Capacitance model (fRC) and an associated low order reduced model (rRC) for use in online calculations.

Figure 3-1 gives an overview of the different models generated. The arrows indicate various conducted comparisons between models or with measurements from the real building. The comparisons "rRC–real" and "rRC-EP" were omitted because of the very similar performance of rRC and fRC.

Table 3-1 summarizes the properties of the various models. In short, EP should be closest to reality, but it is not applicable for MPC; fRC is applicable for MPC but cannot be readily used for the estimation of the system's thermal state (a step required in the context of MPC); and rRC is applicable for both, state estimation and MPC, while presenting only an approximation (albeit a good one) to fRC.

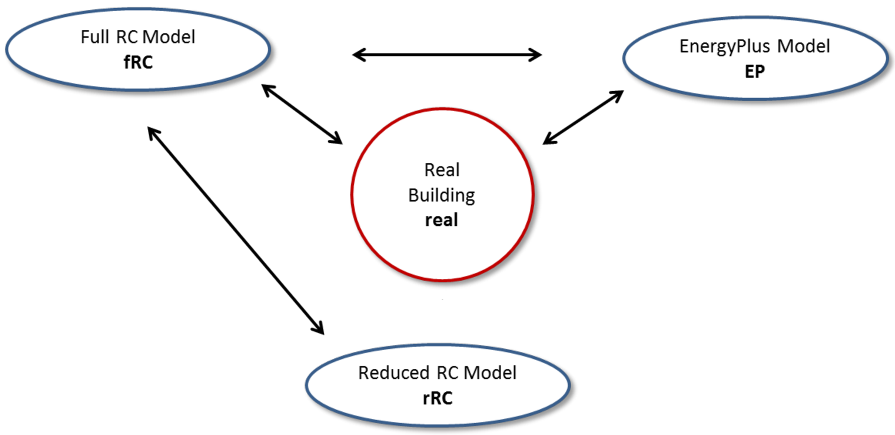


Figure 3-1: Overview of building models and comparisons.

Table 3-1: Properties of the various building models

Model	Advantages	Limitations
EP	• Very detailed nonlinear model → Able to take into account a wide range of physical phenomena • Industry standard • Expected to have the smallest model-reality mismatch of the considered models • Can serve as “truth” model, for experiments which are not possible on the real building	• Cannot be used as MPC model • Restricted modeling flexibility due to built-in black-box components and low-level controllers
fRC	• Bilinear model → can be used as an MPC model • Built from physical first principles • Easy to modify	• Contains too many states to be reliably estimated online • Restriction to bilinear modeling
rRC	• Bilinear model → can be used as an MPC model • Few enough states for use in a state estimator • Can be derived from fRC with modest effort.	• Slightly different behavior than fRC • States do not have a physical interpretation

All models focused on the target building’s second floor. This was due to several reasons:

- By focusing on a single floor we were able to account for all relevant physical processes and actuation details while keeping the computing and post-processing requirements comparatively low. The use of a whole-building model would have required much more resources, while providing only little additional insight into the building’s dynamics and sensitivity to control.
- Another alternative to a single floor model would have been to consider individual building zones in isolation. However, we did not employ this approach in order not to miss important interactions between the zones given the relatively small size of the building (surface area of ca. 32 x 24 meters). A second reason why we chose to consider the simultaneous thermal dynamics of all zones was the presence of a single Thermally Activated Building System (TABS) zone for the entire building.
- The second floor is representative for the overall building usage and it does not include any special facilities (e.g. restaurants, technical spaces).
- There are no interferences from the ground floor or the roof.
- The second floor was the best instrumented and monitored part of the building, while instrumentation on all other floors was restricted to a minimum.

An important requirement to the models was that they should support usage of the same high-level control code for simulation as well as for application to the real building. We chose the following set-up in order to satisfy this requirement: For detailed building energy modeling we used the EP software (see above). For controller development and operation we used the MATLAB scientific computing environment [3]. For run-time coupling of the two environments we used a co-simulation approach based on the Building Controls Virtual Testbed (BCVTB) middleware developed by the Lawrence Berkeley National Laboratory [4].

3.2 Detailed EnergyPlus Simulation Model

3.2.1 Overview

The detailed energy simulation model was based on Version 7.0 of the EP software. It focused on the target building's second floor that is mainly used for office space. Other building floors as well as neighboring buildings were integrated for the sole purpose of modeling building shading correctly. The building's location relative to the neighboring buildings and the used zoning are shown in Figure 3-2, respectively.

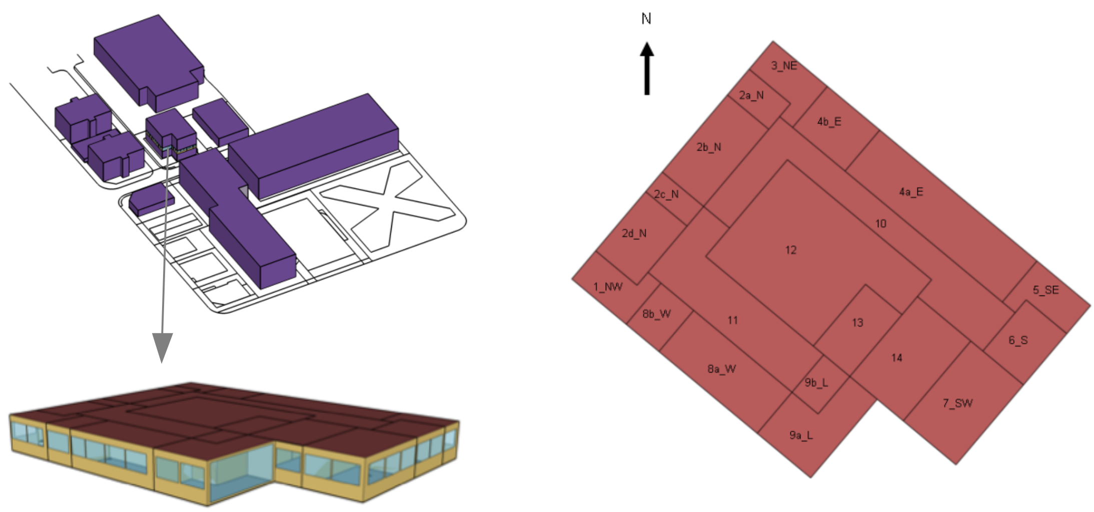


Figure 3-2: Left: Location of the target building "Actelion G03" (top) and representation of its second floor in the EnergyPlus modeling environment (bottom). Right: Zone layout of the target building's second floor. Neighboring buildings were considered for shading calculations only.

The zoning was based on façade orientation. There were considered 20 thermal zones in total. Additional subzones for the non-corner zones were necessary to accurately model mechanical ventilation and the use of the hall as a return air plenum. All zones were thermally coupled. Only floors and ceilings were assumed to be adiabatic.

The model was constructed such as to fit the control of the building's heating, ventilation and air-conditioning systems (HVAC) as closely as possible. In particular all HVAC components were scaled to fit the needs of the second floor only.

Model development was a stepwise process that resulted into three EP models, M1 to M3. They differed in their scope and the amount of detail included.

Model M1 considered but the building's geometry and construction and it was bare of any HVAC components. It was used to simulate the basic thermal dynamics of the building and provided the starting point for the development of an initial RC model (see Section 3.3).

Model M2 resulted by enhancing model M1 by various HVAC components. However, due to limitations in the default modeling capabilities of EP, this model did not appropriately represent the building's AHU.

Therefore a custom AHU submodel had to be developed, and this resulted into the new overall model M3. For the M3 model also the full interface to BCVTB was implemented. Model M3 was thus the most complete and detailed model derived in the project.

In Section 3.2.2 we present the M3 model in more detail. A detailed schematic of the HVAC systems modeled can be found in Section 3.6 (Appendix).

The model was validated using detailed measurements from the building. Since the measurements became increasingly available during the course of the project we were able to continuously improve and refine the model, a process that is described in Section 3.2.3.

3.2.2 Model Description

3.2.2.1 Interface to Building Controls

In order to drive the EP model with measured external data and to be able to use precisely the same control as implemented in the target building the model was coupled to the MATLAB scientific computing environment using the BCVTB software. A detailed description of the co-simulation set-up can be found in [5].

The EP interface to BCVTB allowed setting of all high-level control inputs (such as operating modes and setpoints) and of selected low-level control inputs (such as TABS massflow rates) from within MATLAB (Figure 3-3, see also Section 4.1).

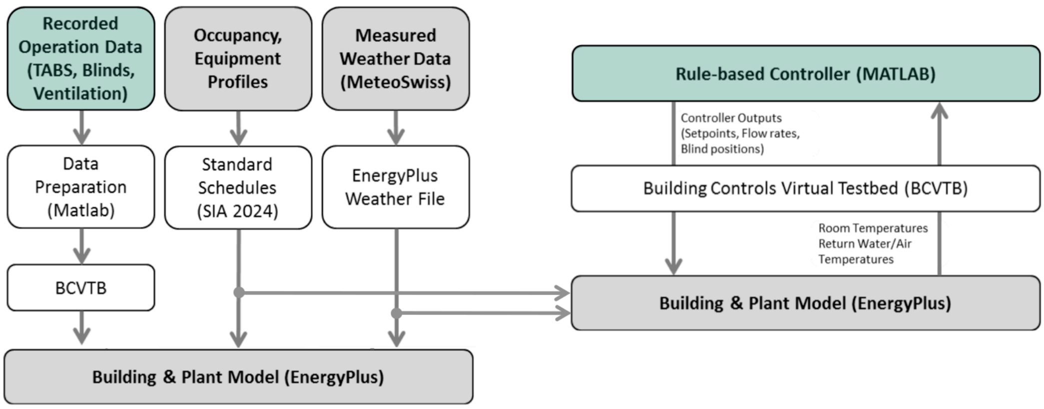


Figure 3-3: Schematic of the signal flows in open (left) and closed loop control (right) simulations used with the implemented co-simulation environment. Note: weather data, occupancy and equipment profiles were also used as inputs in the closed loop control simulations, but for the sake simplicity are not shown in the right-hand part of the figure.

Two kind of simulations were performed: Open loop control (OLC) simulations, where the model was entirely driven by measured control signals for TABS, blinds and ventilation; and closed loop control (CLC) simulations where the model was controlled by the same rule-based or model predictive control procedure as used in the real building (Figure 3-3).

Open loop control was mainly used for model validation, while closed loop simulations were used for model validation and controller development. Both kinds of simulations were driven by measured weather data plus pre-determined, weekly recurring hourly schedules for occupancy and internal loads.

The need to specify low-level control inputs was due to the fact that the EP model invokes at every single integration step a series of proprietary submodels that are solved iteratively using a smaller internal time step. It showed that with regard to the operation of the AHU and of the TABS (in particular the switching between the heating and the cooling modes) the EP model operated internally in a different way than the target building's automation system.

Therefore, these two low-level control loops had to be simulated explicitly. On the side of MATLAB this required an intermediate layer of functions for translating the high-level control decisions into EP specific terms. On the EP side the fast low-level controls were coded using the "EnergyManagementSystem" (EMS) programming features of EP.

All other low-level control decisions (e.g. lighting control, radiators) were kept in the EP control domain.

Thanks to the used modular modeling approach [5] the EP model inputs and outputs could be flexibly defined depending on the currently used controller. In total, up to 294 MATLAB signals were sent to the EP model (Table 3-2). In return, up to 1'081 EP signals representing controler inputs and/or diagnostic outputs were sent to MATLAB.

Table 3-2: Input variables used to drive the EnergyPlus model

Subsystem	Variable	Unit
Blinds	Blind Position (On/Off) Blind Slat Angle	[-] [deg]
TABS	Cooling Availability Heating Availability Cooling Supply Water Temperature Setpoint Heating Supply Water Temperature Setpoint Zone Water Mass Flow Rate	[-] [-] [degC] [degC] [kg/s]
Radiators	Heating Availability Heating Supply Water Temperature Setpoint Room Temperature Thermostat (Upper Bound) Room Temperature Thermostat (Lower Bound)	[-] [degC] [degC] [degC]
Mechanical Ventilation	Fan Air Mass Flow Rate Energy Recovery Supply Air Temperature Setpoint Supply Air Temperature Setpoint Heating Supply Air Temperature Setpoint Cooling	[kg/s] [degC] [degC] [degC]
Internal Gains	Internal Gains Level (Lighting, Equipment) Internal Gains Fraction (Schedule Value) Number of People	[W] [-] [-]
Weather	Outdoor Dry Bulb Temperature Outdoor Humidity Ratio Outdoor Dewpoint Temperature Wind Speed Wind Direction Direct Solar Radiation Diffuse Solar Radiation	[degC] [%] [degC] [m/s] [deg] [W/m2] [W/m2]

The model was typically driven by external data at a time step of 15 minutes (note that EP uses internally a smaller time step to ensure numerical convergence of the results). The 15 minutes time step was chosen to minimize computational effort for model integration and co-simulation. Use of shorter time steps down to one minute was found to have no significant effect on the key validation statistics reported in Section 3.2.3.

For access to the control variables in the EnergyPlus model via the BCVTB interface we used the `ExternalInterface` object types.

3.2.2.2 Building Construction and Façade

For the modeling of the building's construction and façade the original planning data was used whenever available. Otherwise, default construction details for Swiss standard office buildings were used as reported in [6]. This procedure resulted into the following key figures:

- Window/wall ratio: 50%
- Thermal insulation level walls: 0.32 [W/m^{2}K]
- Thermal insulation level windows: 1.34 [W/m^{2}K]
- Solar heat gain coefficient windows: 0.60 [-]
- Construction type: heavy weight
- Outdoor air infiltration 0.1 [1/h]

The main EnergyPlus submodels and components used were:

- Constructions: `Construction`, `Construction:InternalSource`, `InternalMass`
- Glazing: `WindowMaterial:Glazing`
- Outdoor air infiltration: `ZoneInfiltration:DesignFlowRate`

3.2.2.3 Blinds

All modeled windows had an exterior shading. As in the real building, office windows in the model were equipped with venetian blinds (type “Griesser Lamisol 70” of colour “VSR 140” with opaque slats, width 7 cm, and a solar reflectance factor of 0.55), whereas windows in the lobby were equipped with shades (types “Griesser Sigara” and “Soltis 92-2045” with a solar transmittance factor of 0.03).

Blinds and shades were controlled by means of high-level control. Closed blinds and shades were always assumed to cover 100% of the glazing area. For venetian blinds the high level control was used to set next to the blind position also the blind slat angle.

In the model the blinds for each individual window could be set individually. Also, no limitations applied to the blind slat angles. However, artificial limitations were introduced to account for the fact that the blind automation system in the real building supported but a limited number of commands from the building's automation system (see Section 4.1.5.1).

The main EnergyPlus submodels and components used were:

- Blinds: `WindowMaterial:Blind`
- Shades (Lobby): `WindowMaterial:Shade`

3.2.2.4 Thermally Activated Building Systems (TABS)

As is the case with the real building all modeled office zones and the lounge were primarily heated and cooled with the aid of TABS. A single TABS zone serves the real building such that a single supply water temperature and water flow rate were determined also in the model for all zones. Again, as in reality, considered was a constant flow on/off system with no secondary mixing valves or pumps.

Available planning data on the TABS was limited, such that the water flow rates per zone were estimated based on zone areas. The entire second floor is served by ca. 2'600 l/h and 4'200 l/h in the heating and cooling modes, respectively. In both cases the used temperature difference for design was 3K. As in the real building, in the model the operating mode (on/off) and supply water temperature setpoints were set by high-level control.

The main EnergyPlus submodels and components used were:

- Cooling Source: `FluidCooler:SingleSpeed`
- Heating Source: `DistrictHeating`
- Pump: `Pump:VariableSpeed`
- Zone Equipment: `ZoneHVAC:LowTemperatureRadiant:VariableFlow`

3.2.2.5 Radiators

The corner offices and the lounge included radiators using thermostatic control. The used nominal heating capacities are shown in Table 3-3. The modeled room thermostats used dual setpoints with an upper and lower room temperature bound that could both be set by high-level control.

Table 3-3: Radiator heating power

Zone Name	Radiator Heating Power [W]
Zone 01 Office NW	638
Zone 03 Office NE	638
Zone 05 Office SE	638
Zone 07 Office SW	1914
Zone 09a Lounge	2304

The main EnergyPlus submodels and components used were:

- Heating Source: `DistrictHeating`
- Pump: `Pump:VariableSpeed`
- Zone Equipment: `ZoneHVAC:Baseboard:Convective:Water`

3.2.2.6 Mechanical Ventilation

According to the situation in the real building we modeled a single central Air Handling Unit (AHU) that served all offices of the second floor. Table 3-4 gives an overview of the used supply air flow rates for each zone.

Table 3-4: Used supply air flow rates for the various model zones

Zone Name	Supply Air Flow Rate [m3/h]
Zone 01 Office NW	160
Zone 02a Office N	80
Zone 02b Office N	240
Zone 02c Office N	80

Zone Name	Supply Air Flow Rate [m3/h]
Zone 05 Office SE	160
Zone 06 Office S	160
Zone 07 Office SW	750
Zone 08a Office W	300

Zone Name	Supply Air Flow Rate [m3/h]
Zone 02d Office N	160
Zone 03 Office NE	160
Zone 04a Office E	480
Zone 04b Office E	160

Zone Name	Supply Air Flow Rate [m3/h]
Zone 08b Office W	100
Zone 09a Lounge	520
Zone 09b Lounge	120

The AHU in the real building was designed to ensure room air quality only, such that more or less constant outdoor air flow rates apply to all offices. The only exceptions are variable air flow rates in the South-West meeting rooms at each floor. For the sake of simplicity this feature was however not included in the model. Zone-specific air flow rates in the model were set to constant values based on planning data. The hallway and the building core served as a return air plenum.

The AHU in the real building uses an evaporative cooler in the return air for cooling, a heat exchanger for return air heat or cold recovery, and a heating coil in the supply air for air treatment (Figure 3-4). Supply air temperature is determined globally for the entire building, i.e. there are no local reheating coils.

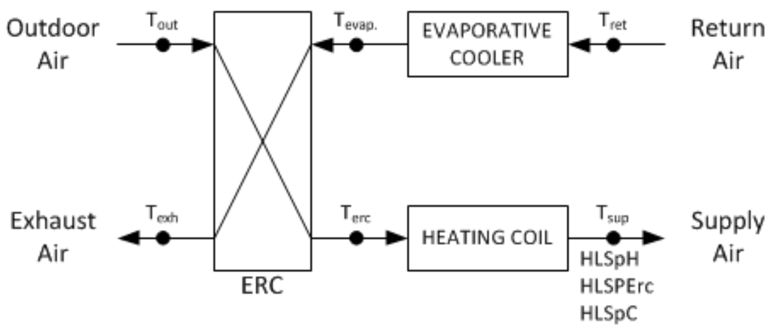


Figure 3-4: Schematic of the target building's Air Handling Unit

The operation of the energy recovery, heating coil and evaporative cooler are determined depending on the return air temperature (T_{ret}). Different supply air temperature setpoints are used depending on whether the system operates in the heating (HLSpH), cooling (HLSpC) or energy recovery (HLSpErc) mode.

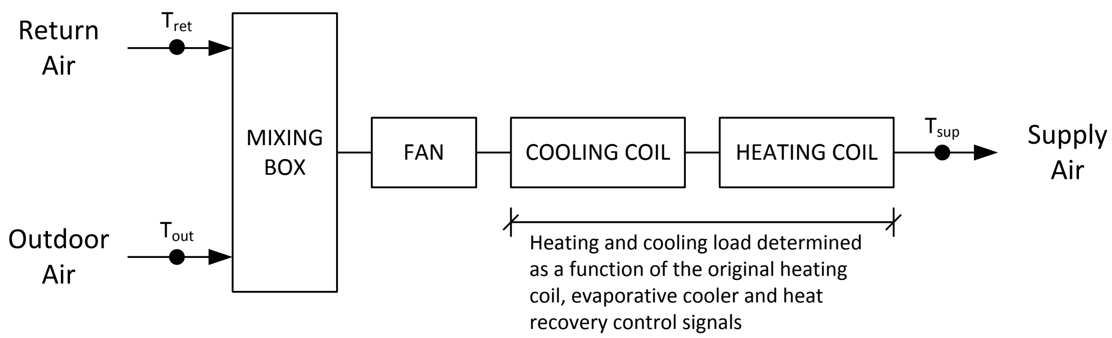


Figure 3-5: Schematic of the Air Handling Unit modeled in EnergyPlus

The AHU was implemented by a custom submodel that was coded in the EMS programing language of EP. In this submodel the original air heat exchanger, the evaporative cooler and the heating coil were replaced by one heating and one cooling coil, respectively, that were both situated in the supply air stream (Figure 3-5).

The idealized coils were operated such as to impose whatever supply air temperature would have been achieved by the original AHU. Their heating and cooling power was determined in an EMS program (see below). The AHU submodel always assumed 100% outdoor air flow, as is the case in the real system. The mixing box shown in Figure 3-5 was only introduced for numerical stability of the EP model.

The AHU submodel was based on the following assumptions:

- Supply and return air flow rate are always balanced
- Energy transfer in evaporative cooler and energy recovery is assumed to be instantaneous (no heat capacity taken into account)
- Energy recovery efficiency is assumed constant
- Evaporative cooler efficiency is assumed constant
- Energy recovery does not include humidity recovery

Below follow the equations of the AHU model coded as an EMS program within EP. They show the calculation of the control variables u_h, u_c, and u_{erc} of the original AHU subsystem (Figure 3-4) that were finally used to determine the supply air temperature and the associated coil heating and cooling power of the simplified model (Figure 3-5).

The first step consisted in determining the Energy Recovery (ERC) operation mode (heating or cooling) that would occur in the real system in absence of any heating/cooling actions:

if $(T_{ret} < T_{out})$ // ERC operates in cooling mode

  $T_{ErcL} = \Phi * (T_{ret} - T_{out}) + T_{out}$

  $T_{ErcH} = T_{out}$

else // ERC operates in heating mode

  $T_{ErcL} = T_{out}$

  $T_{ErcH} = \Phi * (T_{ret} - T_{out}) + T_{out}$

end

$$u_{ERC} = \min\left(1, \frac{HLSpErc - T_{out}}{\Phi * (T_{ret} - T_{out})}\right)$$

$$dT_{\max} = T_{ret} - T_{wetbulb}$$

where

Φ	Efficiency of the heat exchanger (const)	default value: 0.75
$dT_{\max}$	Maximal cooling rate, $f(T_{ret}, T_{wetbulb})$	
T_{ret}	Return air temperature	
T_{out}	Outside air temperature	
$T_{wetbulb}$	Outside air wet bulb temperature	
T_{ErcL}	Lowest temperature which can be reached only through ERC	
T_{ErcH}	Highest temperature which can be reached only through ERC	
u_{ERC}	ERC usage factor given no other heating or cooling actions present (range [0..1]; $u_{ERC} = 0$: outside air used without any ERC heat exchange)	

$HLSpErc$	Energy recovery temperature setpoint (specified by the high-level control)

In a second step the three heating/cooling control variables and the supply air temperature

u_h	Control variable of the heater (range [0..1])
u_c	Control variable of the cooler (range [0..1])
u_{erc}	Control variable for ERC usage factor (range [0..1]; $u_{erc}=0$: outside air used without any ERC heat exchange)
$T_{\sup}$	Supply air temperature

were computed according to

if $((T_{ErcL} < HLSpC) \& (T_{ErcH} > HLSpH))$ // Only ERC

$u_{erc} = \max(0, u_{ERC})$

$u_h = 0$

$u_c = 0$

$T_{\sup} = T_{out}$

else if $(T_{ErcL} > HLSpC)$ // Cooling mode

if $\left(T_{ret} - \eta_{evap} * dT_{\max} \geq T_{out}\right)$ // Cooler is blocked

$u_{erc} = 0;\ \ u_c = 0;\ \ u_h = 0;\ \ T_{\sup} = T_{out}$

else // Cooler is available

$u_{erc} = 1$

$$u_c = \min\left(1, \frac{T_{ret} - T_{out} + \dfrac{T_{out} - HLSpC}{\Phi}}{dT_{\max} * \eta_{evap}}\right)$$

$u_h = 0$

$T_{\sup} = \Phi * (T_{ret} - u_c * \eta_{evap} * dT_{\max} - T_{out}) + T_{out}$

end

else // Heating mode

if $(T_{ret} > T_{out})$ // with preheating

$u_{erc} = 1$

else

$u_{erc} = 0$ // without preheating

end

$u_c = 0$

$$u_h = \min\left(1, \frac{HLSpH - u_{erc} * \Phi(T_{ret} - T_{out}) - T_{out}}{\dot{Q}_{\max}} \dot{m}_{air} * c_{air}\right)$$

$$T_{\sup} = \frac{u_h * \dot{Q}_{\max}}{\dot{m}_{air} * c_{air}} + u_{erc} * \Phi * (T_{ret} - T_{out}) + T_{out}$$

end

where

η_{evap}	Efficiency of the evaporative cooler (const)	default value: 0.8
$HLSpC$	Temperature setpoint for cooling (specified by the high-level control)	

$HLSpH$	Temperature setpoint for heating (specified by the high-level control)
$\dot{Q}_{\max}$	Maximum heating power of the heating coil
$\dot{m}_{air}$	Mass flow rate of air
c_{air}	Heat capacity of air

A series of further variables were computed as follows:

// T_{evap} Evaporative cooler outlet temperature and
// T_{exh} ERC exhaust air temperature
// Q_{erc} ERC power (hPowERC, cPowERC)
// $Q_{erc} > 0$: heating; $Q_{erc} < 0$: cooling

if $(evapCoolerMode = "OFF")$

$$T_{evap} = T_{ret}$$
$$T_{exh} = T_{ret} - u_{erc} * \Phi * (T_{ret} - T_{out})$$
$$Q_{erc} = u_{erc} * \dot{m}_{air} * c_{air} * \Phi * (T_{ret} - T_{out})$$

else

$$T_{evap} = T_{ret} - u_c * dT_{\max} * \eta_{evap}$$
$$T_{exh} = T_{evap} - u_{erc} * \Phi * (T_{evap} - T_{out})$$
$$Q_{erc} = u_{erc} * \dot{m}_{air} * c_{air} * \Phi * (T_{ret} - u_c * dT_{\max} * \eta_{evap} - T_{out})$$

end

// Heating Coil Power (hPowMev)

$$Q_h = u_h * \dot{m}_{air} * c_{air} * (T_{Sup} - u_{erc} * \Phi * (T_{ret} - T_{out}) - T_{out})$$

// Evaporative Cooling Power (cPowMev)

$$Q_c = u_c * \dot{m}_{air} * c_{air} * dT_{\max} * \eta_{evap}$$

The main EnergyPlus submodels and components used were:

- Heating Coil: `Coil:Heating:Water`
- Cooling Coil: `Coil:Cooling:Water`
- Evaporative Cooler: custom model (see code above)
- Cooling Source: `DistrictCooling`
- Heating Source: `DistrictHeating`
- Fan: `Fan:VariableVolume`
- Air Distribution Unit: `ZoneHVAC:AirDistributionUnit`
- Supply air outlet: `AirTerminal:SingleDuct:VAV:NoReheat`

Measurements from the building showed that the temperature of the supply air is significantly modified on its way through the central shaft and partially also through air ducts embedded in the ceiling before entering a zone. Subsequent impacts on AHU modeling are described in Section 3.2.3.

3.2.2.7 Natural Ventilation

Natural ventilation due to possible window openings by occupants was modeled using the simple natural ventilation submodel available in EP. In most simulation studies, however, natural ventilation was not taken into account due to poor knowledge of the occupants' behavior.

An analysis of window contact sensor data became only available towards the end of the project, suggesting that during August and September 2012 on ca. 45% of all days where an office was occupied at least one window had been opened for at least 5 hours.

3.2.2.8 Heat and Cold Generation

All heating consumers in the real building are served by a central gas boiler. The latter was not modeled in detail; instead we considered an ideal heating source with a maximum power of approximately 9.1 kW. This figure was derived by scaling the real gas boiler's maximum power by the floor area fraction of the second floor. The boiler's efficiency was considered for cost analysis, however (see Section 5.5.1).

Cooling energy for cooling with TABS is provided in the real building by a dry cooling tower located at the building's roof. The tower may only be operated at night. It was modeled by using the standard EnergyPlus fluid cooler model with a nominal maximum power of approximately 14.7 kW (scaled to the second floor).

The main EnergyPlus submodels and components used were:

- Gas boiler: `DistrictHeating`
- Cooling tower: `FluidCooler:SingleSpeed`

3.2.2.9 Thermal Comfort

Room temperature setpoints were set by high-level control and they varied between approximately 21°C (heating) and 26°C (cooling).

They were imposed based on the EP `ThermostatSetpoint:DualSetpoint` model.

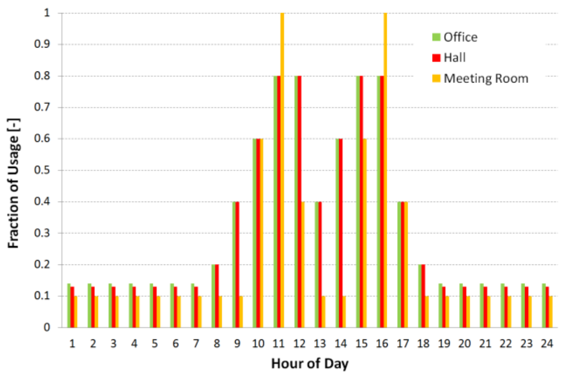
3.2.2.10 Internal Gains

Internal gains due to occupancy, lighting and electric equipment were introduced based on number of workplaces, installed equipment and Swiss standard usage schedules as provided by SIA [7]. The assumed internal gains levels design values are summarized in Table 3-5.

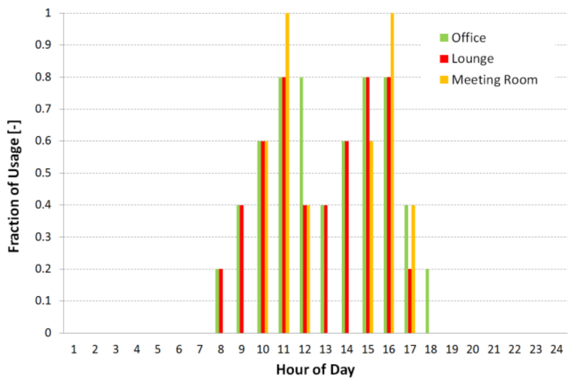
Table 3-5: Internal gains levels design values used in the model

Zone Name	Floor Area [m2]	Number of People [–]	Lighting [W/m2]	Equipment [W/m2]
Zone 01 Office NW	17.79	2	8.4	7
Zone 02a Office N	11.13	1	8.4	7
Zone 02b Office N	33.32	3	8.4	7
Zone 02c Office N	8.47	1	8.4	7
Zone 02d Office N	25.58	3	8.4	7
Zone 03 Office NE	17.75	2	8.4	7
Zone 04a Office E	67.44	9	8.4	7
Zone 04b Office E	22.48	3	8.4	7
Zone 05 Office SE	17.51	2	8.4	7
Zone 06 Office S	21.75	3	8.4	7
Zone 07 Office SW	43.99	12	8.4	3

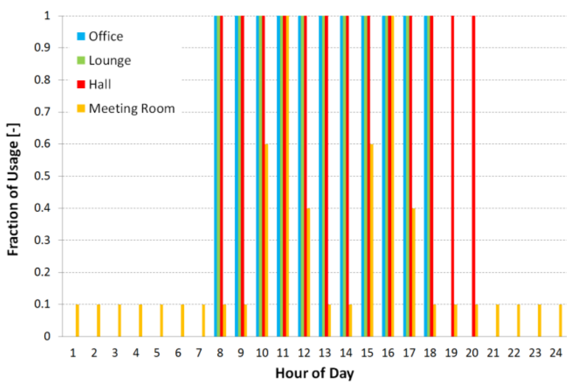
Zone Name	Floor Area [m2]	Number of People [–]	Lighting [W/m2]	Equipment [W/m2]
Zone 08a Office W	42.23	5	8.4	7
Zone 08b Office W	14.08	1	8.4	7
Zone 09a Lounge	33.72	1	8.4	15
Zone 09b Lounge	10.21	1	8.4	15
Zone10 Hall E	82.73	1	7	15
Zone11 Hall W	64.03	1	7	15
Zone12 Core Facilities	121.98	1	1	5
Zone13 Core Meeting	23.54	12	8.4	3
Zone14 Staircase	44.54	1	1	1



Equipment



Occupancy



Lighting

Figure 3-6: Used equipment, occupancy and lighting schedules for workdays

The internal gains at each simulation time step were computed by multiplying the design values with respective factors that varied by day of week and time of day. The factors were determined from schedules taken from Swiss standards [7], and electricity measurements from the building. The used schedules for workdays are shown in Figure 3-6.

For lighting control we introduced in the model daylight sensors in the office and lounge zones. The sensors were used to reduce the energy usage for lighting based on available daylight (taking weather input data and blind position into account).

The main EnergyPlus submodels and components used were:

- Occupancy: `People`

- Equipment: `ElectricEquipment`
- Lighting: `Lights, Daylighting:Controls`

3.2.2.11 Weather

The EP model was simulated using statistically determined weather data (hourly weather data for the site Basel-Binningen, provided by [8]) as well as measured weather data (sub-hourly data provided by MeteoSwiss for Basel-Binningen, and our own on-site measurements). The used weather inputs are reported later, together with the respective simulation results (see Chapter 5).

3.2.2.12 Implementation

All three EP models were implemented based on a common library of *.xls and ASCII files that contained all necessary information to automatically compile the needed EP input files.

Different object types were defined in order to represent, among other things, materials and zone properties, HVAC components, water loops, operation schedules, "EnergyManagementSystem" (EMS) code snippets, control interfaces, monitoring settings, and documentation parts.

The library files were dynamically composed into an EP program code using the automated procedure described in [5]. In the course of the project the procedure was developed further in order to support EnergyPlus Version 7.0 that was released in December 2011.

The EnergyPlus model was used to calculate but net energy usage and therefore it included only ideal heat and cool sources. Plant efficiency rates were considered in a separate post-processing step that operated on the respective model outputs (see Section 5.1.1).

3.2.3 Validation

The modeling of the target building presented an iterative process that consisted of alternating model development and model validation phases. In a model validation phase independent data were used to check in as far the model met certain requirements. The results were then used to further improve the model based on the refinement of submodels, the adjustment of key input assumptions, and the tuning of model parameters.

Here we give an overview of the used procedure, and present selected results from the more detailed publication [9].

3.2.3.1 Measurements

Tuning and validation of the EP model was based on the following measurements:

- Whole-building heating energy consumption by TABS, radiators, and ventilation
- Whole-building cooling energy consumption by TABS
- Electrical consumption for the entire second floor and for lighting and equipment in each individual office of that floor
- Room temperature, presence, illuminance and window opening state in each office of the second floor.

The measurements were originally available at irregular points in time, mostly at a sub-hourly sampling rate. For comparison with the simulated data they were interpolated to hourly totals or hourly mean values, depending on the physical variable.

High-quality hourly weather data for the years 2011 and 2012 were obtained from the MeteoSwiss weather station Basel Binningen at a few kilometers distance from the building site. The following variables were used as an input to the simulations: dry bulb and dew point temperature, and direct normal and diffuse horizontal radiation derived from global horizontal radiation.

3.2.3.2 Simulations and Comparisons Set-Up

Two kinds of simulations were performed: open loop simulations where all control signals came from recorded data, and closed loop simulations where the model was run with the same rule-based control procedure that was also used in the real building (see Section 3.2.2.1). For both kinds of simulations measured weather data were used to drive the model.

The simulations were run for 2011 and 2012, but depending on the availability of measurements only selected time windows could be used for validation. Comparisons between measured and simulated hourly data were done for five selected periods, as summarized in Table 3-6.

Table 3-6: Validation periods

Period	Time Window	Mean Outside Air Temperature [°C]	Description
I	Nov. 2–8, 2011	10.2	AHU experiment
II	Dec. 20–31, 2011	3.5	TABS experiment
III	Jan. 26–Feb 17, 2012	-4.5	Cold period
IV	Mar 1–Apr 19, 2012	8.6	Mild period
V	Aug 8–Sep12, 2012	19.5	Warm period

Period I included the weekend from Nov. 4th–6th, 2011, where an AHU supply air temperature experiment had been performed. Period II covered a TABS excitation experiment that had been executed during Dec. 23–31, 2011. Periods III and IV were heating periods, whereas cooling was active during the warm Period V.

All simulations were done at a 15 minutes time step and their outputs were aggregated to hourly totals or averages for comparison with measurements. Deviations between simulated (s) and measured (m) hourly time series were assessed quantitatively by the mean error (ME) and the mean absolute error with the bias removed (MAE):

$$\mathrm{ME} = \frac{1}{n}\sum(s_i - m_i) \qquad \textit{Equation 3-1}$$

$$\mathrm{MAE} = \frac{1}{n}\sum\left|(s_i - ME) - m_i\right| \qquad \textit{Equation 3-2}$$

Here n and i denote the sample size and the time step index, respectively. ME measures the time-averaged deviation over the comparison period, whereas MAE measures the average deviation in the simulated signal's dynamical behavior after it was shifted to have the same time-mean as the measurements.

The following quantities were analyzed:

- The area weighted mean operative temperature of all offices and of the meeting room of the second floor (T_{RM}).
- The net energy usage for TABS heating and cooling (H_{TABS}, C_{TABS}).
- The net energy usage for AHU (H_{AHU}).
- The net energy usage for radiator heating (H_{RAD}).

The total heating energy usage by TABS, AHU and radiators is denoted as H_{TOT}. Energy measurements where scaled to the second floor based on its fraction of the total building's conditioned area.

3.2.3.3 Validation Stages and Model Adjustments

During the course of the project detailed measurements from the building became increasingly available. This allowed for a further development of the EP model version M3 (see Section 3.2.1). The initial M3 model was model A. Two further models, B and C were derived, as shown in Table 3-7.

Table 3-7: Versions of the EnergyPlus model M3

Model	Main inputs used for model development and validation
A	Planning data, standard weather data, standard internal load profiles, out-of-the-box controls.
B	Measured room temperatures from AHU and TABS excitation experiments; measured weather; measured control signals; realistic control. Tuning of time-mean room operative temperatures.
C	Same as B, but model extended/tuned with focus on room temperature dynamics.

We distinguished three validation stages, as follows.

Stage 1 – Plausibility testing. Result: Model A

As described in Section 3.2.2 the initial model was constructed based on planning data and best practice guesses where no such data were available. It was tested for general correctness and plausibility in simulation studies covering a few days to a whole year using design reference weather data, standard internal load profiles, and out-of-the-box controls.

The simulations were analyzed to make sure that the model (i) is implemented correctly, (ii) shows a physically plausible and consistent behavior, (iii) processes external controller outputs accurately, and (iv) yields room temperatures and energy consumption that were roughly within the observed range.

Stage 2 – Tuning of short-term room temperature dynamics. Result: Models B and C

Tuning was done by driving the models with measured weather data and realistic controls and then comparing the simulated hourly mean operative room temperatures with the room temperature measurements from two multi-day periods (Periods I and II, cf. Table 3-6). To maximize the information content of the measurements during these periods we performed two open-loop control experiments:

In the first experiment we investigated the building's thermal response to an AHU supply air temperature excitation. We employed two doublet signals (+15/-20/+5 K, and -5/+20/-15 K), as shown in Figure 3-7 (top).

The second experiment allowed us to measure responses from step changes in the TABS supply water temperature. The TABS were first operated at maximum cooling capacity for three days, after that maximum heating was switched on (Figure 3-7, bottom). During both experiments the blinds were kept generally closed to minimize the influence of solar gains on the measured temperature trajectories.

Model B resulted from model A by implementing the following changes: modification of the assumed construction of the floor covering/internal ceiling; removal of insulation layer in the internal walls; raising of radiator setpoints in the corner rooms; reduction of infiltration and internal gains in the core zone; introduction of base load in equipment schedules based on measured electricity consumption. These modifications affected only issues where no planning data were available. Where planning data were available they were not modified.

Model C was motivated by the fact that models A and B were both found to only poorly reproduce the room temperature dynamics from the AHU excitation experiment (Figure 3-7, top). Additional measurements during a two-week special monitoring phase showed that the air temperature at the office zones' air outlets differed from the measured supply air temperature that is set in the AHU located at the building's basement by up to 2-4 K. A closer investigation showed, firstly, unexpectedly high heat losses during the transport in the shaft. Secondly, we discovered that the ducts to the offices are partially embedded in the concrete core of the ceiling, such that the supply air is apparently strongly conditioned towards the concrete temperature.

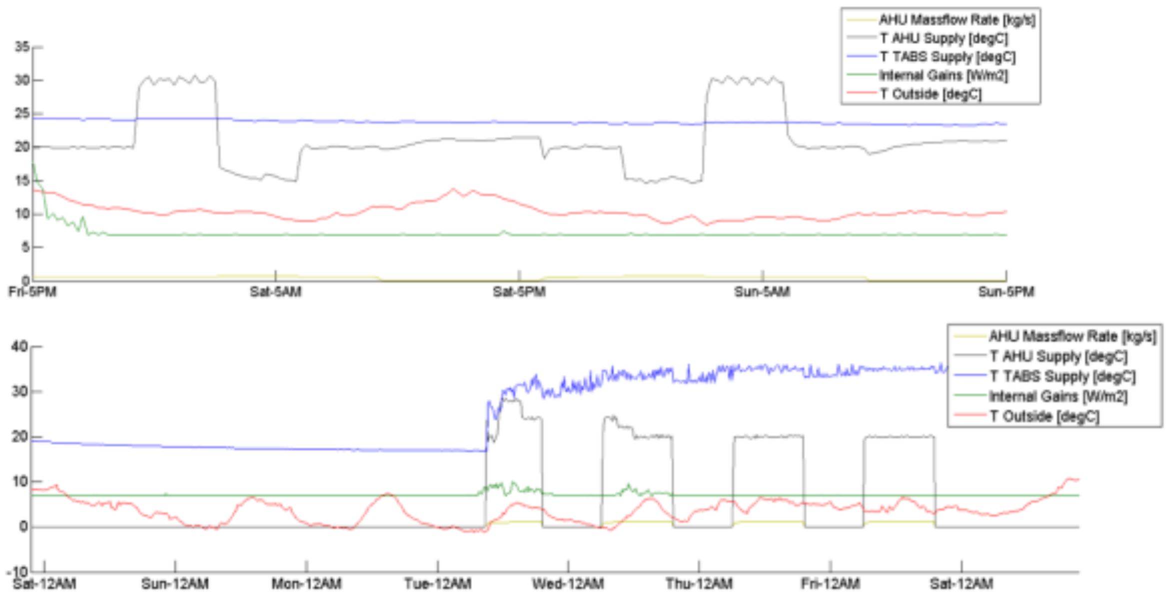


Figure 3-7: HVAC actuation, and measured outside air temperature and internal gains during the AHU (top) and the TABS (bottom) excitation experiments. From [9].

Model C was derived from model B by modifying the temperature of the supply air entering the office rooms as a function of supply air temperature in the basement. This was accomplished based on linear regressions fitted to data from the special monitoring phase. Details can be found in [9].

In addition, model C accounted for the fact that the outdoor air travels to the AHU via an earth embedded duct of several meters length. To predict the air temperature at the AHU supply air inlet we used a first-order model that was tuned to several months of hourly temperature measurements. This extension influenced the heating and cooling energy used by the AHU, but otherwise it did not affect the model's dynamical behavior.

Stage 3 – Comparison of long-term energy and operative room temperature statistics

Here we applied the models M3-A to C to three further periods (Periods III–IV, Table 3-6) of several weeks each. During these periods the building was operated normally. Simulation results for these periods were compared to measured data for both, operative room temperatures, as well as net heating/cooling energy usage. The result of Stage 3 were the EP models' final validation statistics.

3.2.3.4 Results

Figure 3-8 compares the measured temperatures for two selected office rooms with the simulated operative temperatures for the corresponding model zones during Periods I and II, respectively. It can be seen that during Period I all three subversions A–C of the M3 model overestimated the amplitude of the room temperature responses to the imposed changes in AHU supply air temperature. Model C was however clearly the best. Quite differently, in Period II this model showed the poorest performance in reproducing the effect of the imposed TABS heating step.

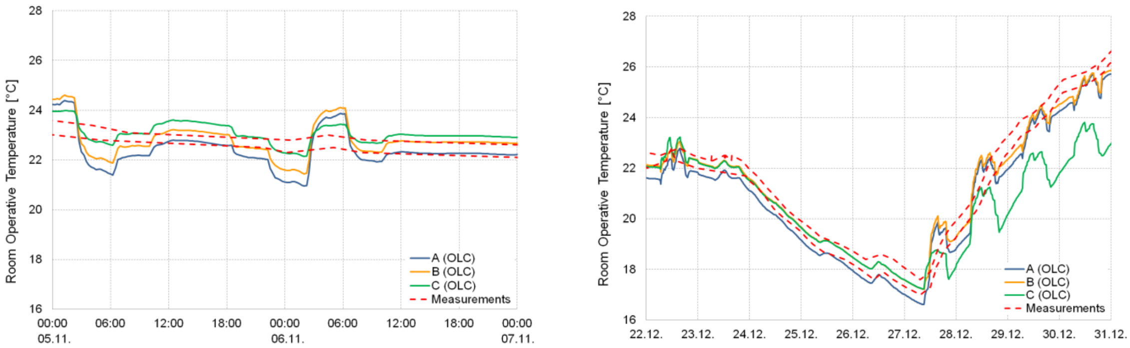


Figure 3-8: Measured office room temperatures (red) and simulated operative temperatures in Periods I (AHU experiment, left) and II (TABS experiment, right). A–C: Versions of model M3. Data refer to two selected office rooms and the related model zone with façade orientation "West". From [9].

Figure 3-9 a) shows the T_{RM} mean error (ME) statistic for all model versions and validation periods. The results shown for Periods I and II confirm the findings from Figure 3-8 for the entire second floor. For Periods III–V the mean errors range from -2.1 K to 0.7 K, depending on Period and model version. Further can be seen that the closed loop simulation experiments gave in general smaller ME as compared to the open loop case.

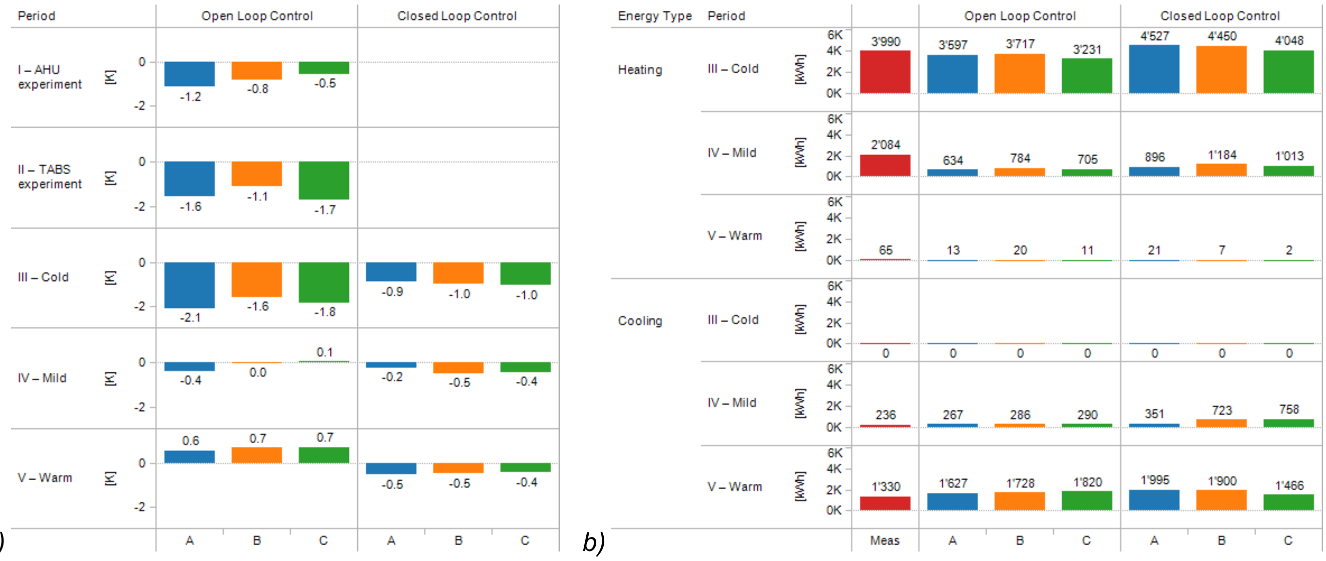


Figure 3-9: a) Mean error (ME) from the comparison of measured and simulated room operative temperatures T_{RM}. b) Measured (Meas) and simulated total net energy usages for heating (H_{TOT}, top) and cooling (C_{TABS}, bottom). A–C: Versions of model M3. From [9].

Figure 3-9 b) compares measured and simulated total net energy usages for heating and cooling in Periods III–V. It can be seen that the simulations captured the differences between the different Periods and between the total heating and cooling demand roughly right. However, except for Period III, relative deviations from the measured values (not shown) were found to be large, often > 50%.

3.2.3.5 Discussion

The validation exercise revealed a very varied picture about the ability of the three models A–C to predict measured room temperatures and net energy usage. Moreover, results depended strongly on the use of open loop vs. closed loop simulations.

The found deviations between measurements and simulations depended on a multitude of modeling decisions, input data sets and assumptions. This made it very difficult to trace the various model-reality mismatches to a single cause. Possible causes are differences in real vs. simulated low-level control (in particular due to differences in assumed radiator setpoints and sensor locations); differences in blind positions and hence also in solar heat gains (manual blind repositioning could not be measured in the real building); and the omission of natural ventilation in the simulations (an analysis of window contact sensor data from the building suggested that cooling energy demand was actually substantially reduced thanks to natural ventilation).

The differences between open and closed loop simulations related to the fact that in the open loop case occupancy-induced internal loads and possible blind repositioning or opening of windows by the occupants were implicitly accounted for. This was because the recorded control sequences included the control system's response to these disturbances. Quite differently, the closed loop simulations depended entirely on the assumed internal loads schedules and did not account for windows opening and blinds operation by the occupants.

Further factors that may have contributed to the found deviations between measurements and simulations are the limited accuracy of the room temperature measurements; the use of non-local weather inputs in the simulations; various assumptions on construction details that are very difficult to check; the assumed boundary conditions to the adjacent floors; the lack of realistic submodels for air and water transport; the use of a quasi-steady-state submodel for the radiators; the need to rescale HVAC design values and measured energies to the second floor; and finally limitations of the EP software, such as the inability to simultaneously model TABS and embedded air ducts, limitations in the simultaneous use of the TABS heating and cooling loops, and the limited ability of EP users to influence the software's low-level control.

In spite of the found deviations, the model proved very useful for the development and testing of the new control strategies. The model's limited predictive accurracy was not too critical since the developed control solutions were robust and general enough not to depend on the details of the demonstrator building.

Further results and a more detailed discussion can be found in [9].

3.2.3.6 Conclusions

Overall, the model development, tuning and validation process described here proved very challenging. The model's predictive accuracy for room temperature dynamics and net energy usage was found to depend as much on the correctness of the building and HVAC submodels, as on control details and the choice of various input data sets and assumptions. While average measured office room temperatures and room temperature dynamics could be reproduced well, the validation revealed large deviations between simulated and measured energy usages.

The magnitude of the found errors suggests that it is not possible to draw firm conclusions with regard to the real building's energy usage from the simulations alone. The models are probably more suitable to assess long-term *differential* effects on the building's energy usage due to alternative building, HVAC systems or control designs. To be on the safe side, it was concluded that such differential assessments should consider a variety of parameter settings and disturbance regimes (weather, occupancy etc.).

3.3 Thermal Resistance-Capacitance Models

This section is concerned with how the building was modeled specifically for the use of MPC. Large parts of this section base on [10]. We first present the development and validation of a fully detailed thermal Resistance-Capacitance model (fRC) and present the derivation of an associated low order reduced model (rRC).

3.3.1 Derivation of the Full RC Model

For the resulting MPC optimization problem to be tractable, the model needs to have a linear structure. However, some of the building dynamics cannot be reasonably modeled linearly, but require bilinear terms (e.g., ventilation energy leaving a room is linearly proportional to both zone temperature, a state, and ventilation mass flow rate, an input). Hence we generalized the acceptable model class to bilinear models and used a sequential linear programming approach (see Section 4.3.3.1) to solve it. The model was derived in continuous time (as a set of coupled differential equations) and subsequently discretized.

The discretized bilinear model was mathematically expressed as

$$x_{k+1} = Ax_k + B_u u_k + B_v v_k + \sum_{i=1}^{n_u} \left[\left(B_{vu,i} v_k + B_{xu,i} x_k \right) u_{k,i} \right] \qquad \text{Equation 3-3}$$

$$y_k = Cx_k + D_u u_k + D_v v_k + \sum_{i=1}^{n_u} \left[\left(D_{vu,i} v_k + D_{xu,i} x_k \right) u_{k,i} \right] \qquad \text{Equation 3-4}$$

and describes the relationship between states x (dynamically modeled temperatures of the zones, walls and floors), control inputs u, disturbance inputs v and outputs y, with n_u, n_v being the number of control and disturbance inputs, respectively. Table 3-8 shows a detailed list of the main outputs as well as the control and disturbance inputs.

Table 3-8: Overview of model variables. {N,E,W,S} in the subscript of a variable denotes that there are individual variables per façade orientation north/east/west/south.

Variable	Unit	Description
$y_{\text{avg room T,\{N,E,W,S\}}}$	°C	Averaged room temperature for each zone group
$u_{\text{TABS heating}}$	W	TABS heating heat flux
$u_{\text{TABS cooling}}$	W	TABS cooling heat flux
$u_{\text{transm solar, \{N,E,W,S\}}}$	W/m^2	Average transmitted solar heat flux for each zone group
$u_{\text{AHU m ERC}}$	kg/s	Air massflow through ERC
$u_{\text{AHU m noERC}}$	kg/s	Air massflow bypassing ERC

Variable	Unit	Description
$u_{\text{AHU m cooler}}$	kg/s	Air massflow through air cooler
$u_{\text{AHU heater}}$	W	AHU heat coil heat flux
$u_{\text{lighting, \{N,E,W,S\}}}$	W/m^2	Lighting power for the offices of each zone group
v_{IGoff}	W/m^2	Internal gains in the offices due to people and equipment
v_{IGnonoff}	W/m^2	Internal gains in non-offices due to people, equipment and lighting
$v_{\text{T ambient}}$	°C	Outside air temperature
$v_{\text{solar, \{N,E,W,S\}}}$	W/m^2	Solar radiation for every façade orientation

Note that the outputs describe averaged zone temperatures of a *zone group*. The grouping of multiple zones and its motivation is described in Section 3.3.1.4.

The costs and constraints associated with the control inputs were linearly expressed as

$$c_k^T u_k \qquad \text{Equation 3-5}$$

$$Fx_k + G_u u_k + G_v v_k \leq g_k \qquad \text{Equation 3-6}$$

Equations 3.3–3.6 represent the mathematical model of the building's thermal dynamics as a function of the disturbances and actuation. In the following sections, the modeling procedure that was applied to construct this model is described in more detail.

3.3.1.1 Modeling Procedure

We chose to construct the model from building construction data using physical first principles. Alternatives would have been to identify a black box model from experiments with the real building, or from EnergyPlus simulations. However, we did not pursue this approach because experimentation with the fully occupied building was possible only to a very limited extent, and because we aimed at a solution that would work also without a sophisticated simulation tool such as EnergyPlus. Moreover, modeling from first principles has the advantage that the model's dynamics (i.e., the numerical values entered in the system matrices, Equations 3.3 and 3.4) can be physically interpreted and directly modified as desired, e.g. when additional knowledge about the building becomes available.

As described in Section 1.2, the actuators comprise a TABS system, an Air Handling Unit (AHU), and the blinds. In order to be able to predict lateral temperature variations within the building, we chose to model the entire second floor. The floors and ceilings were modeled to have adiabatic boundary conditions. We used the following procedure to generate the model:

- First, as described in Section 3.3.1.2, we used standard geometry and construction data to derive in an automated way a physical first-principles based linear model of the building's thermal dynamics. This described the evolution of zone, wall, floor and ceiling temperatures on a per zone level as a function of external heat fluxes q (e.g., solar gains, heating/cooling system heat fluxes etc.).

  $$\dot{x}(t) = A_t x(t) + B_{t,q} q(t) \qquad \text{Equation 3-7}$$

- Second, as outlined in Section 0, we modeled all external heat fluxes (i.e., heat fluxes into the building and to its hull that are not direct heat exchanges among building elements and zones) as bilinear functions of control inputs and disturbance inputs and states

$$q(x(t),u(t),v(t)) = A_q x(t) + B_{q,u} u(t) + B_{q,v} v(t) + \sum_{i=1}^{n_u} \left[\left(B_{q,vu,i} v(t) + D_{q,xu,i} x(t) \right) u_i(t) \right]$$

Equation 3-8

- Third, we discretized the system and tuned a limited number of physically meaningful parameters to obtain fRC. This part is described in more detail in [10].
- Finally, as described in Section 3.3.1.4, we used model reduction algorithms to derive the low-order model rRC that is suitable for use in MPC.

3.3.1.2 Automated Derivation of Linear Thermal Model

The approach for constructing the thermal model was an adaptation of the approach already used in the predecessor project OptiControl-I [1]. However, rather than relying on a pre-specified materials database and a fixed zone geometry as was the case in OptiControl-I, all relevant information was now extracted from the EnergyPlus (EP) model definition files[4]. The data could also have been specified directly e.g. in an Excel spreadsheet, which makes our approach easily reusable also for other buildings where the geometry and construction data may not be available in form of EP model definition files. Our overall procedure uses Linux “bash” scripts to generate the input objects tables from the EP model definition files, and a modular and generic MATLAB code to generate the A_t and $B_{t,q}$ matrices.

More concretely, the thermal model was generated as follows. With every zone and every layer of the walls and floors a state describing its temperature was associated. The heat flux between two adjacent states was modeled to be proportional to their temperature difference and a thermal resistance that can be computed from the materials data. As a simple example consider two adjacent layers “a” and “b” in a wall. Their dynamics considering only mutual heat exchange can be described as

$$C_a \dot{x}_a(t) = (x_b(t) - x_a(t)) / R$$ Equation 3-9

$$C_b \dot{x}_b(t) = (x_a(t) - x_b(t)) / R$$ Equation 3-10

where C_a, C_b denote the heat capacitances and R the thermal resistance. Repeating this for all wall/floor layers and zones and including external heat fluxes to the appropriate states yields one large system that can be written in the form of Equation 3.7.

[4] In EnergyPlus jargon these files are named “input data files” (*.idf). Here we prefer to use the term “model definition files” instead.

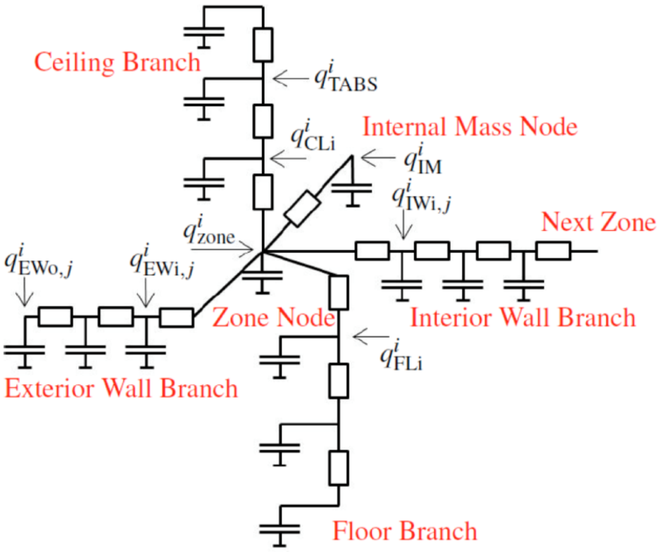


Figure 3-10: RC network for a generic zone i. Capacitances represent states, resistances the thermal resistances and q external heat fluxes.

Figure 3-10 visualizes the RC network for a generic zone i with indicated external heat fluxes q. For simplicity, in Figure 3-10 only one interior and exterior wall branch and a fixed number of three states (capacitances) per building element are shown (there may be more or less).

Table 3-9: External heat fluxes.

Symbol	Node of application	Physical heat flux
q^i_{zone}	zone	Internal gains, window heat fluxes, AHU gains, and natural air change (infiltration) heat fluxes
$q^i_{\mathrm{EWo},j}$	outermost of ext. wall j	Solar radiation and heat exchange with outside air
q^i_{TABS}	TABS layer	TABS gains, AHU gains
q^i_{FLi}	innermost of floor	Solar radiation
q^i_{CLi}	innermost of ceiling	Solar radiation
$q^i_{\mathrm{EWi},j}$	innermost of ext. wall j	Solar radiation
$q^i_{\mathrm{IWi},j}$	innermost of int. wall j	Solar radiation
q^i_{IM}	internal mass	Solar radiation

All thermal model parameters were derived from geometry and materials data (heat capacity, thermal resistance), except for the convective coefficients of the inner walls, floors and ceilings, which were fitted as described in [10]. The parameters are listed in Table 3-10, together with the parameters of the external heat flux models that are described later on.

Table 3-10: Model parameters.
EP = EnergyPlus; NRPE = Non-Renewable Primary Energy;
TABS = Thermally Activated Building Systems; AHU = Air Handling Unit

Parameter	Unit	Description	Derived from
α_{CL}	W/(m^{2}K)	Convective heat transfer coefficient ceiling/room	Parameter fitting using EP model

Parameter	Unit	Description	Derived from
α_{FL}	W/(m²K)	Convective heat transfer coefficient floor/room	Parameter fitting using EP model
α_{IW}	W/(m²K)	Convective heat transfer coefficient internal wall/room	Parameter fitting using EP model
a_i	m²	Floor area of zone i	Geometry data
f_{gas}^{NRPE}	-	Gas to NRPE conversion factor	As in [11]
$f_{\mathrm{electricity}}^{NRPE}$	-	Electricity to NRPE conversion factor	As in [11]
f_{lumEffic}	lm/W	Luminous efficacy of lighting	Standard value
f_{illum}	lm/W	Conversion factor from transmitted solar radiation to illumination	Parameter fitting using EP model
$a_{\mathrm{EW},j}^{i}$	m²	Area of external wall j of zone i	Geometry data
α_{EW}	W/(m²K)	Convective heat transfer coefficient external wall/environment	Parameter fitting using EP model
ρ_{air}	kg/ m³	Density of air	Standard tables
γ_{absorp}	-	Solar absorption coefficient	Parameter fitting using EP model
$a_{TABS,tot}$	m²	Total area of all TABS zones	Geometry data
$Q_{\mathrm{TABS,heating,max}}$	W	Maximum heating power of boiler	Planning data
R_{TABS}	W/K	Heat transfer resistance of the TABS cooling circuit between ambient temperature and averaged TABS slab temperature	Computed as in [12]
$P_{\mathrm{CTowFanMax}}$	W	Electrical power consumption of the cooling tower running at maximum capacity	Manufacturer data sheet
C_{air}	J/(kg K)	Specific heat capacity of air	Standard tables
h	m	Room height	Geometry data
γ_{infilt}	1/s	Natural air change rate (room volumes per second)	Assumption & fitted to experimental data
$\gamma_{\mathrm{inflow},j}^{i}$	-	Inflow from zone j to zone i as a fraction of total AHU mass flow rate	Planning data
$\gamma_{\mathrm{AHU}}^{i}$	-	AHU inflow to zone i as a fraction of total AHU mass flow rate	Planning data
p_{AHUfan}	W/(kg s)	AHU fan electric power per air mass flow rate	Manufacturer datasheet
$p_{\mathrm{AHU\ cooling}}$	W/(kg s)	Adiabatic cooler electric power per air mass flow rate	Manufacturer datasheet
$m_{\mathrm{AHU,max}}$	kg/s	Maximum achievable AHU mass flow rate	Manufacturer datasheet

3.3.1.3 External Heat Fluxes

External heat fluxes are defined as all heat fluxes into the building and to its hull that are not direct heat exchanges among building elements and zones. Different building cases may share some similar external heat flux models (e.g. for convective losses to the environment, or for internal gains), but otherwise the models will vary substantially depending on HVAC subsystem. The modeling approach proposed here allows for a modular addition of different subsystem models to the building's thermal dynamics model.

As also described in Section 4.1.2, the control was structured hierarchically, and the interface between high- and low-level control comprised temperature setpoints and operating modes. Hence, it would have been ideal to model the external heat fluxes of the actuators as a function of those temperature setpoints and operating modes. However, it turned out that this was not possible for the blinds and TABS subsystems within the bilinear framework required for MPC. Therefore we shifted our perspective from temperature setpoint control to heat flux setpoint control and modeled the blinds and TABS actuators as simple heat fluxes.

Since the constraints on the heat fluxes can be typically expressed as (potentially time-varying) lower and upper bounds and their costs are (mostly linearly) proportional to their magnitude, this approach was apt to express the actuators' costs and constraints in a linear way. The nonlinearity of the actuator physics could thus be moved to the pre-processing stage of computing costs and constraints (typically as a function of predictions). This however also implied a post-processing step where the setpoints provided by high-level control had to be computed from the "intermediate" heat fluxes values considered in the optimization. A similar approach was also proposed in [13].

In the following, we will describe how we modelled the individual external heat fluxes (Figure 3-10 visualizes the RC network for a generic zone i with indicated external heat fluxes q. For simplicity, in Figure 3-10 only one interior and exterior wall branch and a fixed number of three states (capacitances) per building element are shown (there may be more or less).

Table 3-9) and – for the heat fluxes that depended on control inputs – the corresponding control costs and constraints.

For the control costs here we will consider only Non Renewable Primary Energy (NRPE) usage. Adaptation to (potentially time-varying) electricity costs is straightforward.

The overall external heat flux to a given zone's room node consists of four parts (internal gains, windows, air handling unit and infiltration):

$$q^i_{\mathrm{zone}} = q^i_{\mathrm{zone,IG}} + q^i_{\mathrm{zone,win}} + q^i_{\mathrm{zone,AHU}} + q^i_{\mathrm{zone,infilt}} \qquad \text{Equation 3-11}$$

Building Hull and Infiltration

The heat exchange associated with the building hull (excepting the windows) was considered to consist of a conductive and a radiative part. The conductive heat exchange from the façade was modeled using a standard heat transfer coefficient, while the radiative solar gains were calculated as the product of the incident solar radiation on the façade and an absorption factor. Hence, for the outermost layer of external wall *j* of zone *i* (with $x^i_{\mathrm{EWo},j}$ being its temperature) we have

$$q^i_{\mathrm{EWo},j} = a^i_{\mathrm{EW},j}\alpha_{EW}(v_{\mathrm{T\,ambient}}(t) - x^i_{\mathrm{EWo},j}(t)) + \gamma_{\mathrm{absorp}} a^i_{\mathrm{EW},j} v_{\mathrm{solar},fac}(t) \qquad \text{Equation 3-12}$$

where fac denotes the orientation of the external wall. Infiltration is simply considered as a fixed air change rate. Hence with $x^i_{\mathrm{zone}}(t)$ being the temperature of room *i*

$$q^i_{\mathrm{zone,infilt}} = C_{\mathrm{air}}\rho_{\mathrm{air}} a^i h \gamma_{\mathrm{infilt}}(v_{\mathrm{T\,ambient}}(t) - x^i_{\mathrm{zone}}(t)) \qquad \text{Equation 3-13}$$

TABS

The TABS piping system in the office floors can be connected either to the TABS heat or TABS cold generation system. An obvious approach would have been to model the TABS heat flux proportional to the difference of a supply temperature setpoint and an average concrete core temperature. However, in the target building the mass flows differed significantly between cooling and heating operation. This implied a varying proportionality constant that rendered this modeling approach inaccurate.

Therefore we modeled the heat flux to the TABS layer i as a fraction of the total supplied TABS heating and cooling heat fluxes

$$q^i_{TABS} = \frac{a^i}{a_{TABS,tot}}\left(u_{\text{TABS,heating}}(t) - u_{\text{TABS,cooling}}(t)\right)$$ Equation 3-14

The heat fluxes were enforced to be non-negative and upper constrained by the maximum available heating power of the boiler and the maximum cooling power of the cooling tower:

$$0 \le u_{\text{TABS,heating}}(t) \le Q_{\text{TABS,heating,max}}$$ Equation 3-15

$$0 \le u_{\text{TABS,heating}}(t) \le Q_{\text{TABS,heating,max}}$$ Equation 3-16

where $T_{avgTABSslab}(x(t))$ is the area weighted TABS slab temperature as a linear function of $x(t)$. The costs of the TABS operation were modeled by

$$f^{NRPE}_{\text{gas}} u_{\text{TABS,heating}}(t) + f^{NRPE}_{\text{electricity}} \frac{u_{\text{TABS,cooling}}(t)}{Q_{\text{TABS,cooling,max}}(t)} P_{\text{CTowFanMax}}$$ Equation 3-17

Windows

We considered the heat flux through the windows in three parts: a radiation part which we modeled to directly act on the innermost layers of the building elements directly in contact with the zone's air (see Figure 3-10); a heat flux due to conduction through the window; and an additional heat flux due to absorption of solar radiation and subsequent heating up of the window. The first part constitutes the heat fluxes $q^i_{\text{FLi}}, q^i_{\text{CLi}}, q^i_{\text{EWi},j}, q^i_{\text{IWi},j}, q^i_{\text{IM}}$ while the latter two are reflected in $q^i_{\text{zone,win}}$. We modeled the transmitted solar heat flux to zone *i* as a controllable area specific (i.e., in W/m^2) heat flux. For our target building the blinds can only be controlled façade-wise. Accordingly we defined one independently settable heat flux $u_{\text{transm solar, \{N,E,W,S\}}}$ per façade. For the window heat flux acting on the zone node we got

$$q^i_{\text{zone,win}} = U_{\text{win}} a^i_{\text{win,tot}} \left(v_{\text{T ambient}}(t) - x^i_{\text{zone}}(t)\right) + \gamma_{\text{winSolAbs}} \sum_{fac \in \{N,E,W,S\}} a^i_{\text{win},fac} u_{\text{transm solar},fac}(t)$$

Equation 3-18

For the heat flux on the building element nodes (here shown for interior wall *j*, analogously for the other building elements) we used

$$q^i_{\text{IWi},j} = \frac{a^i_{\text{IWi},j}}{a^i_{\text{BE,tot}}} \sum_{fac \in \{N,E,W,S\}} a^i_{\text{win},fac} u_{\text{transm solar},fac}(t)$$ Equation 3-19

Encoding the constraints on the blinds actuation was not trivial, since the availability of only four possible blinds position setpoints (see Section 4.1.5) made the optimization problem into a so-called integer program that is very hard to solve. To overcome this problem, we first relaxed the integer constraints by assuming that the blinds could be set to any intermediate position and computed lower and upper bounds on the solar transmitted heat fluxes

$$Q_{\text{transm solar}}(\text{bPos}_{\text{maxShading},fac}, ...) \le u_{\text{transm solar},fac}(t) \le Q_{\text{transm solar}}(\text{bPos}_{\text{minShading},fac}, ...)$$

Equation 3-20

Then we performed the optimization, and determined from $u_{\text{transm solar, \{N,E,W,S\}}}$ the best matching allowed blinds positions. The used procedure and the computation of $Q_{\text{transm solar}}(\text{bPos},...)$ are detailed in Section 4.3.3.4. No actuation costs were associated with $u_{\text{transm solar, \{N,E,W,S\}}}$.

Internal Gains

Internal gains due to occupants, lighting and appliances were considered as simple convective heat sources acting on the zone nodes. We distinguished between office and non-office zones. The former had an illumination controlled lighting system, while the lighting of the latter was scheduled. For a non-office zone i we simply used

$$q^{i}_{\text{zone,IG}} = a_i v_{\text{IGnonoff}}(t) \qquad \text{Equation 3-21}$$

while for an office zone i we used

$$q^{i}_{\text{zone,IG}} = a_i v_{\text{IGoff}}(t) + a_i u_{\text{lighting},fac}(t) \qquad \text{Equation 3-22}$$

where fac denotes the facade of the zone group that zone i is associated with (see Figure 3-12). The constraints on the lighting, enforcing a minimum illumination of 500 lux during working hours, were formulated as

$$500 \le f_{\text{lumEffic}} u_{\text{lighting},fac}(t) + f_{\text{illum}} u_{\text{transm solar},fac}(t) \qquad \text{Equation 3-23}$$

During non-working hours, the constraint was neglected. The natural illumination was modeled to be linearly proportional to the transmitted solar radiation[5], i.e. as a function of the blinds position. The lighting costs (only shown for one office zone *i*) were computed as

$$f^{NRPE}_{\text{electricity}} a_i u_{\text{lighting},fac}(t) \qquad \text{Equation 3-24}$$

It is important to mention that the lighting was not controlled. The variables $u_{\text{lighting},fac}(t)$ were merely a means to encode the lighting costs in order to take them into account when determining the blinds positions.

Air Handling Unit

Figure 3-11 provides an overview of the building's AHU. It consists of three main elements for air conditioning: a heat exchanger (energy recovery unit), an evaporative cooler and a heater. The (possibly pre-cooled) extract air and the outside air flow into the heat exchanger where the outside air can be heated or cooled (depending on the operating mode of the heat exchanger and on the temperature difference $\vartheta_{\text{cooler}}$-$\vartheta_{\text{outside}}$ to ϑ_{HEX}). The air coming from the heat exchanger may then get heated to $\vartheta_{\text{supply}}$.

The AHU is always operated by setting pressure setpoints in supply and extract air ducts and three temperature setpoints, one each for the heater (T_h), cooler (T_c) and heat exchanger (T_{HEX}) respectively, where $T_h \le T_{HEX} \le T_c$. In any case, the heat exchanger will try to move $\vartheta_{\text{supply}}$ to T_{HEX}, if the temperature difference $\vartheta_{\text{cooler}}$-$\vartheta_{\text{outside}}$ allows for it. Furthermore if $\vartheta_{\text{supply}} \le T_h$ the heater and if $T_c \le \vartheta_{\text{supply}}$ the cooler becomes active.

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[5] Given how we modeled the transmitted solar radiation, this was the only way to couple it to the natural illumination and still end up with a convex optimization problem.

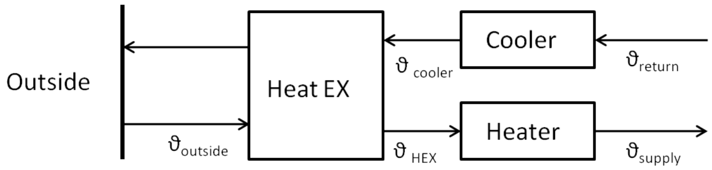


Figure 3-11: Schematic of the modelled Air Handling Unit.

The described behavior made the construction of a bilinear model for the supplied heat flux, the energy costs and the actuator constraints a challenging task. However, we were able to reformulate the problem into the requested type, the derivation being outlined in [14]. The resulting controller sets all three setpoints such that they track a requested $\vartheta_{\text{supply}}$, while internally ensuring the feasibility of this value and taking into account the corresponding energy costs.

The heat flux induced by the mechanical ventilation, $q^i_{\text{zone,AHU}}$, had two parts. First, we accounted for a zone-to-zone air exchange heat flux due to the fact that the supply and extract ventilation ducts are located in different zones

$$q^i_{\text{zone,AHU,zone to zone}} = C_{\text{air}}(u_{\text{AHU m ERC}}(t) + u_{\text{AHU m noERC}}(t))\sum_j \gamma^j_{\text{inflow},j}(x^j_{\text{zone}}(t) - x^i_{\text{zone}}(t))$$

Equation 3-25

Second, we considered the heat flux due to the AHU air supply (derivation given in [14]):

$$\begin{aligned} q^i_{\text{zone,AHU,direct}} = \gamma^i_{\text{AHU}}[& (p_{\text{AHUfan}} + C_{air}(v_{\text{T ambient}}(t) - x^i_{\text{zone}}(t)))(u_{\text{AHU m ERC}}(t) + u_{\text{AHU m noERC}}(t)) \\ & + u_{\text{AHU heater}}(t) \\ & + C_{air}\eta_{\text{ERC}}(T_{\text{AHUreturn}}(x(t)) - v_{\text{T ambient}}(t))u_{\text{AHU m ERC}}(t) \\ & - C_{air}\eta_{\text{ERC}}\eta_{\text{cooler}}\Delta_{\text{wb}}u_{\text{AHU m cooler}}] \end{aligned}$$

Equation 3-26

with the constraints

$$0 \le u_{\text{AHU m cooler}}(t), u_{\text{AHU heater}}(t), u_{\text{AHU m ERC}}(t), u_{\text{AHU m noERC}}(t)$$ Equation 3-27

$$u_{\text{AHU m cooler}}(t) \le u_{\text{AHU m ERC}}(t)$$ Equation 3-28

$$u_{\text{AHU heater}}(t) \le Q_{\text{AHU heating max}}$$ Equation 3-29

$$m_{\text{AHU,min}}(t) \le u_{\text{AHU m ERC}}(t) + u_{\text{AHU m noERC}}(t) \le m_{\text{AHU,max}}$$ Equation 3-30

where $m_{\text{AHU,min}}(t)$ is the minimum required mass flow rate required to ensure comfort (see Section 4.1.5). The actuation costs of the AHU were modeled as

$$f^{NRPE}_{\text{gas}}u_{\text{AHU,heating}}(t) + f^{NRPE}_{\text{electricity}}p_{\text{AHU cooling}}u_{\text{AHU m cooler}}(t) + f^{NRPE}_{\text{electricity}}p_{\text{AHUfan}}(u_{\text{AHU m ERC}}(t) + u_{\text{AHU m noERC}}(t))$$

Equation 3-31

As described in Section 3.2.3.3 in the target building there was a significant interaction between the TABS and the supply air. The model was adjusted to include this effect by introducing a heat transfer between the ceiling core node and the room node.

3.3.1.4 Model Reduction

MPC requires as an initial condition for the calculation of the optimal control inputs an estimate of the building's thermal state. The performance of the state estimation depends however heavily on the number of states. Since the fRC model for the second floor had ca. 300 states, it was necessary to find an approximate model that had a similar input-output behavior but fewer states.

As a rule of thumb, the smaller the number of inputs and outputs of a model, the smaller is the needed number of states to represent it. According to this, instead of considering the temperature of every single zone as an output, average zone temperatures for each façade and for the core zones were used, as shown in Figure 3-12.

We experimented with various model reduction methods and finally chose a standard truncated Hankel singular value reduction. This approach transforms the states and orders them according to a mathematically defined importance measure while ensuring an identical input-output behavior. Then only the most important states are used to define the reduced model, while all the others discarded. In our case we found that a reduced model rRC with 35 states gives satisfactory results. We tested the reduction by comparing the responses of zone group average temperatures to steps in external heat flux forcing for the fRC and rRC models and found very similar results. Hence in the following Section, validation results are shown for the fRC model only.

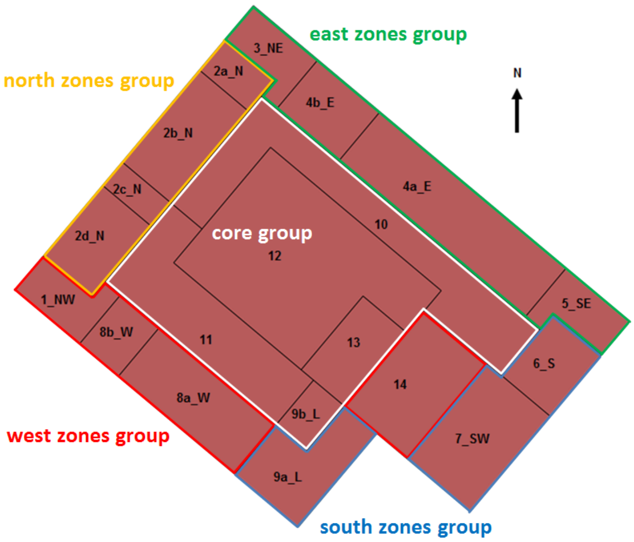


Figure 3-12: Zone grouping used for model reduction. From [10].

3.3.2 Validation

Two main possibilities exist for testing of a simulation model: the model's predictions are compared to independent measurements taken from the real system, or they are compared to the predictions of a reference model. Clearly, the first approach allows a more definitive statement on the model performance since the final goal is to accurately predict the real variables relevant for the task at hand. The second approach is, however, also very valuable, because it can provide insight into potential model discrepancies thanks to flexibility in setting up simulation experiments that test specific situations, and the ability to access and analyze large data sets containing a large number of physical variables.

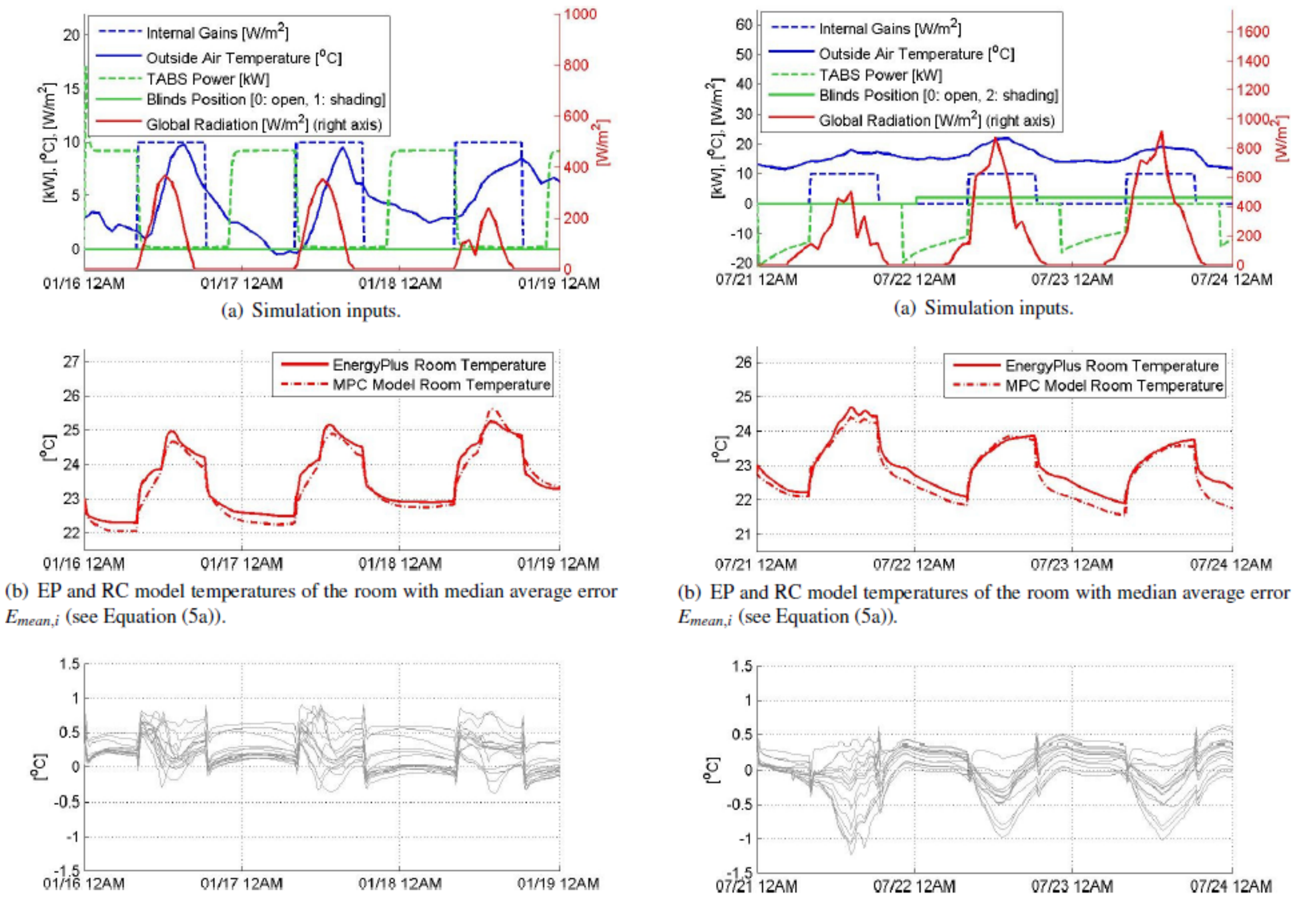
Accordingly, two validation exercises were conducted. The aim was to test how well the fRC model is able to predict zone temperatures in open-loop simulations. In the following two subsections we compare, firstly, simulated zone temperatures of open-loop simulations with fRC to those obtained from an EnergyPlus (EP) simulation with identical inputs. Second, we compare the outputs of another open-loop fRC simulation to measurements taken during a five-day experiment on the building.

3.3.2.1 Comparison to EnergyPlus

This section directly bases on the results of [10]. There we considered four EP simulations: two three-day periods with spring and autumn conditions for tuning, and two three-day periods with summer and winter conditions for testing of the fRC model, respectively. The inputs to EP were weather data, internal gains, and heating/cooling/blinds commands. The considered outputs were zone temperature trajectories.

For all simulations and both models we used the same initial condition: the building temperatures showed a constant temperature of 23°C. For all simulations we used real weather data recorded in Basel in 2011.

Model tuning consisted in running the fRC model using the EP input data for the spring and autumn cases and systematically modifying a subset of six key fRC model parameters to find the parameter settings that best reproduced the EP-simulated zone temperatures (see [10]). For testing of the fRC model we considered the two independent EP input/output data pairs from the winter (heating) and summer (cooling) case, respectively.



(a) Simulation inputs. (a) Simulation inputs.

(b) EP and RC model temperatures of the room with median average error $E_{mean,i}$ (see Equation (5a)). (b) EP and RC model temperatures of the room with median average error $E_{mean,i}$ (see Equation (5a)).

(c) Zone temperature errors $T_{\mathrm{EP},i}(k) - x^i_{\mathrm{zone}}(k)$ of all 20 zones. (c) Zone temperature errors $T_{\mathrm{EP},i}(k) - x^i_{\mathrm{zone}}(k)$ of all 20 zones.

Figure 3-13: Comparison of fRC and EnergyPlus simulated zone temperatures. Left: winter case; right: summer case. From [10].

The top panels in Figure 3-13 show for the two test cases the inputs to the simulations, the middle panels show the simulated EP and fRC temperatures of the zone with median time-averaged error, and the bottom panels show the differences between the simulated EP and fRC temperatures of all 20 zones.

The left panels in Figure 3-13 refer to the heating case simulation that started on January 16, 2011. From the middle left panel can be seen that in the selected zone the mean and maximum errors were around 0.25°C and 0.5°C, respectively, with a temperature trajectory peak-to-peak value of 3°C. The bottom left panel finally shows the errors of all zones which range from -0.4°C to +0.9°C, with an overall average of 0.25°C.

The right panels in Figure 3-13 show results from the cooling case simulation that started on July 21. In the middle right panels can be seen that the mean and maximum errors of the selected zone were around 0.2°C and 0.5°C, respectively, with a peak-to-peak value of 2.7°C. The errors of all zones (bottom left panels) ranged from -1.2K to +0.7°C with an overall average of 0.21°C.

These results showed that the fRC model is capable of predicting individual zone temperatures over a period of three days in a cooling and a heating case with a maximum error of 1.2°C and a much smaller average error of around 0.25°C when compared to EnergyPlus simulations.

3.3.2.2 Comparison to Measurements

Here we considered zone temperature data recorded during a field experiment that was conducted around Christmas 2012 (December 21–26). In the main phase of the experiment (December 21–25), all blinds were closed, the AHU was shut off and a doublet excitation signal was applied to the TABS control inputs. The used TABS inputs imposed maximum heating during December 21–23, and maximum cooling during December 23–25. For the rest of the experiment, the normal MPC control was again activated.

The fRC model was then simulated in open-loop mode using the measured control inputs and disturbances.

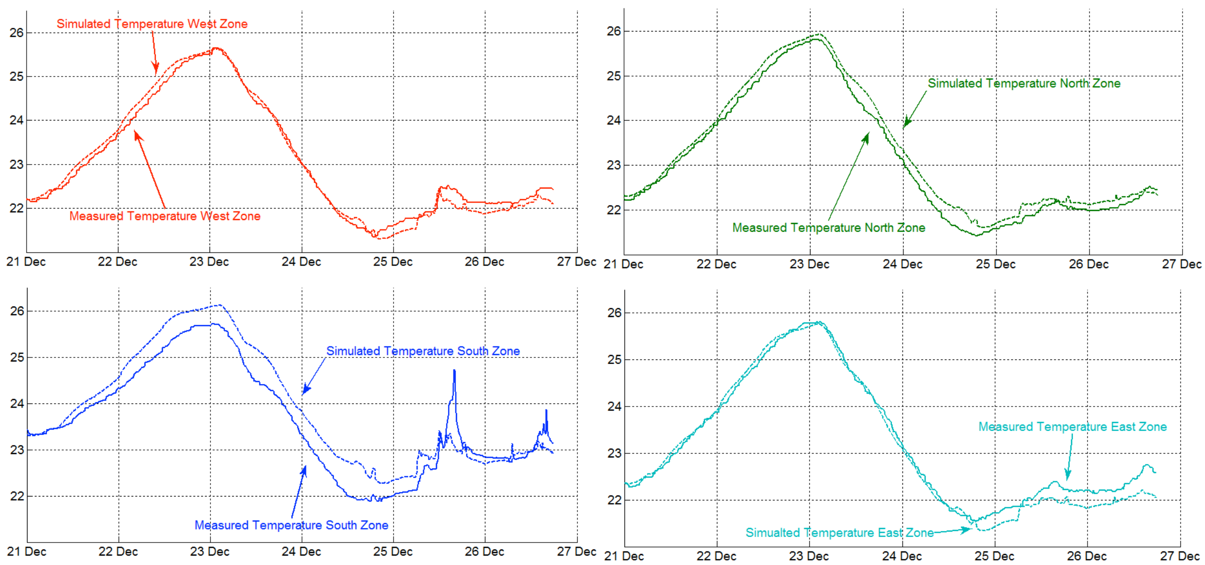


Figure 3-14: Comparison of fRC simulated and measured room temperature trajectories during the 2012 Christmas experiment.

Figure 3-14 shows the resulting simulated and measured mean zone group temperatures for the façade orientations north/east/west/south. The results show a good accordance during the TABS steps, except for the zone group south where the simulated temperatures were too high. Further it can be seen that the response to the TABS actuation (December 21–25) was well simulated, but that under occupancy (December 26) the zone group temperatures were less well reproduced, since in the course of this day the measured and simulated trajectories started to diverge.

3.3.2.3 Concluding Remarks

The thermal model, i.e. the heat exchanges among nodes representing the room air and material layers in the walls, floors and ceilings was parametrized and automatically generated from building data. The automated approach circumvented the error-prone and cumbersome task of modeling the thermal model by hand. The external heat flux models, i.e. the heat gains and losses due to ambient temperature, solar radiation, internal gains and building systems, were separately modeled and could be systematically and modularly added to the thermal model.

It turned out that the restriction to bilinear models was too restrictive for appropriate modeling of the TABS (due to different massflow rates in heating and cooling) and blinds (only discrete settings possible, transfer function “blinds position” & “solar radiation” to “heat flux into room” was nonlinear). These systems were therefore modeled as simple heat fluxes and the nonlinearities were moved to the pre- and postprocessing steps.

We abstained from obtaining the RC model based on a model identification approach because of uncertain success prospects due to the system’s multiple-input-multiple-output structure, and due to the fact that the necessary experimental effort for identification would have been prohibitive in practice. Moreover, models obtained from identification can not be linked to the physical processes in the system.

Our approach to rely on physical principles and construction data had however a downside: the detailed building model depended on appropriate modeling of complex physical phenomena, in particular the solar transmission through windows and blinds. An alternative, empirically based approach to windows and blinds modeling is described in the following Section 3.4.1.

Comparison of the RC model to EP, showed that after tuning of a small number of key parameters the RC model was able to reproduce the EP temperature dynamics in two independent validation periods well. Validation with measured data during the Christmas TABS step experiment also showed satisfying results. The validation also showed that the RC model can be tuned easier than the EnergyPlus model, thanks to a smaller number of relevant parameters and easier manipulation of the various involved submodels.

3.4 Simplification of Modeling for MPC

3.4.1 Measurement-Based Estimation of Solar Heat Fluxes

Depending on situation solar heat gains can present both, a convenient energy source for heating, or an undesirable load that has to be compensated by cooling. Correct estimation of the time-variation of solar heat fluxes is thus essential for good MPC performance.

In practice solar gains are not measured in individual rooms of a building. At best, solar radiation vertical to the main façade orientations is measured by a weather station typically mounted on the building’s roof. The heat fluxes into the building depend heavily on the building's geometry, the operation of shading devices, and the presence of surrounding objects such as other buildings, mountains or trees.

As detailed in Section 4.3.3.4, in our original MPC model the transmitted solar radiation $Q_{\text{transm solar}}$ into a zone was calculated in two steps.

In the first step, a function f_{hor2incl} was employed to compute direct and diffuse radiations on inclined surfaces $v_{\text{solDirIncl}}$, $v_{\text{solDiffIncl}}$, from global horizontal solar radiation $v_{\text{solGlobHor}}$, the current time t and a position (longitude, latitude, main façade orientation) vector pos, i.e.:

$$[v_{\text{solDirIncl}}, v_{\text{solDiffIncl}}] = f_{\text{hor2incl}}(v_{\text{solGlobHor}}, t, \text{pos}) \quad \text{Equation 3-32}$$

This function takes into account the geographical location and orientation of the building, plus any self-shadowing and shadowing by surrounding objects. The time information is necessary for the calculation of the sun's azimuth and altitude angles.

In the second step a further function $f_{\text{incl2transm}}$ used the results from the first step, a blinds position parameter bPos and the time t to calculate $Q_{\text{transm solar}}$, i.e.

$$Q_{\text{transm solar}} = f_{\text{incl2transm}}(v_{\text{solDirIncl}}, v_{\text{solDiffIncl}}, \text{bPos}, t) \quad \text{Equation 3-33}$$

This function depends on the properties of the windows and the blinds. Whereas function f_{hor2incl} can be formulated in a generic way using basic geometrical considerations and some approximations for the involved physics (e.g., consideration of the average albedo of the area surrounding the building), the function $f_{\text{incl2transm}}$ accounts for complex, non-linear small-scale radiation and heat transfers through the windows/blinds and their interaction with the building structure. In our original MPC model we therefore determined $f^{EP}_{\text{incl2transm}}$ based on a regression fit using results from detailed simulations with the EnergyPlus software.

This approach introduced, however, a crucial dependency on complex building modeling software and specific know-how not commonly available to control engineers. Therefore, here we present an alternative approach to estimate the solar heat fluxes based on measurements of room temperatures and solar radiation from the buildings' weather station.

3.4.1.1 Empirical Modeling Method

Even though we have reasonable confidence in calculating the inputs to $f_{\text{incl2transm}}$, its output, transmitted solar radiation, can be measured only indirectly by the zone's room temperature sensors. One approach to make use of the room temperature data would have been to run simulations of the full-scale RC model with measured weather data and multiple candidate versions $f^{\text{cand}}_{\text{incl2transm}}$, to compare the simulated to the measured room temperature trajectories, and to then choose the candidate function which produces the best match.

This direct approach faces however several difficulties: the initial conditions of the system (in particular the temperatures of the constructions) are not well known, the RC model is far from perfect, and the signal to noise ratio of the temperature measurements is not very good. For example, the measured changes in room temperatures on a sunny day that can be attributed to solar radiation are typically only around 1.5 °C (reflecting the building's heavy construction), while the measurements have a quantization of ±0.3 °C.

In order to circumvent the uncertain initial conditions and any RC model deficiencies, we considered the idea of estimating the solar heat gains by considering the evolution of the temperature *difference* of two zones as a function of *difference* in solar gains. The validity of this approach depends on the key assumptions that (i) the superposition principle of linear systems is applicable, that the two considered zones (ii) have the same construction and (iii) experience the same actuation, and that they have more or less identical (iv) initial conditions and (v) internal gains.

Assumptions (i) and (iv) are supported by intuition (and have to be validated). Assumptions (ii) and (iii) are met by construction for the target building (as long one does not compare normal office rooms with corner rooms, where in addition to TABS radiators are present). Assumption (v) can be fulfilled by considering data from unoccupied rooms only.

The general idea of the proposed estimation algorithm is to simulate one zone of the large scale RC model starting from a zero initial condition (for all states) and to then apply to this zone the difference in solar radiation from a second zone, as calculated from measurements by f_{hor2incl} and by a candidate function $f_{\mathrm{incl2transm}}^{\mathrm{cand}}$. The resulting simulated temperature trajectory is then compared to the measured temperature difference between the two zones. The procedure is repeated a number of times and the best fitting candidate function is selected.

3.4.1.2 Application

In the following, we describe how the procedure was applied to measured data from the target building. As a first step, appropriate data sets had to be prepared by elimination of corrupt or implausible measurements etc. For all subsequent steps we then assumed that the data is of good quality.

The relevant measurements were: i) room temperatures, ii) global solar radiation measurements from the roof-mounted weather station (horizontal/N/E/W/S), iii) blinds commands sent by the controller, iv) illumination sensors (on the facades and in the rooms), v) presence sensors, and vi) windows contacts. Note that since only the central blinds commands were logged but occupants were allowed to manipulate the blinds positions, only data when no occupants were present (i.e. mostly weekend data) was considered.

***Step 1a**: Validation of f_{hor2incl} without shadowing.* We used f_{hor2incl} to compute the global (direct+diffuse) radiation values on the inclined N/E/W/S surfaces of the weather station and compared them to the corresponding measurements. Since the weather station is mounted on the roof and none of the surrounding buildings is significantly higher, no shadowing effects were considered (but also no such effects could be validated).

In the process, it turned out that the weather station's sensors for the measurement of radiation fluxes on vertical surfaces were not aligned exactly with the orientation of the main building facades. This became apparent from initial data analyses, and was subsequently verified by an inspection of the weather station. The building is oriented with a north façade azimuth offset of -50° while the mismatch between measured and calculated radiation fluxes was minimized at an offset of -34° (Figure 3-15). The same comparison was also used to tune the albedo value employed in f_{hor2incl} (the original value of 0.2 was replaced by 0.25).

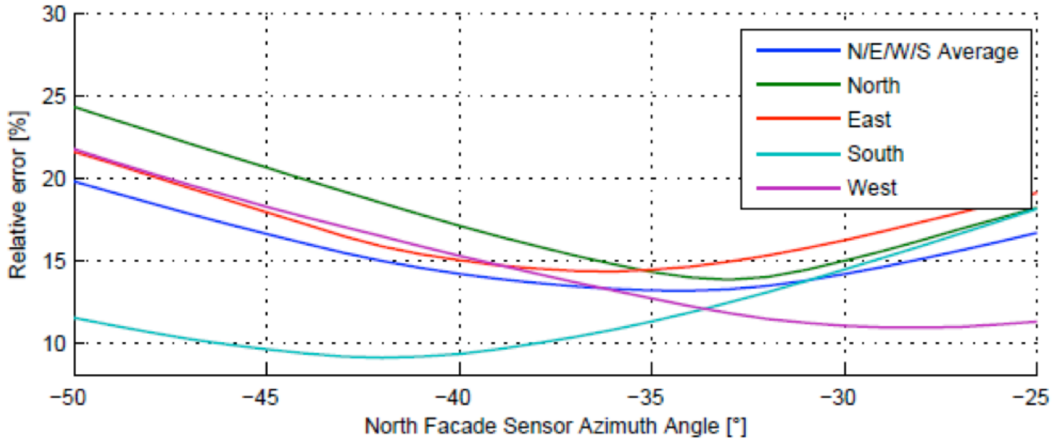


Figure 3-15: Relative error of global radiation estimation as a function of north facade sensor azimuth angle (the east, south and west façade sensors use azimuth angle offsets of +90°, +180° and +270° compared to the north façade sensor, respectively).

In Figure 3-16 various measured and calculated global radiation time series are shown over a five day interval. The total average relative error (average over all facades of the integrated absolute error divided by the integrated measured signal) was around 13%. This result as well as the optimal parameter values were very well reproduced across different measurement periods (not shown).

Step 1b*: Validation of the shadowing by adjacent buildings*. In this step, we compared illumination measurements on the facades and in the offices to the estimated $v_{\mathrm{solGlobIncl}}$ values of the corresponding facades. Since the illumination value is linearly proportional to the intensity when the spectral distribution of the radiation stays the same, it was possible to analyze also the shadowing part of f_{hor2incl} by comparing the estimated to the measured illumination values, in particular by looking at the correlation of both signals during times of large fluctuations (indicative of changes in direct radiation). The proportionality constant was estimated using least squares. This analysis led to some further adjustments in f_{hor2incl}, in particular to the internal shadowing model.

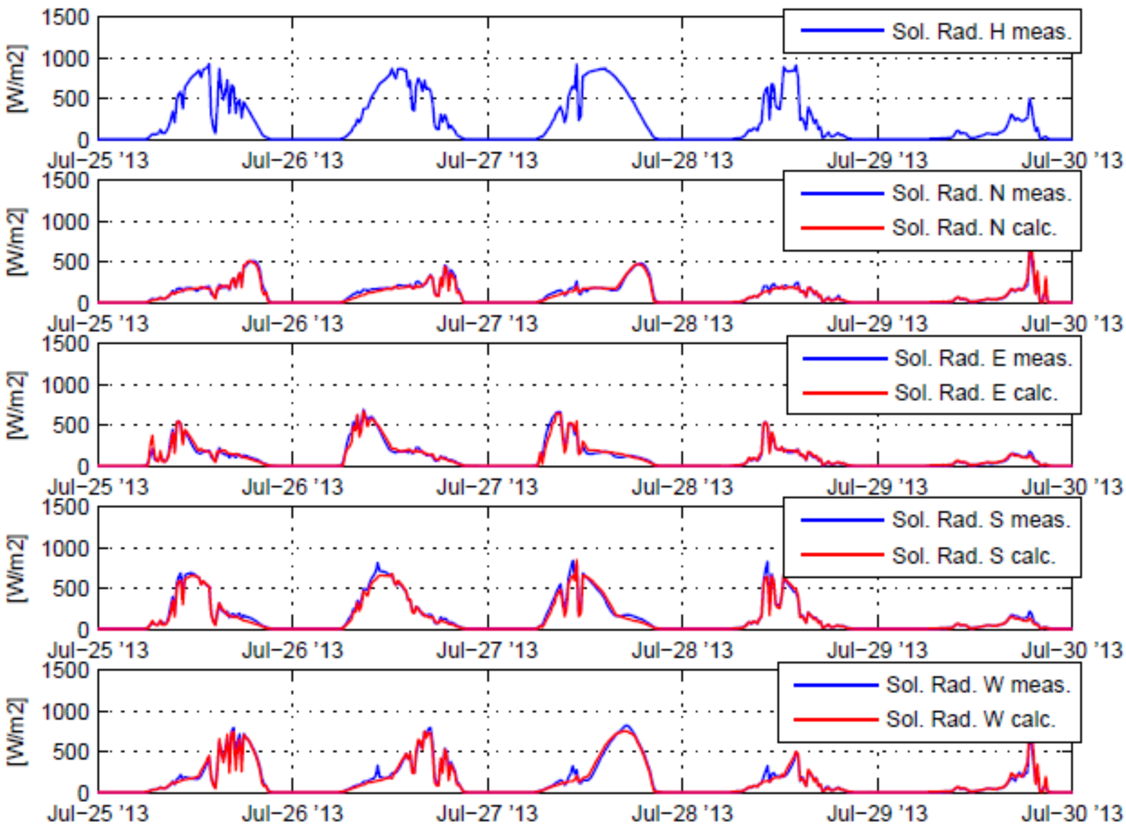


Figure 3-16: Measured global radiation on the horizontal plane (top panel) and comparison of measured and calculated global radiation values for every sensor orientation (second to last panel) of the weather station.

***Step 2**: Data selection*. For the reasons discussed earlier, we considered only data from times with no occupancy. In addition, we required all windows being closed, as evaluated based on the available window contact measurements. Moreover, to account for the temperature sensors' quantization we selected only data that yielded a large difference in the transmitted solar radiation. Since opposite façades never experience direct radiation at the same time, the NW-SE and NE-SW zones were compared. The consideration of zones instead of individual rooms helped to further alleviate the quantization effect. For both cases, the 10 days with maximum and the 8 days with minimum difference in $Q_{\text{transm solar}}$ were selected. The latter were used in Step 3 to validate the assumption that the temperatures in both zones evolve (more or less) identically when the difference in $Q_{\text{transm solar}}$ is negligible.

***Step 3**: Validation of homogeneous temperature response assumption*. In the "minimum differences" dataset, the blinds were closed all the time, i.e. even when the difference in $v_{\text{solGlobIncl}}$ was not negligible, the difference in $Q_{\text{transm solar}}$ was. In Figure 3-17, $v_{\text{solGlobIncl}}$, ambient temperature, the temperatures of the NE and SW zones as well as their differences are plotted. The variation of the temperature differences after subtraction of the mean was within ±0.25°C. From this we concluded that our assumption that when no solar gains are present the temperatures in both zones show the same evolution is basically correct.

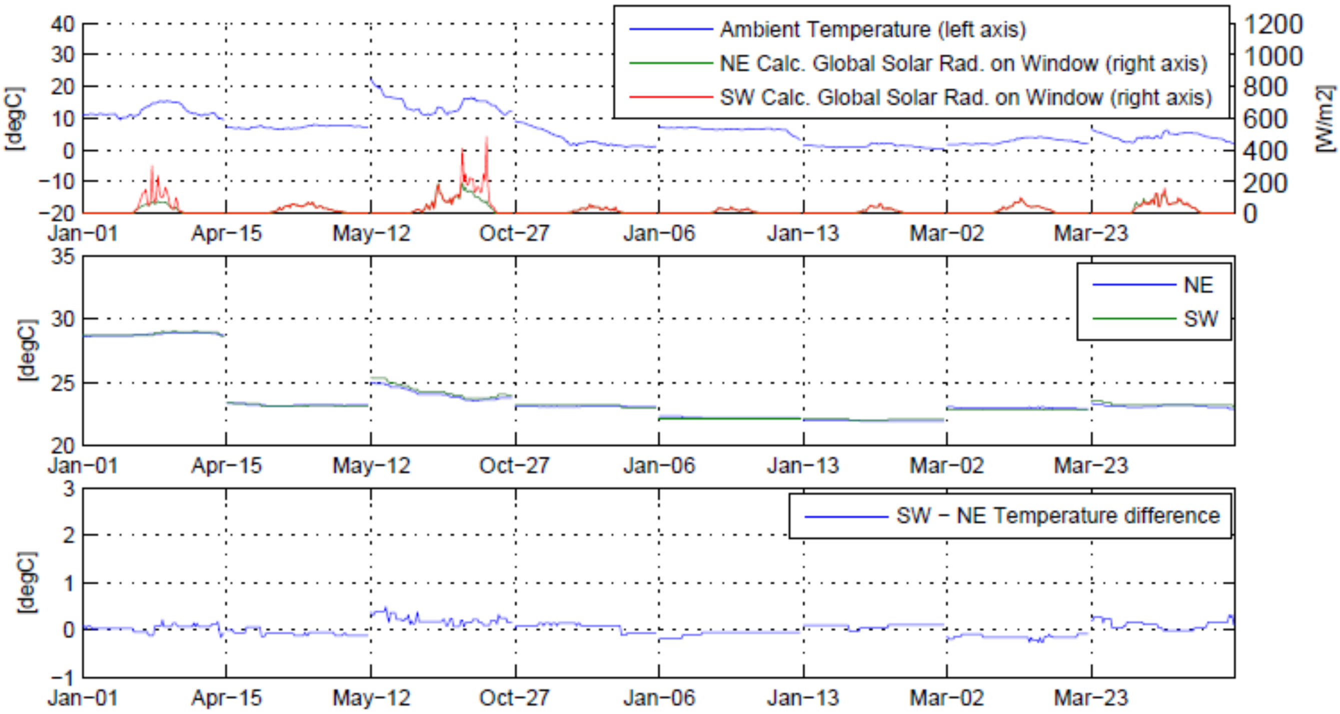


Figure 3-17: Measured weather data, measured SW and NE zone temperatures and their difference for days with little solar radiation and closed blinds.

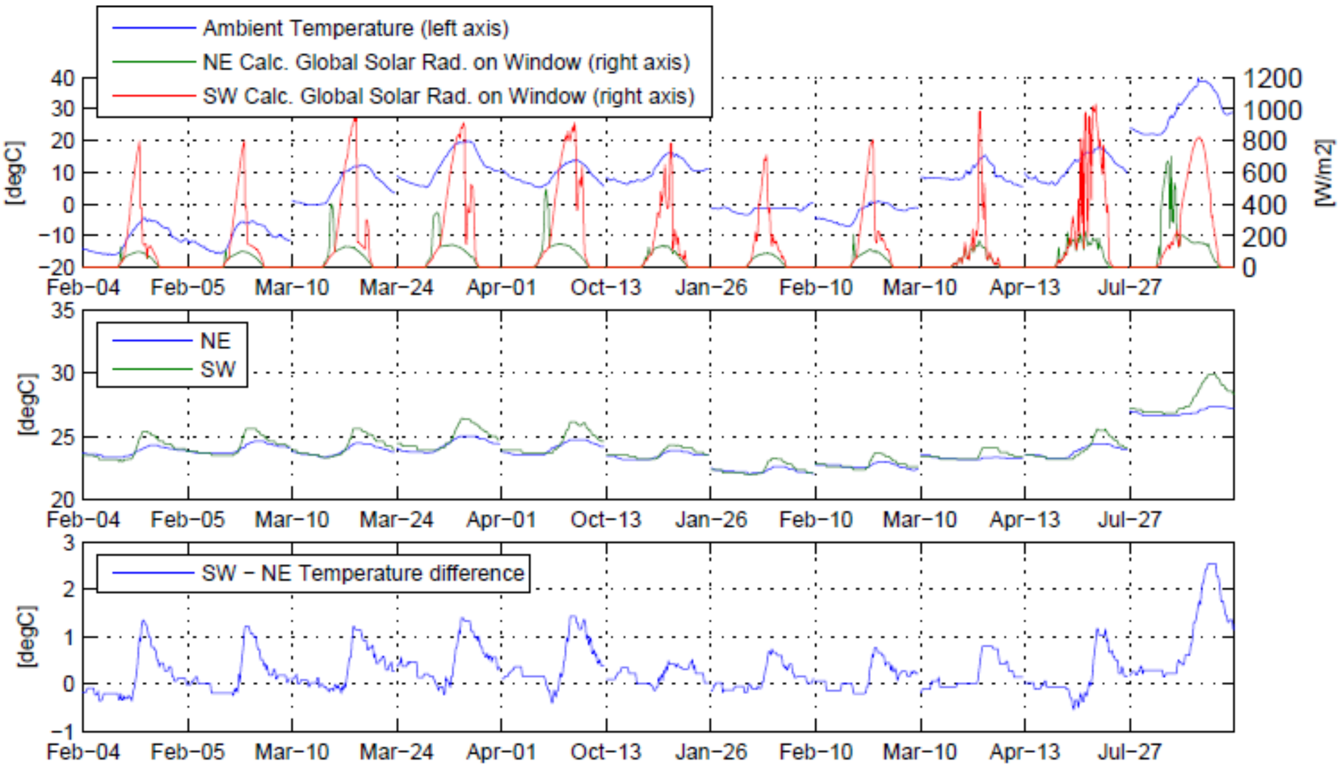


Figure 3-18: Measured weather data, measured SW and NE zone temperatures and their difference for days with high solar radiation and open blinds.

***Step 4**: Model fitting*. We assumed for $f_{\text{incl2transm}}$ a very simple empirical model $f^{emp}_{\text{incl2transm}}$: For every blinds position (closed, high shading, low shading, open) we used a linear relationship

$$f_{\text{incl2transm}}(v_{\text{solDirIncl}}, v_{\text{solDiffIncl}}, \text{bPos}, t) = c(\text{bPos})(v_{\text{solDirIncl}} + v_{\text{solDiffIncl}}) \quad \text{Equation 3-34}$$

with three to be determined model parameters $c(\text{bPos})$ (for the closed position we neglected secondary heat transfer and assumed $c(\text{closed}) = 0$). The quality of the estimation of $c(\text{bPos})$ depended heavily on the signal to noise ratio of the available temperature. It proved that $c(\text{open})$ could be reliably estimated, whereas the parameters for $c(\text{high shading})$ and $c(\text{low shading})$ could not be well determined due to large measurement noise. We found it however safe to assume for these parameters a small value in the range of 0.05-0.1. Since the effect of solar radiation at the respective blind positions is comparatively small, it can be expected that the uncertainty present should not cause large errors in the prediction of the zone temperatures.

In Figure 3-18, $v_{\text{solGlobIncl}}$, ambient temperature, the zone temperatures and their difference are plotted for days with high solar radiation and blinds open for the two considered zones. For a set of candidate values of $c(\text{open})$, we performed simulations for all days considered in Figure 3-18. Comparing to the measured temperature trajectories, we found that the value minimizing the estimation error was $c(\text{open}) = 0.35$.

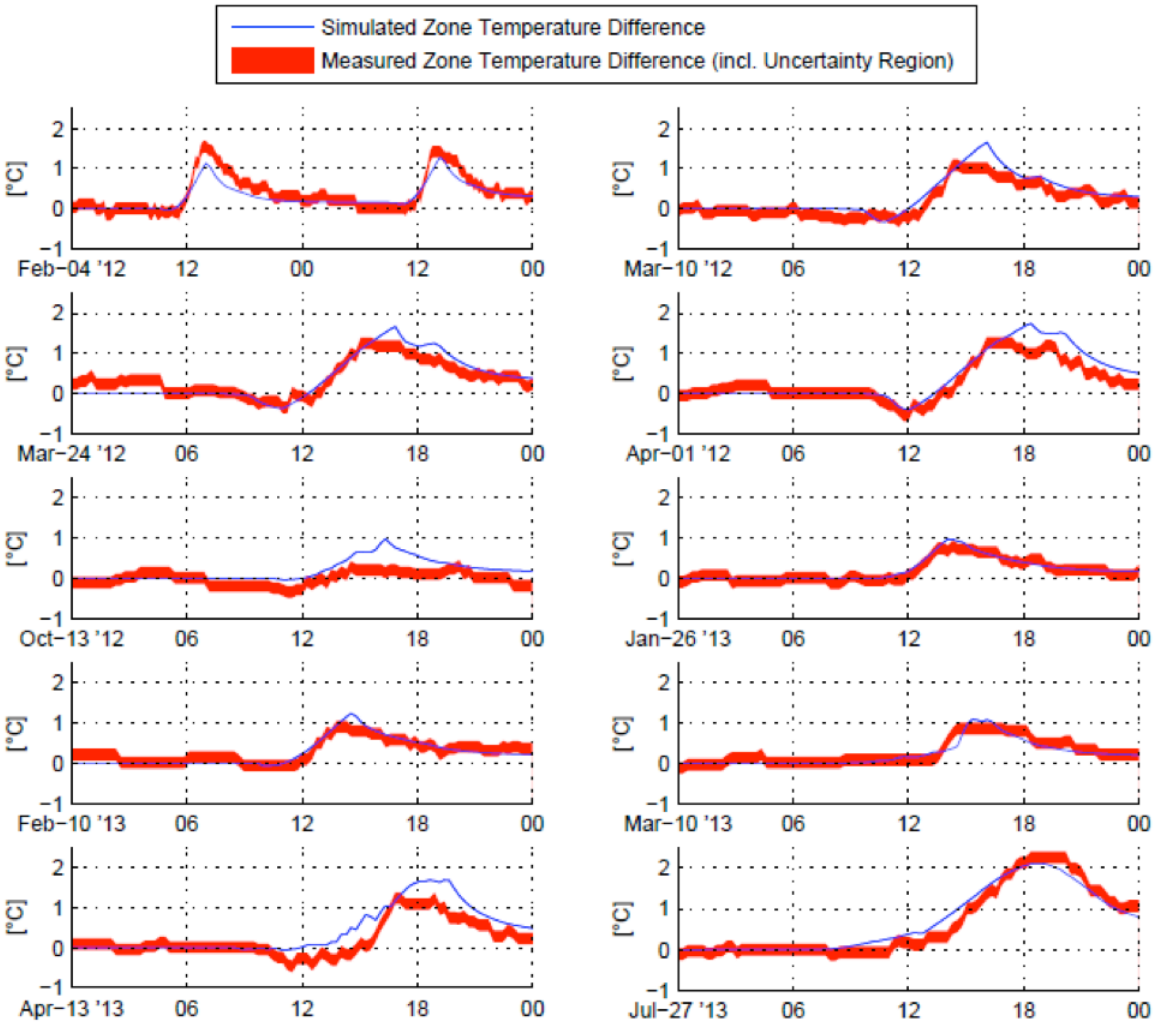


Figure 3-19: Simulated and measured differences in zone temperatures for 10 cases.

Figure 3-19 shows the resulting simulated and measured differences of the zone temperatures for all 10 cases (note that the first simulation comprised two consecutive days). The red region shows an uncertainty range of ±0.15°C around the measured values.

Note that the radiation inputs to the simulation were shifted to 45 minutes later in order to produce the match shown in Figure 3-18. This may sound arbitrary, but indeed this shift lead across all cases to a consistently better fit. We attribute this observation partly to the fact that the sensors send data points only every 1000 seconds (unless the measured value shows a large variation) and partly to the fact that the sensors do not measure the operative temperature (given by the average of the room air temperature and the surface temperatures of the wall) as modeled, but they are dominated by the surface temperature of the wall on which they are mounted. The found delay probably corresponds to the time the sensors need to follow the changing wall surface temperature. Similar delays have been observed in other experiments [15].

Although not perfect, the simulation results fit the measurements reasonably well. Moreover, calculating $Q_{\text{transm solar}}$ using the identified value of $c(\text{open})$ fits the values calculated by $f_{\text{incl2transm}}^{EP}$ very closely. Note that $Q_{\text{transm solar}}$ corresponds only to the directly transmitted solar radiation and does not include secondary effects that come from absorption in the blinds and windows (these are taken into account within the RC model), which explains the rather low value compared to standard transmissivity factors. Note also that the data shown in Figure 3-18 is the same that we used for fitting the parameters because of the limited dataset. This is justified by the very simple one-parameteric form of the function that was fitted.

3.4.1.3 Conclusion

For the two cases blinds opened and blinds closed, we showed that an estimation of the solar heat fluxes by room temperature difference measurements is feasible using typical building automation sensor equipment. A comparison (not shown) of the transmitted power outputs of $f_{\text{incl2transm}}^{EP}$ and $f_{\text{incl2transm}}^{emp}$ for these two blinds positions showed very similar results.

The measurement based approach allows for a validation of the solar heat fluxes, whereas in the complex modeling approach, the solar heat flux estimation is part of the whole building model and cannot be separately validated using typical building automation sensor instrumentation.

A practical application of the presented approach still requires a high effort, in particular the data pre-processing and the off-line identification tasks. However, with further development the effort may be reduced and a fully automated on-line identification of the simple blind model may become possible.

3.4.2 The BRCM Toolbox

3.4.2.1 Purpose, Implementation and Deployment

The aim of the Building thermal Resistance-Capacitance Modeling (BRCM) Toolbox is to provide a means for the fast generation of MPC usable models from basic geometry, construction and building systems data. The Toolbox will also provide support for generating appropriate cost and constraint functions for MPC.

The Toolbox has been written for the MATLAB scientific computing environment and is fully self-contained. It will be open source, and Version 1.0 will be published in Autumn 2013 under the GPL 3.0 license.

A detailed documentation will be uploaded to a dedicated ETH website (www.brcm.ethz.ch), while the actual deployment will make use of the Toolbox Manager (www.tbxmanager.com). Corresponding links will be made available on the project's website (www.opticontrol.ethz.ch).

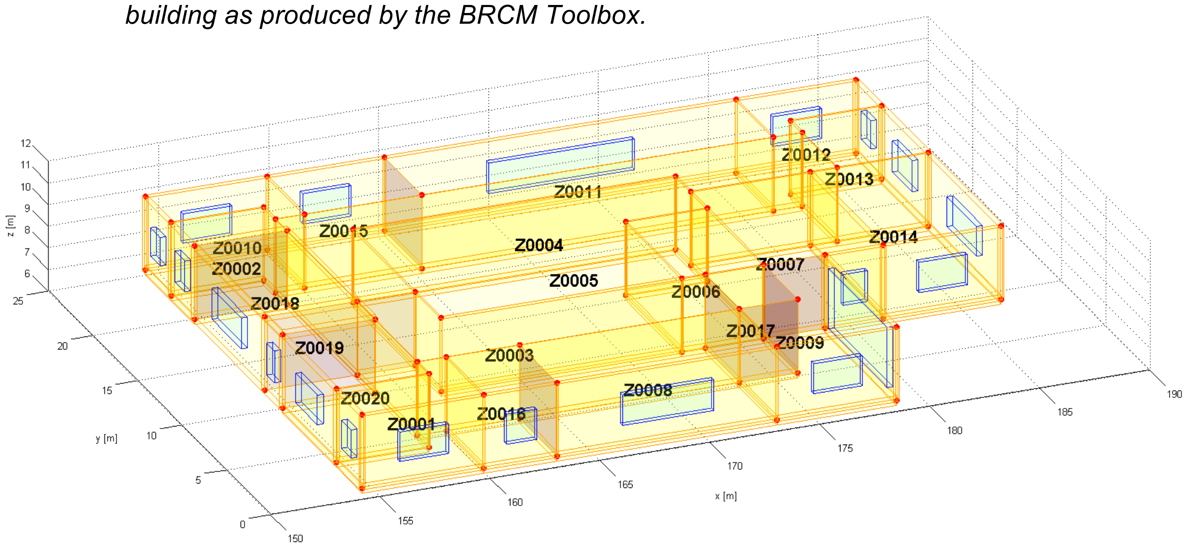
3.4.2.2 Description

The Toolbox supports a modular, stepwise model development procedure based on a powerful object-oriented programmer's interface. The interface has been designed such that a graphical user interface could be easily added at a later stage.

All input data are flexibly retrieved from a structured database that is implemented as a collection of Excel or Comma Separated Values (CSV) formatted tables.

The Toolbox further provides basic functionality for the three-dimensional display of the target building's geometry, and for the simulation of a discrete time representation of the model in open- and closed-loop. It supports simultaneous use of any number of models.

Figure 3-20: Visualization of the geometry of the second floor of the OptiControl-II target building as produced by the BRCM Toolbox.



The starting point for model development is always a model for the thermal dynamics of the building structure (walls, floors, ceilings, room air volumes). This model can then be augmented by the addition of any number of external heat flux (EHF) submodels that represent heat fluxes from and to the building structure (see Section 3.3.1.3).

The BRCM Toolbox Version 1.0 supports the following building geometries: any number of thermal zones, floor plans including oblique walls, oblique floors/ceilings, windows and structural openings as well as possibilites to model outdoor, ground or adiabatic boundary conditions.

Version 1.0 further supports the following EHF submodels: building envelope heat fluxes, solar gains, internal gains, ventilation (including heating/cooling/energy recovery), floor heating, chilled ceilings, radiators and TABS. The software architecture is such that further EHF models can be easily developed and integrated into the Toolbox at a later point in time also by other parties.

All model components are defined based on information retrieved from Excel or CSV files with well-defined structures. The files were defined such as to make the specification as simple and non-redundant as possible while still allowing for a high degree of flexibility. All input data are rigorously checked at runtime for their correctness and consistency.

The core model generation algorithm compiles the input data into a bilinear model and according costs and constraints using the algorithms described in Section 3.3.1 and [10].

3.4.2.3 Functionality

In the following, the functionality of the BRCM Toolbox Version 1.0 is described.

At the time of writing of this document (end of August 2013) most of the core functionality has already been implemented and thoroughly tested, but some parts are still ongoing work. They are denoted below by asterisks (*).

Loading of building data for definition of thermal model. For the thermal model, seven input files are parsed and checked: zones, building elements, regular constructions, “no mass” constructions, materials, windows, parameters.

Generation of thermal model. Automatic generation of the thermal model as in Equation 3.7 based on the building data.

Loading and generation of EHF submodels (*). Loading of the data and generation of all required EHF submodels for a particular case. Combination of the EHF submodels with the thermal model into an overall model.

Visualization. Based on the building data a 3D plot of the building can be generated, e.g. for quick checking of the model’s completeness, see Figure 3-20.

Manipulation of model data. For sensitivity studies the Toolbox supports easy, model-wide changes to model parameters.

Saving of model data. Saving of thermal and EHF submodel data to disk in Excel or CSV format.

Definition of (diagnostic) outputs (*). For simulation studies it is planned to support the possibility of defining as outputs linear combinations of the states (i.e. temperatures) and aggregated heat fluxes, such as the total convective heat flux in a particular zone or the total solar heat flux to the building.

Simulation. The thermal model or the full model (thermal model combined with EHF models) can be simulated either in open-loop by specifying input trajectories or in closed-loop by providing a handle function that can be used to directly simulate an MPC controller.

Generation of thermal model input data files from EnergyPlus model definition code (*). MATLAB based parsing of EnergyPlus “input data files”.

3.5 References

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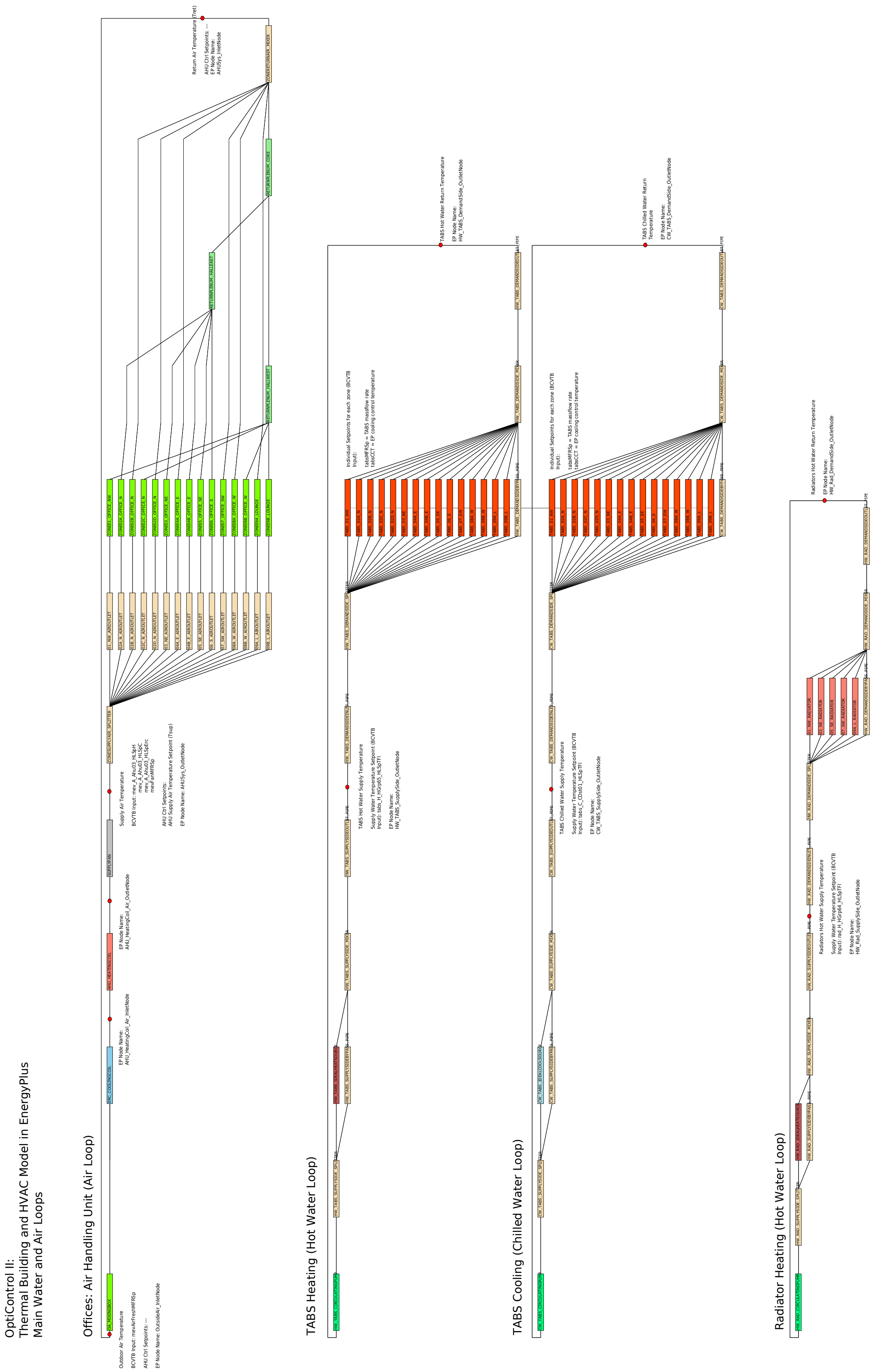
3.6 Appendix

Schematics of HVAC systems as modeled in the EnergyPlus software.



4 Controller Development

D. STURZENEGGER, M. GWERDER, D. GYALISTRAS, & R.S. SMITH

Starting point for the controller development was the work accomplished in the forerunner project OptiControl-I [2]. As was the case in OptiControl-I, we again focused on the two control approaches Rule Based Control (RBC) and Model Predictive Control (MPC).

The control application of the target building was, however, quite different from the applications studied during OptiControl-I. Controller development was therefore executed in two steps: Firstly, the available RBC and MPC algorithms were adapted to the target building. Secondly, completely new control strategies were also developed.

All new control solutions were developed within a common conceptual and technical framework that is described in Section 4.1. The various developed RBC and MPC controllers are described in Sections 4.2 and 4.3, respectively.

4.1 Development Framework

4.1.1 Software Development Environment

Controller development was heavily based on simulations. It presented an iterative process that typically involved the definition, execution and careful post-analysis of a large number of whole-year simulation runs. This enabled us to evaluate and test the controllers under a wide range of operating conditions prior to applying them to the building.

All control strategies were programmed and executed in the MATLAB scientific computing environment. All programs were written such that they could be applied without any changes either to the real building, or to a model of the building as described in Section 3.1.2.1.

The simulations were based on various models of the 2nd floor of the target building. The models provided the full high-level control interface (for a definition of high- and low-level control see the next section), and they implemented the underlying low-level control to various degrees of detail. For further information see Chapter 3.

The RBC solutions were developed based on simulations solely with a detailed model that was based on the EnergyPlus software (Section 3.1). For MPC development a simplified thermal Resistance-Capacitance Model (Section 3.2.1.4) running within the MATLAB environment was also used.

4.1.2 System Topology

The target building was operated throughout using a hierarchical control structure that was apparent not only in the software, but also in the installed hardware.

Figure 4-1 shows the system topology of the Siemens building automation system DESIGO (see [1]). There, the control is structured in three levels, from bottom to top: the field level, the automation level and the management level.

The field level includes all sensors and actuators and the individual room control. Field level devices execute room temperature control by valve/damper operation to given setpoints, room ventilation control by damper operation, and presence dependent room luminance control (possibly to a given luminance setpoint). The automation level executes primary plant control (e.g. control of air handling units, heat/cold generation and distribution). Further it integrates the individual room controllers and it does the building usage/occupancy scheduling. The management level is mainly used for operation and monitoring.

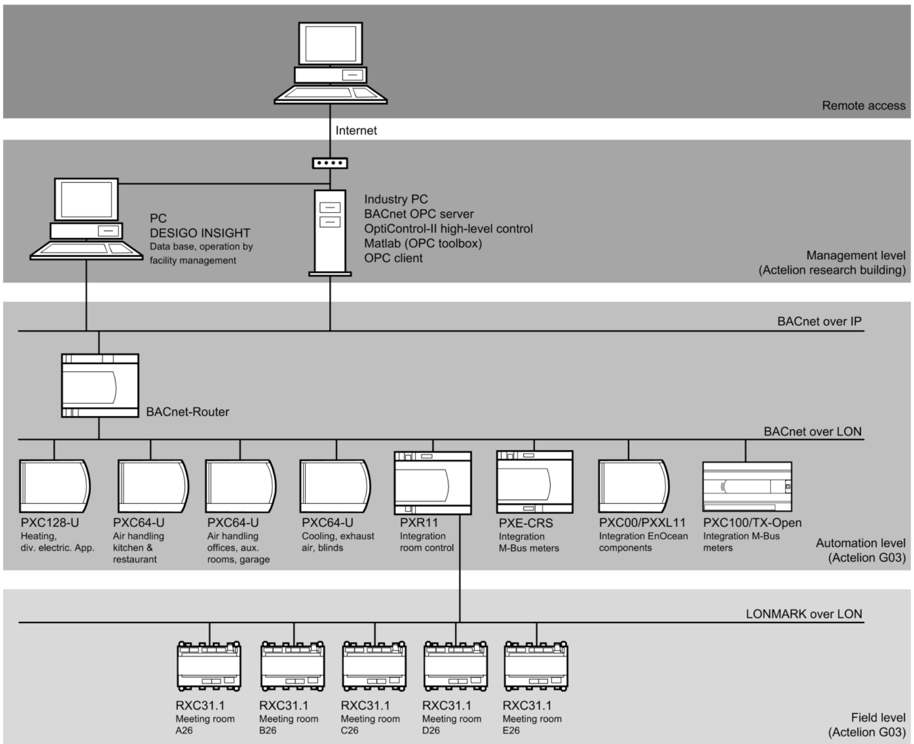


Figure 4-1: System topology (hardware) of the Siemens building automation system in the Actelion G03 demonstrator building

All newly developed control algorithms were realized in a new control layer that implemented so-called **high-level (HL) control**. The task of a HL controller is to specify operating modes and setpoints that are sent to various underlying low-level (LL) controllers. The latter execute all appropriate actions and deliver measurements (e.g. room temperatures), heat/cold demand, setpoints etc. back to the HL controller.

HL control was realized completely on an industry PC. The PC ran a Building Automation and Control networks (BACnet) Object Linking and Embedding for Process Control (OPC) server to communicate with the other parts of the building's automation system. The HL control algorithms were executed in MATLAB using the OPC toolbox to connect to the BACnet OPC server.

The collection of control tasks running on the field and automation levels presented the so-called **low-level (LL) control**. The original pre-OptiControl-II (default) control strategy was actually implemented as LL control only.

4.1.3 High-Level/Low-Level Control Interface

All developed controllers used the same, common HL–LL interface. The HL control's input interface required only a small subset of the information available at the LL (ca. 260 of several thousand available signals, not shown). The HL control's output interface was defined to act on an even smaller number of carefully chosen data points (Table 4-1).

The HL–LL control interaction was deliberately designed in this way in order (i) to limit the interference of the HL control with the LL control programs to the smallest possible amount of relevant information, (ii) to limit the HL-LL control interaction to once every 15 minutes, and (iii) to be able to optionally run the overall automation system without any HL control (fall-back strategy, see Section 4.1.6).

Table 4-1: Output interface of High-Level Control

	Description	Unit	Range	BACnet object name
	Enable high-level control	No/Yes	[0, 1]	B02'AfAs'HLCtl'EnHLCtl
	Life check set	No/Yes	[0, 1]	B02'AfAs'HLCtl'LchkSet
	High-level control version	---	[0, MAX]	B02'AfAs'HLCtl'HLCtlVer
Heating TABS	Enable high-level control	No/Yes	[0, 1]	B02'H'HGrp65'EnHLCtl
	High-level operating mode	---	[Auto/Off/On]	B02'H'HGrp65'HLOpMod
	High-level flow temperature setpoint	°C	[10…35]	B02'H'HGrp65'HLSpTFl
	High-level enable PWM	No/Yes	[0, 1]	B02'H'HGrp65'HLEnPwm
Cooling TABS	Enable high-level control	No/Yes	[0, 1]	B02'C'CDst01'EnHLCtl
	High-level operating mode	---	[Auto/Off/On]	B02'C'CDst01'HLOpMod
	High-level flow temperature setpoint	°C	[10…35]	B02'C'CDst01'HLSpTFl
Heating Static	Enable high-level control	No/Yes	[0, 1]	B02'H'HGrp64'EnHLCtl
	High-level operating mode	---	[Auto/Off/On]	B02'H'HGrp64'HLOpMod
	High-level flow temperature setpoint	°C	[10…35]	B02'H'HGrp64'HLSpTFl
Ventilation offices	Enable high-level control	No/Yes	[0, 1]	B02'A'Ahu03'EnHLCtl
	High-level operating mode	---	[Auto/Off/On]	B02'A'Ahu03'HLOpMod
	High-level supply air temperature setpoint heating	°C	[10…35]	B02'A'Ahu03'HLSpH
	High-level supply air temperature setpoint cooling	°C	[10…35]	B02'A'Ahu03'HLSpC
	High-level supply air temperature setpoint ERC	°C	[10…35]	B02'A'Ahu03'HLSpErc
	High-level differential pressure setpoint supply	Pa	[0…300]	B02'A'Ahu03'FanSuMgt'HLSpPSu
	High-level differential pressure setpoint exhaust	Pa	[0…300]	B02'A'Ahu03'FanExMgt'HLSpPEx
Blinds	Enable high-level control	No/Yes	[0, 1]	B02'E'Bls'EnHLCtl
	High-level control open N	No/Yes	[0, 1]	B02'E'Bls'HLOpenN
	High-level control close N	No/Yes	[0, 1]	B02'E'Bls'HLCloseN
	High-level control pos.1 N	No/Yes	[0, 1]	B02'E'Bls'HLPos1N
	High-level control pos.2 N	No/Yes	[0, 1]	B02'E'Bls'HLPos2N
	High-level control open E	No/Yes	[0, 1]	B02'E'Bls'HLOpenE
	High-level control close E	No/Yes	[0, 1]	B02'E'Bls'HLCloseE
	High-level control pos.1 E	No/Yes	[0, 1]	B02'E'Bls'HLPos1E
	High-level control pos.2 E	No/Yes	[0, 1]	B02'E'Bls'HLPos2E
	High-level control open S	No/Yes	[0, 1]	B02'E'Bls'HLOpenS
	High-level control close S	No/Yes	[0, 1]	B02'E'Bls'HLCloseS
	High-level control pos.1 S	No/Yes	[0, 1]	B02'E'Bls'HLPos1S
	High-level control pos.2 S	No/Yes	[0, 1]	B02'E'Bls'HLPos2S
	High-level control open W	No/Yes	[0, 1]	B02'E'Bls'HLOpenW
	High-level control close W	No/Yes	[0, 1]	B02'E'Bls'HLCloseW
	High-level control pos.1 W	No/Yes	[0, 1]	B02'E'Bls'HLPos1W
	High-level control pos.2 W	No/Yes	[0, 1]	B02'E'Bls'HLPos2W
	High-level control enable shading	No/Yes	[0, 1]	B02'E'Bls'HLEnShd
	High-level control disable scheduling	No/Yes	[0, 1]	B02'E'Bls'HLDsSched
	High-level control open Awning	No/Yes	[0, 1]	B02'E'Bls'HLOpenAw
	High-level control close Awning	No/Yes	[0, 1]	B02'E'Bls'HLCloseAw

4.1.4 Low-Level Control

The LL control program was an industry standard solution for the various needed control applications. It was not essentially changed during the course of the project. Below follows a concise report of the LL actions associated with the various HL signals.

4.1.4.1 TABS Heating

- If the TABS heating “HL operating mode“ is set to “Off”, the TABS heating circuit is switched off (turn off pump and close mixing valve).
- If the TABS heating “HL operating mode“ is set to “On”, the TABS heating circuit is switched on (turn on pump), and the flow temperature is controlled to the TABS heating “HL flow temperature setpoint” by opening/closing the TABS heating mixing valve.
- If the TABS heating “HL operating mode“ is set to “Auto”, the TABS heating circuit is switched on or off based on the LL control.
- In addition, if the TABS heating “HL enable PWM” flag is set to 1, the LL control executes a Pulse Width Modulation (PWM) control.

4.1.4.2 TABS Cooling

- If the TABS cooling “HL operating mode“ is set to “Off”, the TABS cooling circuit is switched off (turn off pump).
- If the TABS cooling “HL operating mode“ is set to “On”, the TABS cooling circuit is switched on (turn on pump), and the primary flow temperature (cooling tower outlet temperature) is controlled to the TABS cooling “HL flow temperature setpoint” by LL-operation of the cooling tower.
- If the TABS cooling “HL operating mode“ is set to “Auto”, the TABS cooling circuit is switched on or off based on the LL control.

4.1.4.3 Static Heating

- If the static heating “HL operating mode” is set to “Off”, the static heating circuit is switched off (turn off pump and close mixing valve).
- If the static heating “HL operating mode” is set to “On”, the static heating circuit is switched on (turn on pump) and the static heating flow temperature is controlled to the “Static heating HL flow temperature setpoint” by LL-operation of the static heating mixing valve.
- If the static heating “HL operating mode” is set to “Auto”, the static heating circuit is switched on or off based on the LL control.

4.1.4.4 Ventilation

- If the Ventilation “HL operating mode” is set to “Off”, the ventilation is turned off.
- If the Ventilation “HL operating mode” is set to “On”, the supply and exhaust fans are turned on, and they are LL-controlled to maintain the “HL differential pressure setpoint supply” and “HL differential pressure setpoint exhaust”, respectively.
- If the Ventilation “HL operating mode” is set to “Auto”, the ventilation is turned on or off based on the LL control.
- If the fans are running, the supply air temperature is LL-controlled by (i) the heating coil (to the “HL supply air temperature setpoint heating”), (ii) the cooling coil (to the “HL supply air temperature setpoint cooing”), and (iii) the energy recovery unit (to the “HL supply air temperature setpoint ERC”).

4.1.4.5 Blinds

- The blinds on façade X (equal to North, East, South or West) are

opened if the flag “HL control open X” is set to 1,
closed if the flag “HL control close X” is set to 1,
set to shading position 1 if the flag “HL control pos.1 X” is set to 1,
set to shading position 2 if the flag “HL control pos.2 X” is set to 1.

- If the “HL control enable shading” flag is set to 1, the LL control blind shading control is enabled, i.e. blinds are controlled based on LL control luminance measurements to protect from glare. Otherwise, the LL control blind shading program is disabled.
- If the “HL control disable scheduling” flag is set to 1, the LL control blind scheduling is disabled. Otherwise, the LL control blind scheduling is enabled.
- Finally, the vertical awnings on the south façade (lounges) are
  opened if the flag “HL control open Awning” is set to 1,
  closed if the flag “HL control close Awning” is set to 1.

4.1.5 General Control Settings

4.1.5.1 Blind Control Restrictions

Blind control is of major importance for the management of solar heat gains and reduction of night-time energy losses. At the same time it presents a delicate issue with regard to user acceptance given its large impact on workplace visual, aesthetic and acoustic comfort.

Prior to starting with controller development we therefore discussed possible blind control options with the facility managers of the demonstrator building. It was decided to strongly limit automatic blind control actions in order to keep disturbance for the occupants at a minimum level.

Firstly, all control solutions were allowed to execute only one automatic blind control action at 13:00 during daytime at working days (all times of day reported here were those used in the simulations; in the real building slightly different values were used). From 19:00 to 07:00 (night-time) and at weekends, however, no restrictions were applied.

Secondly, in order to ensure minimum natural daylight levels, HL control was allowed to fully close the blinds only outside of working hours (i.e., workdays from 07:00 to 19:00).

Thirdly, in order to protect occupants from glare, if the measured solar radiation on a given façade orientation was higher than 200 W/m2, the set of admissible HL blind control actions for all offices with that façade orientation at 13:00 on workdays was limited such as to prohibit direct radiation entering the room.

A further restriction occurred due to technical limitations of the blinds control subsystem. The subsystem was such that it allowed HL control to command but four blind positions: open, close, shading position one (defined as blinds down, lamellas at 45° angle position) and shading position two (defined as blinds down, lamellas at 70° angle position).

4.1.5.2 Ventilation

The target building’s ventilation system supplies all offices and the outer meeting rooms of the upper floors. Variable air volume control is only available in the meeting rooms. In order to satisfy (potential) air demand in the offices, the ventilation was therefore always operated from 07:00 to 19:00 on workdays.

The volumetric flow control was not affected by HL control. A typical constant pressure control was always applied: The supply fan maintains a constant pressure in the supply air duct, and the extract fan maintains a constant pressure in the extract air duct. In simulations, this was approximated by applying constant air flows to the zones.

4.1.5.3 Thermal Comfort Settings

The simulations used default thermal comfort settings as shown in Figure 4-2. The default comfort range for winter was [21°C, 25°C] and for summer it was [22°C, 26°C]. In midseason, the comfort range was shifted depending on the running mean of the outside air temperature. The running mean and the shift were calculated according to EN 15251 .

The thermal comfort settings applied to the real building varied somewhat across different phases of operation. In particular, the lower bound of the comfort range was set to 22°C also in wintertime for most field experiments.

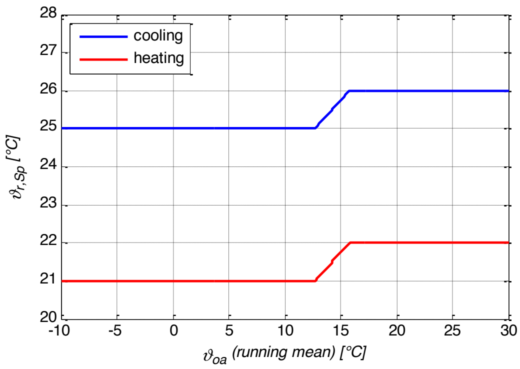


Figure 4-2: Room temperature comfort range (default case for simulations)

4.1.5.4 Weather Predictions

All newly developed control strategies (except for strategy “RBC-1”, see below) implemented predictive control. They incorporated local weather predictions from the “COSMO-7” operational numerical forecast system operated by the Swiss Federal Office of Meteorology and Climatology, MeteoSwiss [4]. The predictions consist of hourly values of several weather variables (most importantly outside air temperature and global radiation) over a prediction horizon of 72 hours.

For control of the real building the COSMO-7 data sets were retrieved from a Secure File Transfer Protocol (SFTP) server hosted at ETH. New predictions were uploaded to this server by MeteoSwiss three times per day having prediction start times of 00:00, 06:00 and 12:00 UTC.

For simulations, locally stored, archived MeteoSwiss weather forecasts were used. The forecasts used in the simulations started at 00:00 and 12:00 UTC.

4.1.5.5 Supply Air Temperature Restrictions

In order to maintain comfort in the building – in particular to prevent undesired air draught – the supply air temperature setpoints were limited. The minimal allowed setpoint was 16°C in summer and 22°C in winter. The maximal allowed setpoint was 28°C.

4.1.6 High-Level Control Implementation

All HL control algorithms were executed in the MATLAB computing environment that was running on a 2.8 GHz dual core industry PC under the Windows Server 2003 operating system. Control was done at a sampling interval of 15 minutes. The MATLAB software was restarted at the beginning of every control time step by a periodic operating system task in order to be robust against previous execution errors and to avoid memory fragmentation.

Since the building was occupied throughout the experiments, a robust operation of the high-level (HL) control was of major importance. All developed HL control solutions were defined such that switching back to the original control solution (that ran independently from the industry PC) was possible at all times. The fallback strategy was as follows: The control system's functioning is continuously monitored at the automation level. In case of a problem an alarm is triggered and if the problem persists for a pre-specified time the system switches automatically back to the default strategy. For example, in case of a HL–LL communication failure, it was specified that the default strategy gets activated after 4 hours.

4.2 Rule-Based Control

4.2.1 Overview

During the course of the project we considered five different Rule-Based Control (RBC) strategies, RBC-0 to RBC-4. Table 4-2 summarizes their characteristics.

RBC-0 was the control strategy that was running in the building prior to the start of the project. It served as a reference control strategy. Strategies RBC-1 to RBC-4 were newly developed within the project OptiControl-II.

The novel strategies RBC-1 to RBC-4 implemented integrated control, i.e. they featured communication and coordination between control of heating, cooling, ventilation and blinds. The strategies build upon each other and present a stepwise increase in complexity with the goal to improve control performance. This resulted into different instrumentation requirements as well as varying engineering, tuning and optimization effort (Table 4-2, see also Chapter 7).

Table 4-2: Characteristics of the investigated RBC strategies

	RBC-0	RBC-1	RBC-2	RBC-3	RBC-4
Integrated control	-	✓	✓	✓	✓
Predictive control	-	-	✓	✓	✓
Model-based control	-	-	-	✓	✓
Instrumentation effort	Low	Low	Medium	Medium	Medium
Engineering effort	Low	Medium	Medium	Medium	Medium
Initial tuning and optimization effort	High	Medium	Low	High	Medium

4.2.2 RBC-0: Reference Control

The control strategy RBC-0 emulated the building's original control strategy that was in operation before the OptiControl-II project. It is not predictive and it does not follow an integrated approach, i.e. heating by TABS, cooling by TABS, heating by radiators, ventilation operation, and blinds and electrical lighting actuation are all controlled independently from each other.

The simulation of RBC-0 proved to be quite challenging since manual interactions of the facility manager such as the switching between TABS heating and cooling mode twice a year had to be incorporated somehow. In addition, during the course of the project erroneous outside air temperature measurements were detected (sensors were exposed to direct solar radiation, Section 2.3), and this probably had a significant effect on historical RBC-0 control performance. This effect could not be reproduced with reasonable effort in the simulations.

4.2.3 RBC-1: Simple Integrated Control

RBC-1 [5] was the first newly developed control strategy. It featured simple integrated control. Most important element of this integrated control is the assessment of actual and past heat and cold demand by all relevant heat and cold consumers. The strategy was derived from the strategy Ref-3 described in [6]; it uses similar rules to determine operation of blind positioning and heat recovery of the mechanical ventilation.

The integrated control ensures that two cheap energy sources – the ventilation system's energy recovery system and the blinds operation – are used to support the active heating and cooling of the building. Control of TABS was done as described in [7], but using no room temperature control. For TABS heating intermittent operation, so called Pulse Width Modulation (PWM), was incorporated as an option. It served minimizing the on/off switching and runtime of the pump that operates the TABS heating circuit.

4.2.3.1 Preparation of Control Inputs

The inputs required by RBC-1 were prepared at the beginning of each HL control time step based on the following actions:

(1) *Determine relevant outside air temperature*
The building automation station had access to four outside air temperature measurements from sensors located at the building's four façades. Depending on day of year and time of day each sensor may catch sunlight, but there is always a sensor that does not. Therefore, the relevant outside air temperature was calculated by taking the minimum value of the four measurements.

(2) *Calculate running mean of outside air temperature*
The running mean of the outside air temperature was required as an input to the calculation of the room temperature comfort range according to EN 15251 [3]. It was calculated by filtering the time series of relevant outside air temperature from Step (1) using a 1st order low pass filter with a time constant of 100 hours.

(3) *Calculate mean outside air temperature of the last 24 hours*
The mean outside air temperature of the last 24 hours $\bar{\vartheta}_{oa}$ was calculated by averaging all available relevant outside air temperature values from the last 24 hours.

(4) *Determine historical heat and cold demand status*
The historical heat and cold demand status was determined at each HL time step separately for TABS heating, TABS cooling, ventilation heating, ventilation cooling, and static heating. The demand status of a given consumer was a boolean variable that was assigned the result of the following condition: "During the last N (default: 24) hours the consumer has demanded the given energy type at least once for a duration of M (default: 60) minutes". A boolean "AND" operation was performed to determine aggregated historical heat and cold demand signals, and the type of the last demand (none, heating, cooling, heating & cooling) was also determined and stored in a separate variable.

(5) *Determine relevant room temperatures*
Room temperature measurements may vary largely across rooms depending on, e.g., time of day and occupant behavior. The following room groups were introduced: all office rooms (for TABS and ventilation cooling control), all non-corner offices (for TABS and ventilation heating control), all meeting rooms on the south façade (optionally for ventilation control), office and meeting rooms per façade (for blind control). For all room groups, the available room temperature measurements were collected and outlier measurements were removed. Then each group's minimal and maximal values were computed for further processing by the controller. The group's average temperature value was also determined for diagnostic reasons.

(6) *Calculate room temperature comfort range*
The current room temperature comfort range (i.e., the system's current heating setpoint $\vartheta_{r,SpH}$ and cooling setpoint $\vartheta_{r,SpC}$) was calculated for each group of rooms using the temperature data from Step (2) and the procedure outlined in Section 4.1.5.3.

(7) *Calculate solar position*
The following quantities were calculated: the current solar position (azimuth and elevation angles), the profile angle (projected solar elevation angle) per façade, and the potential occurrence of direct solar radiation per façade.

(8) *Calculate historical room temperature deviations from comfort range*
For each room temperature group from Step (5) was first calculated the deviation of the minimal room temperature from the lower comfort range from Step (6), and the deviation of the maximal room temperature from the upper comfort range from Step (6). Then, the minimal deviations of the specified number of past N (default: 24) hours were determined and named $\Delta\vartheta_{r,H}$ and $\Delta\vartheta_{r,C}$ ($\Delta\vartheta_{r,H}$ > 0, $\Delta\vartheta_{r,C}$ > 0 if all room room temperatures of the past N hours within comfort range).

4.2.3.2 TABS Control

The main idea for the HL control of the TABS was based on [7], [8], [9] and [10]. Figure 4-3 shows the main HL control parts as well as the output interface to the LL control (BACnet object names printed in blue, cf. Table 4-1).

First, supply water temperature setpoints $\vartheta_{sw,SpH}$ and $\vartheta_{sw,SpC}$ as well as operating modes operating modes for continuous operation are calculated based on room temperature setpoints and the mean outside air temperature of the last 24 hours. In a second step, a pulse width modulation for cooling operation is performed optionally (default: PWM active), changing the cooling supply water temperature setpoint and cooling operating mode.

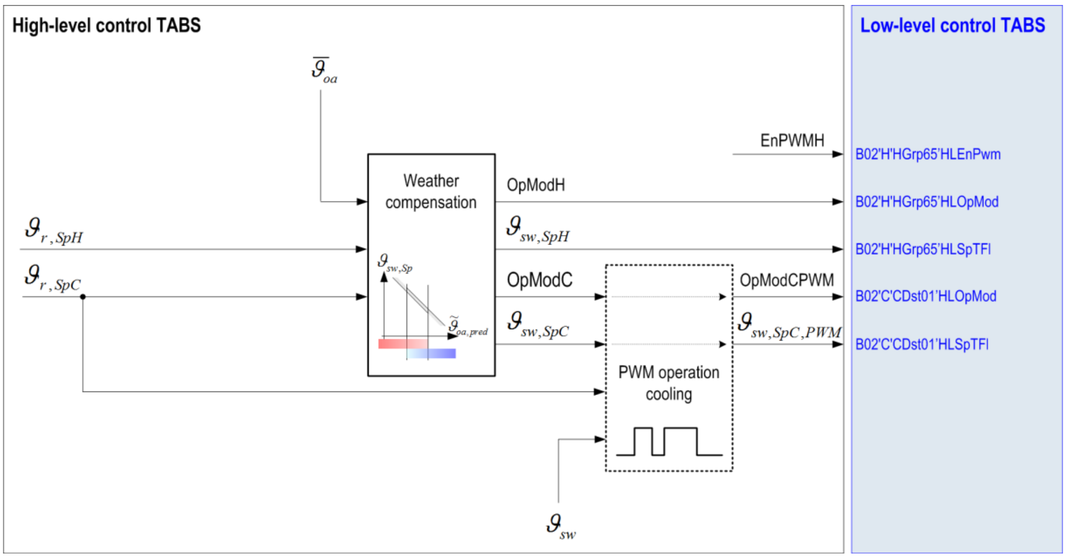


Figure 4-3: TABS high-level control and output interface to low-level control

4.2.3.3 Blind Control

Figure 4-4 shows the main parts of the HL blind control as well as the output interface to the LL control (cf. Table 4-1). The primary goal of this HL control is to position the blinds such that energy demand is minimized.

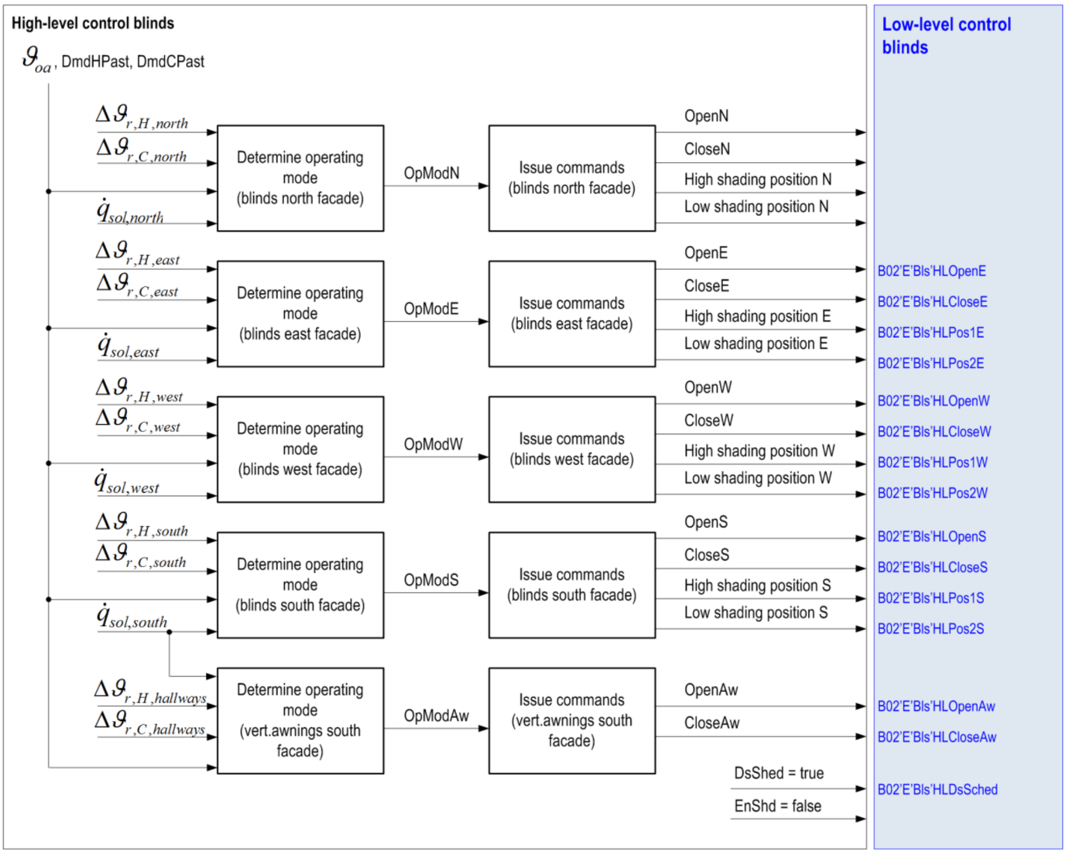


Figure 4-4: Blinds high-level control and output interface to low-level control

Figure 4-5: High-level control of RBC-1, part blinds (executed separately per façade)

The blinds are set on a per façade basis to one of the blind operating modes LOAD, UNLOAD, SHADE_MIN or SHADE_MAX. This is done depending on historical heat/cold demand, room temperatures, outside air temperature and solar radiation on the façade (Figure 4-5). The operating modes are then translated into blind commands that are issued per façade: E.g., the operating mode LOAD is translated during daytime to the command "open", during night-time to the command "close".

Glare protection is handled neither by the HL (except blind commands issued during working hours) nor by the LL control; it is entirely left over to the occupants.

4.2.3.4 Ventilation Control

Figure 4-6 shows the main elements of the HL ventilation control as well as its output interface to LL control (cf. Table 4-1).

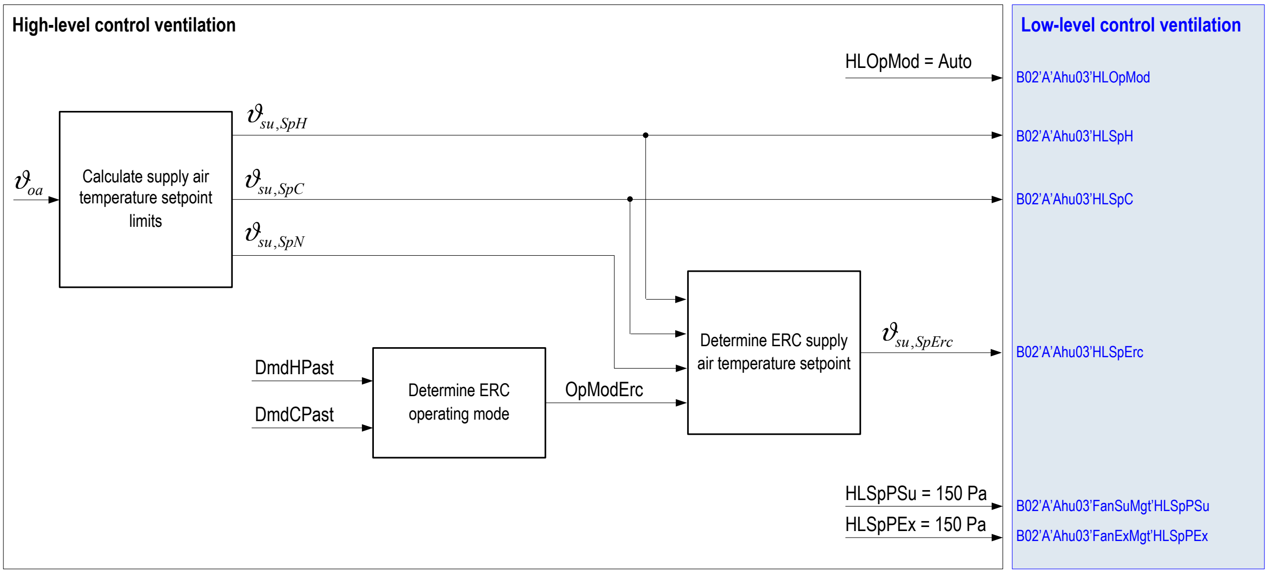


Figure 4-6: Ventilation high-level control and output interface to low-level control

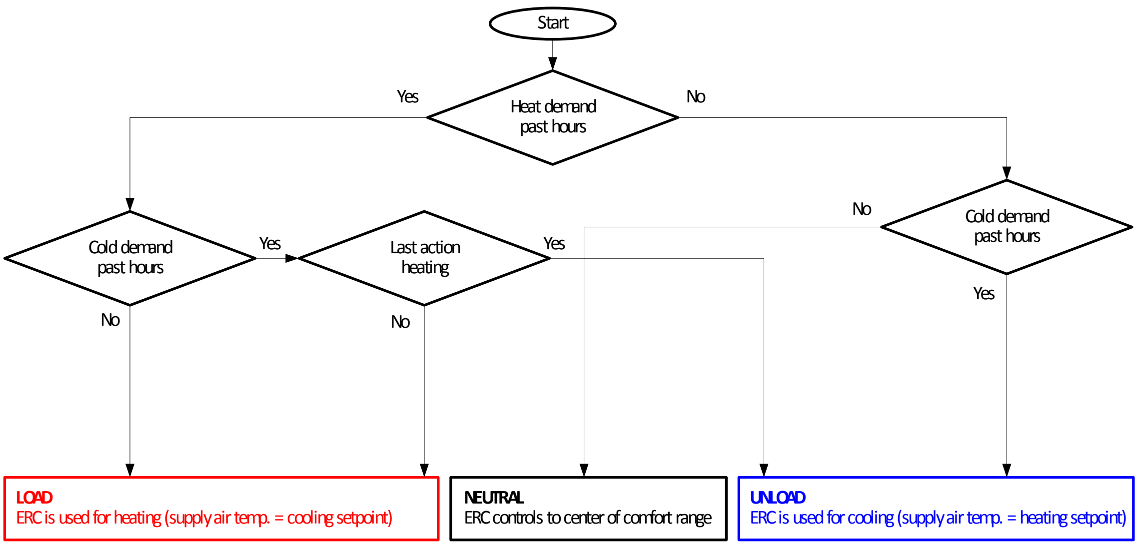


Figure 4-7: High-level control of RBC-1, part ventilation

Ventilation is operated according to a schedule and it is controlled by maintaining differential air pressure setpoints between (i) the main supply duct and the outside and (ii) the extract air and the outside. The setpoint for both, supply and exhaust fan control, is 150 Pa.

The ventilation system's energy recovery unit consists of a plate heat exchanger and a bypass of the exchanger for the supply air. The fraction of total supply air flowing through the exchanger can be varied by a damper. In LL control, the damper is controlled to maintain a given ERC supply air temperature setpoint. This setpoint is determined based on the ERC operating mode which is calculated with the rules shown in Figure 4-7.

4.2.4 RBC-2: Advanced Integrated and Predictive Control

The second developed algorithm, RBC-2 [11], was predictive and had an intermediate complexity. It was derived partly based on the strategy Ref-3 described in [6] and partly based on the predictive rule-based control described in [11]. RBC-2 uses outside air temperature and global radiation forecasts from MeteoSwiss [4] for the control of both TABS and blinds. Unlike RBC-1, the strategy uses room temperature measurements in the offices not only for blind but also for TABS control, thereby reducing tuning and optimization effort.

4.2.4.1 Preparation of Control Inputs

RBC-2 requires the same preparation steps as RBC-1, plus an additional one:

- *Prepare weather prediction data*
  COSMO-7 weather predictions are retrieved as described in Section 4.1.5.4. If the download fails or contains invalid data, a persistence forecast is applied as a fall-back solution. The predicted hourly values are resampled for all required prediction points in time. Global solar radiation fluxes at each building façade are calculated from the forecasted horizontal global radiation values by using the radiation conversion algorithm reported in [13].

4.2.4.2 TABS Control

The used TABS control approach is outlined in Figure 4-8. It extends the procedure implemented in RBC-1 by room temperature control as described in [7] (Chapter 9.1), plus by an algorithm to include weather forecasts and optionally also blind operation information.

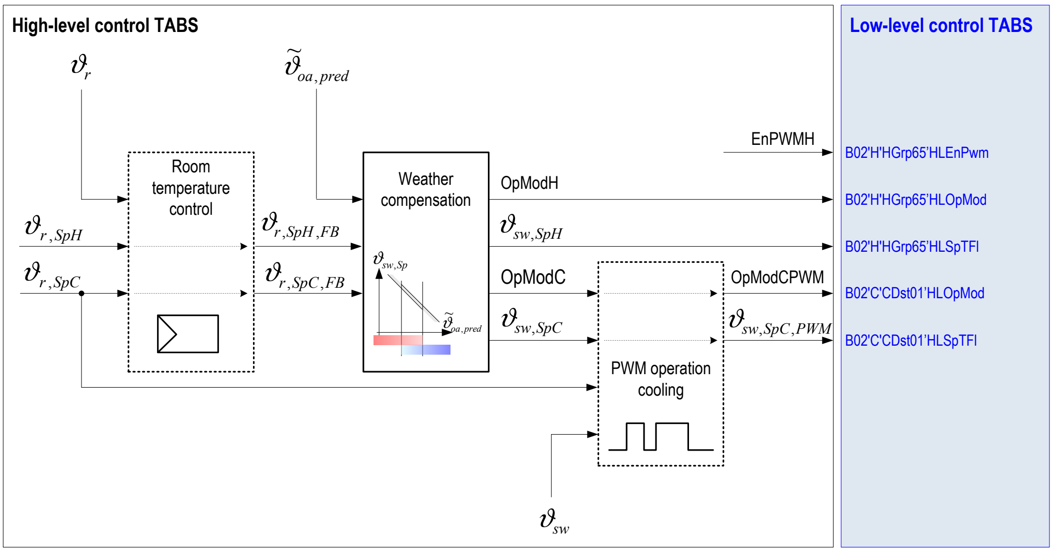


Figure 4-8: TABS high-level control and output interface to low-level control

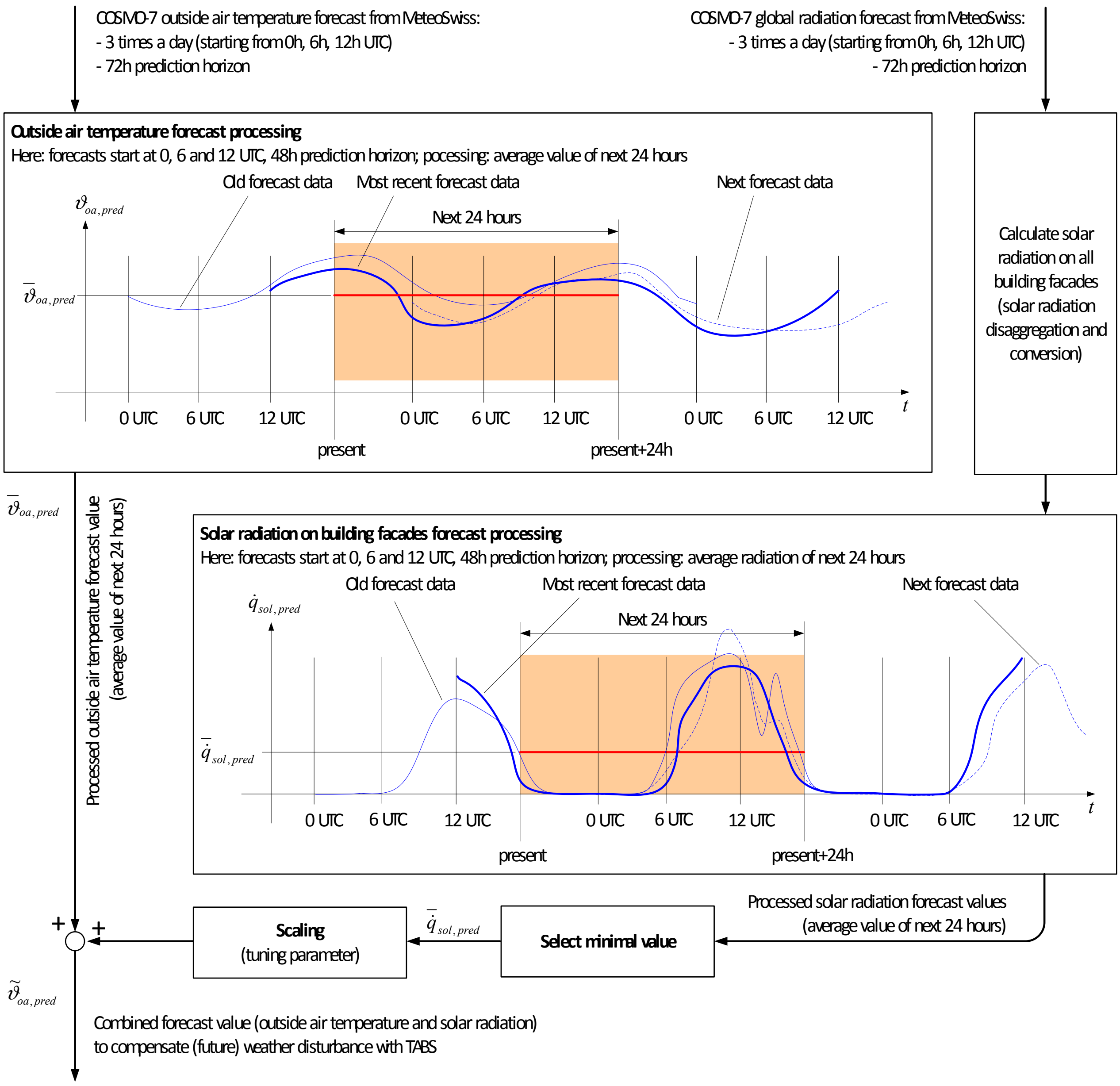


Figure 4-9: Calculation of the effective temperature used to compensate future weather disturbances with TABS

Different from RBC-1, the disturbance input $\tilde{\vartheta}_{oa,pred}$ for the weather compensation function (cf. Figure 4-8) is not given by the average outside air temperature of the past 24 hours, but rather by an “effective” average future temperature value that is constructed from the most recent available COSMO-7 forecast. The procedure used is outlined in Figure 4-9. The effective temperature is calculated as the sum of the average predicted temperature for the next 24 hours and of the scaled minimal 24 hour mean predicted value of global solar radiation from all building façades. The scaling factor is computed as the product of a base factor with a secondary factor that accounts for the future blind status. Future blind positions are estimated based on the actual blind operating mode.

4.2.4.3 Blind Control

Blind control is done similar as for RBC-1, except that the blind operating modes are determined in a slightly different manner: if the current point in time lies just before a phase with restricted blind usage or is an exception time point within a restriction phase (i.e., workday at 07:00 or exception time point 13:00, see Section 4.1.5.1), the blind operating mode is not determined from actual measurements but from the following predicted values:

- Maximum predicted outside air temperature in the restricted blind usage phase ahead
- Mean predicted solar radiation on the façade in the restricted blind usage phase ahead

In these cases, the blind operating mode is set to SHADE_MIN if either maximum predicted outside air temperature is higher than a threshold value (default: 17°C) or mean predicted solar radiation on the façade for the restricted phase ahead is higher than a threshold value (default: 150 W/m^2), see Figure 4-10.

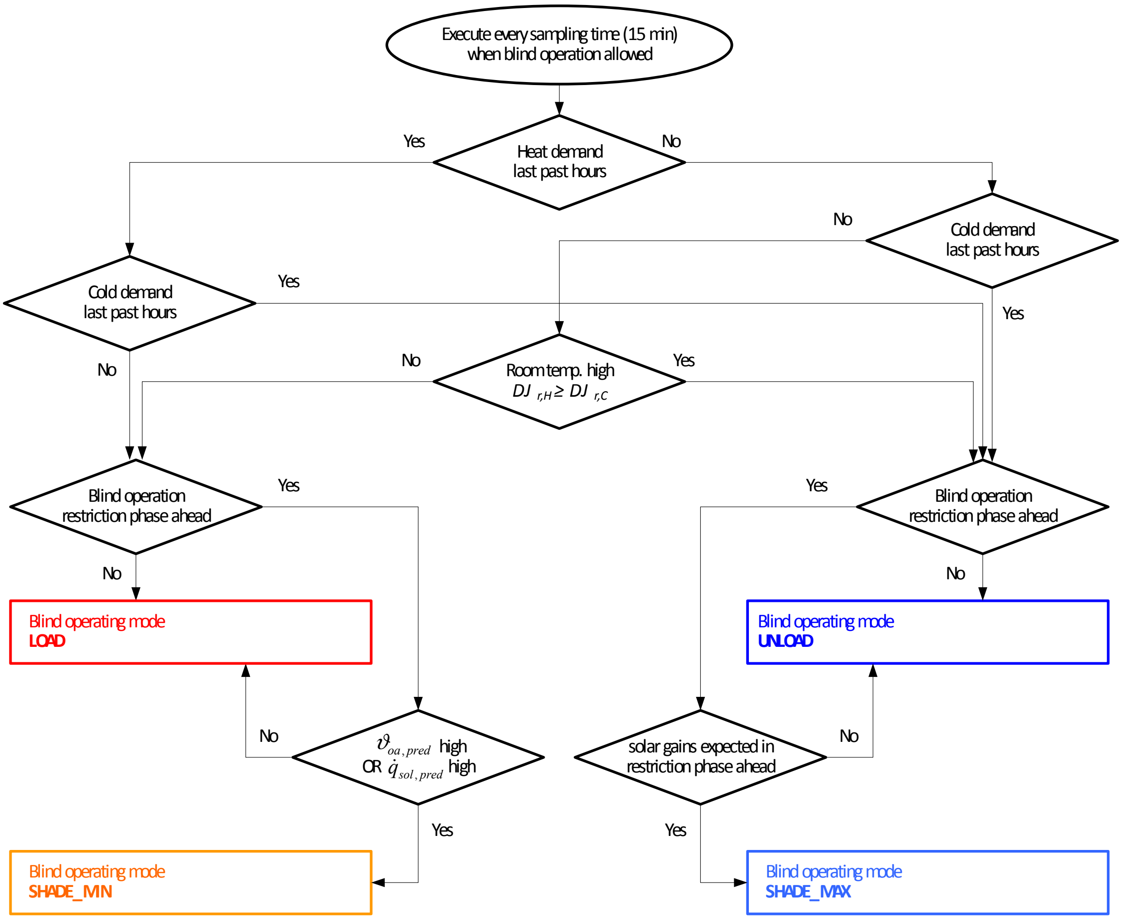


Figure 4-10: High-level control of RBC-2, part blinds (executed separately per façade)

4.2.4.4 Ventilation Control

Ventilation control is done in a similar way as for RBC-1, except that RBC-2 considers in addition a room temperature (cascade master) controller, see Figure 4-11. The minimal and maximal supply air temperature setpoint limits are calculated depending on the mean predicted outside air temperature of the next 24 hours. The room temperature control function controls the room temperatures by changing supply air temperature setpoints. For all offices equipped with room temperature sensors, room temperature deviations from the comfort range are controlled to zero. I.e., the relevant minimal room temperature (see Section 4.2.3.1) is controlled to the lower limit of the comfort range and the relevant maximal room temperature is controlled to the upper limit of the comfort range. In addition, a third control loop controls the mean relevant room temperature to the center of the comfort range.

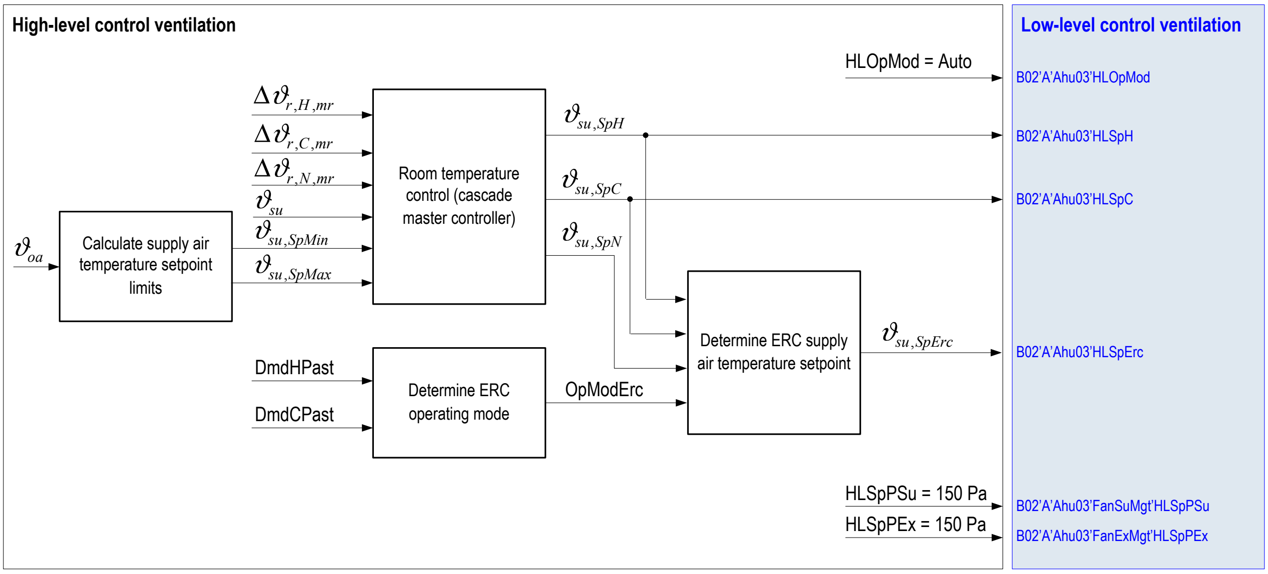


Figure 4-11: High-level control of RBC-2, part ventilation

The setpoint control is accomplished by means of a Proportional-Integral (PI) controller using output tracking of the measured supply air temperature to calculate the integral action part. The three control errors lead to three different proportional action parts and to the three control outputs: the lower and upper supply air temperature setpoints (which are sent directly to LL control), and the intermediate supply air temperature setpoint which is used depending on the ERC operating mode. There, the lower value is used to control the heating coil; the upper value is used to control the cooling coil. A minimal supply air temperature setpoint range width is maintained. Therefore, the upper setpoint is corrected if necessary.

4.2.5 RBC-3/4: Model-based Integrated and Predictive Control

Both RBC-3 and RBC-4 [14] control the blinds and ventilation in exactly the same way as RBC-2. They only differ from RBC-2 with respect to the control of TABS.

4.2.5.1 TABS Control RBC-3

The RBC-3 TABS control relies more heavily on the details of the forecasts for solar radiation and outside air temperature than RBC-2 by using the predicted hourly profiles instead of 24-hour mean values. Furthermore, the predictive character of RBC-3 is enhanced by up-to-date information on the expected heat gains to the room.

The basic idea behind RBC-3 is the continuous application of the Unknown-But-Bounded (UBB) method described in [7]. Thereby the TABS heating and cooling curves are updated at every control step, as shown in Figure 4-12.

The UBB method calculates the quasi-stationary response of a simple single-room dynamic thermal resistance-capacitance model (RC model, cf. Section 3.3) under the expected range (lower and upper bounds) of internal and external heat gains. Based on this information the optimal TABS heating and cooling flow temperature setpoints are determined. This makes RBC-3 a model-based and predictive control algorithm although it involves no numerical optimization as this is the case in classical MPC algorithms.

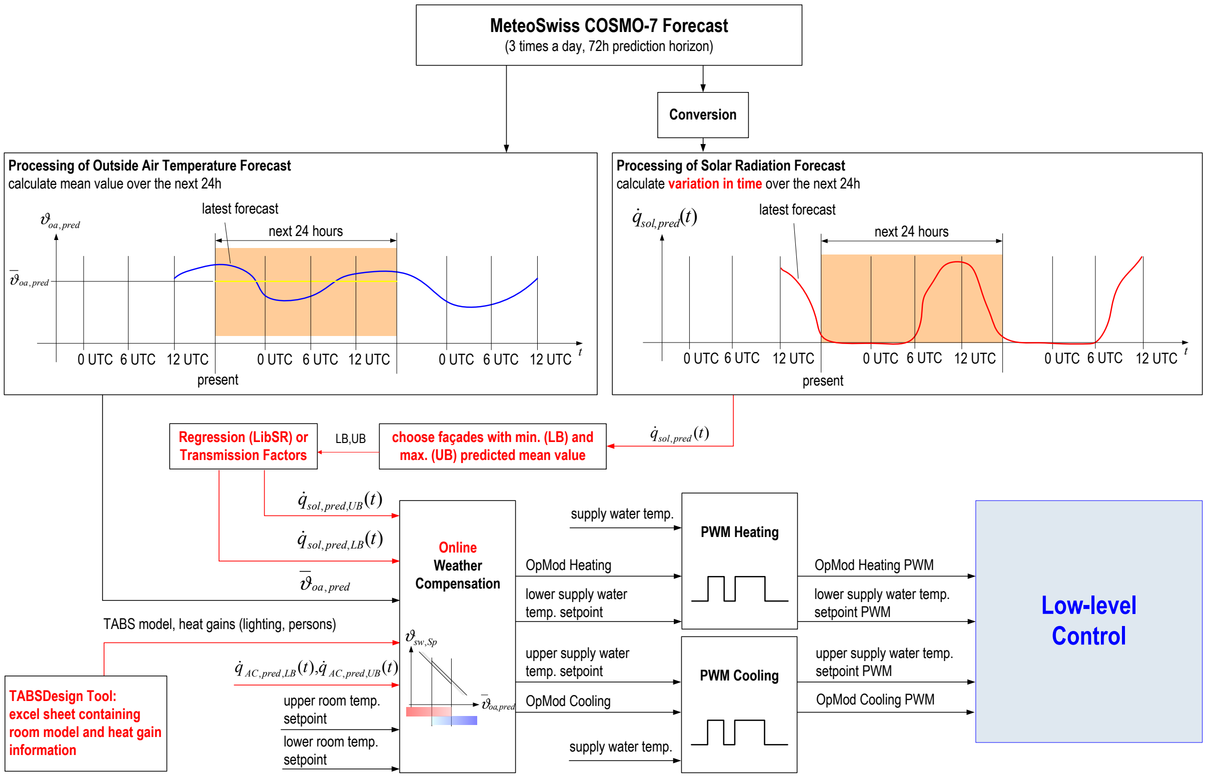


Figure 4-12: High-level control of RBC-3, part TABS

4.2.5.2 TABS Control RBC-4

RBC-4 uses exactly the same thermal RC model that is employed in RBC-3, and also the same predictions of the relevant disturbances acting on the building. However, RBC-4 extends the TABS control algorithm by use of an MPC procedure, as shown in Figure 4-13.

The control solution includes the following key components

- State estimator. It serves the estimation of the ceiling, floor, wall and concrete core temperatures of the single-room RC model. This information is needed as an initial state for the model-based optimization procedure. The estimator was realized as a Kalman filter that is fed by the newest available room temperature measurements at every HL control time step.
- Model predictive control algorithm. This algorithm is also executed at every HL control step. Model states over the next 24 hours are predicted and the lower and upper supply water temperature setpoints are optimized. There is only one heating and one cooling supply water temperature setpoint optimized over the whole prediction horizon. For heating, the setpoint is minimized while comfort requirements are still kept. For cooling, the setpoint is maximized while comfort requirements are still kept.

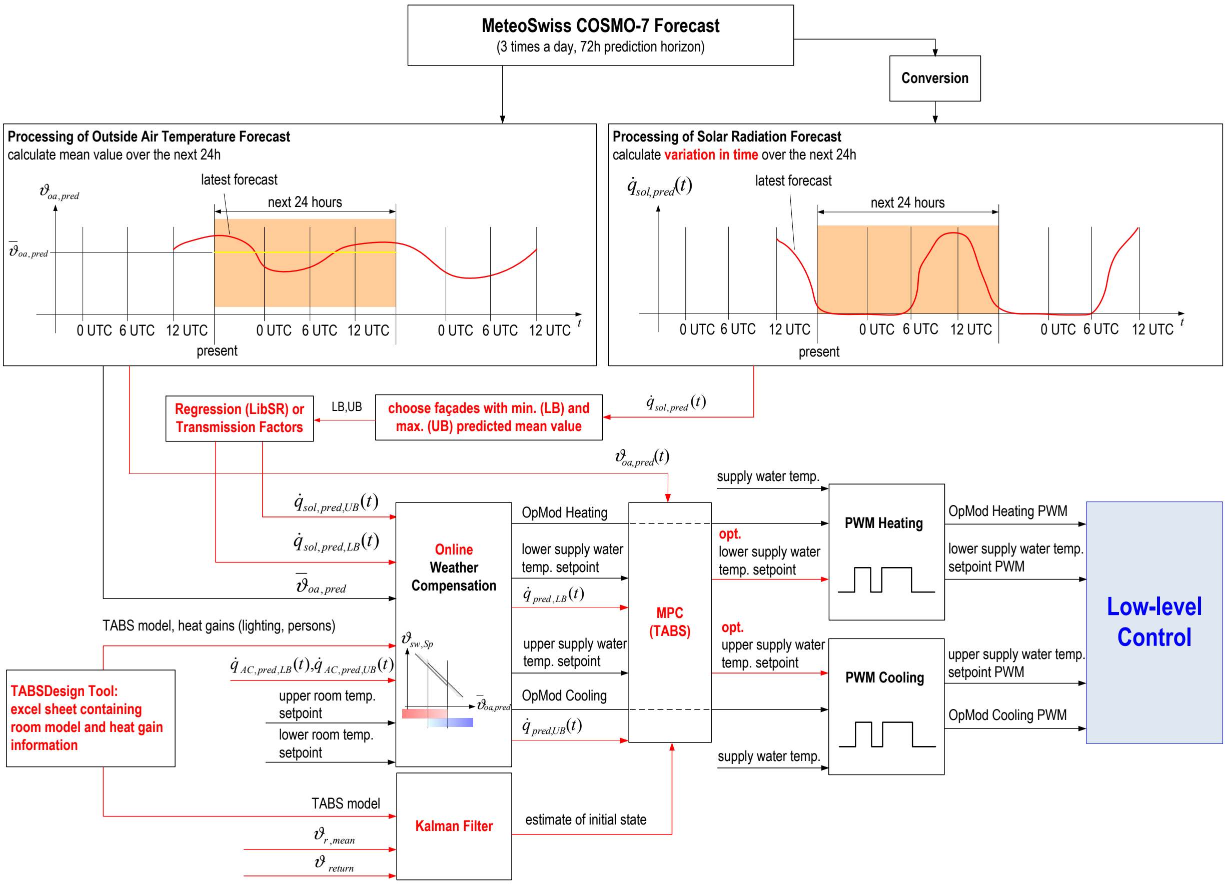


Figure 4-13: High-level control of RBC-4, part TABS

4.2.6 High-Level Control Parameters

4.2.6.1 General Control Parameters

The general control parameters used by the controllers RBC-1 to RBC-4 and their default values are given in Table 4-3. Most of the parameter values are supposed to be defined during the engineering or commissioning phase. The only parameters supposed to be used as tuning parameters during the operation phase are those related to the specification of the thermal comfort. The tuning will typically be done based on a combination of both, prescribed thermal comfort requirements and feedback by the building's users.

Table 4-3: General control parameter default values. Major tuning parameters are printed in bold.

Description	Unit	Value (def.)	RBC-
Real building operation: high-level control sampling time	H	0.25	1-4
Real building operation: repetition interval for equal blind commands	h	2.0	1-4
Building: latitude north of location	degAgl	47.55	1-4
Building: longitude east of location	degAgl	7.536	1-4
Building: azimuth angle of north facade from north (clockwise)	degAgl	-50.0	1-4
Thermal comfort: room temperature setpoint heating winter	degC	**21.0**	1-4
Thermal comfort: room temperature setpoint cooling winter	degC	**25.0**	1-4
Thermal comfort: room temperature setpoint heating summer	degC	**22.0**	1-4
Thermal comfort: room temperature setpoint cooling summer	degC	**26.0**	1-4
Control general: past number of hours to be considered for demand calculations	h	24.0	1-4

Description	Unit	Value (def.)	RBC-
Control general: past number of hours to be considered for setpoint deviation calc.	h	24.0	1-4
Control general: minimal time of consecutive demand for historical demand calc.	h	1	1-4
Control general: weather prediction type (cosmo7, pers)	–	cosmo7	2-4
Control general: weather prediction lead time	h	24.0	2-4
Control general: weather prediction variables	–	T_2M, GLOB	2-4

4.2.6.2 TABS Control Parameters

The TABS control parameters including default values are given in Table 4-4. Preferably, determination of the main TABS control parameters is already done in the design process, e.g. by using the approach described in [7] and the dedicated software tool. All parameters marked by an asterisk in Table 4-4 can be determined by this approach. Typically, the settings determined in the design process should already lead to good results. A tuning procedure – e.g. the one described in [7] – can be executed in real operation if necessary to tune the parameters printed in bold. All other parameters are set during engineering or commissioning.

Table 4-4: TABS control parameter default values. Major tuning parameters are printed in bold.

Description	Unit	Value (def.)	RBC-
Nominal room temperature setpoint heating *	degC	21.0	1-4
Design outside air temperature heating *	degC	-11.0	1-4
Flow temperature setpoint heating design *	degC	**29.2**	1-4
High outside air temperature heating *	degC	15.0	1-4
Flow temperature setpoint heating high outside air temperature *	degC	**21.6**	1-4
Nominal room temperature setpoint cooling *	degC	25.0	1-4
Design outside air temperature cooling *	degC	30.0	1-4
Flow temperature setpoint cooling design *	degC	**18.2**	1-4
Heating limit outside air temperature *	degC	**15.0**	1-4
Cooling limit outside air temperature *	degC	**12.2**	1-4
Flow temperature setpoint weekend shift heating *	K	**0.8**	1-4
Flow temperature setpoint weekend shift cooling *	K	**2.8**	1-4
Cooling availability start	h	22.0	1-4
Cooling availability stop	h	10.0	1-4
Heating availability start	h	0.0	2-4
Heating availability stop	h	24.0	2-4
Enable room temperature control	–	1	2
Radiation scaling factor open blinds (used to calculate effective outside temp.)	–	0.14	2
Radiation scaling factor closed blinds (used to calculate effective outside temp.)	–	0.03	2
Enable PWM heating (low-level controlled)	–	1	1-4
Enable PWM cooling (high-level controlled)	–	1	1-4
PWM cooling max. flow temperature setpoint correction	K	5.0	1-4
PWM cooling minimal purge time	h	0.5	1-4
PWM thermal resistance ratio *	%	45.0	1-4

RBC-2 and RBC-4 include room temperature feedback control. If representative room temperatures are measured and the feedback control is in operation, tuning of the parameters in Table 4-4 is not necessary. In case the room temperature feedback control does not lead to an acceptable performance, it is recommended to turn it off, see information on troubleshooting in [14].

4.2.6.3 Blind Control Parameters

The blind control parameters including default values are given in Table 4-5. Control parameters regarding HL control command restrictions need to be specified in order to minimize disturbance of room users while supporting energy efficient operation as much as possible. The value of the parameter “High solar radiation actual measurement” may be lowered if glare is encountered when blinds are commanded open during working hours. Conversely, it may be increased when no disturbance due to glare is encountered. Parameters “High outside air temperature” and “High solar radiation prediction” are set based on experience. For building facades with a high (low) window area fraction, somewhat lower (higher) values should be used.

Table 4-5: Blind control parameter default values. Major tuning parameters are printed in bold.

Description	Unit	Value (def.)	RBC-
High outside air temperature	degC	**17.0**	1-4
High solar radiation prediction (mean value)	W/m2	**150.0**	1-4
High solar radiation actual measurement	W/m2	**200.0**	1-4
Solar radiation threshold value to separate day and night	W/m2	15.0	1-4
No blind commands start (workdays), i.e. expected building use begin	h	**7.0**	1-4
No blind commands stop (workdays), i.e. expected building use end	h	**19.0**	1-4
Hour of day blind command exceptions	h	**[12.5]**	1-4
Slat width	m	0.07	1-4
Slat separation	m	0.061	1-4
Shading slat angle 1 (0° closed, 90° horizontal), more closed position	degAgl	45.0	1-4
Shading slat angle 2 (0° closed, 90° horizontal), more opened position	degAgl	70.0	1-4
Open angle range left (from inside)	degAgl	85.0	1-4
Open angle range right (from inside)	degAgl	85.0	1-4
Open angle range up	degAgl	85.0	1-4
Open angle range down	degAgl	-3.0	1-4

4.2.6.4 Ventilation Control Parameters

Ventilation control parameters including their default values are given in Table 4-6. Of course, ventilation operating hours should be set according to building usage hours.

Since RBC-1 does not feature room temperature feedback control, the parameters printed in bold are important tuning parameters. For efficient control they must be coordinated with the TABS control parameter settings.

For RBC-2, RBC-3 and RBC-4, the parameters printed in bold only represent boundaries for supply air temperature setpoints and therefore they are much simpler to specify – room temperature control is done by a cascade master controller. The boundaries can be relaxed such that no discomfort form air draught results. Bold values in Table 4-6 are default values for RBC-1 only, default values for the other controllers are not shown here.

Table 4-6: Ventilation control parameter default values. Major tuning parameters are printed in bold.

Description	Unit	Value (def.)	RBC-
Use ventilation schedule from BMS	-	1	1-4
Hour of day start ventilation (workdays)	h	6.0	1-4
Hour of day stop ventilation (workdays)	h	19.0	1-4
Minimal supply air temperature setpoint	degC	16.0	1-4
Maximal supply air temperature setpoint	degC	26.0	1-4

Description	Unit	Value (def.)	RBC-
Nominal supply air temperature setpoint heating	degC	**18.0**	1-4
Nominal supply air temperature setpoint cooling	degC	**21.0**	1-4
Winter compensation high outside air temperature	degC	**10.0**	1-4
Winter compensation low outside air temperature	degC	**-10.0**	1-4
Winter compensation supply air temperature shift	K	**5.0**	1-4
Summer compensation high outside air temperature	degC	**30.0**	1-4
Summer compensation low outside air temperature	degC	**10.0**	1-4
Summer compensation supply air temperature shift	K	**5.0**	1-4
Force minimal supply air temperature setpoint (to reduce heating coil actions)	-	0	1-4
Minimal supply air temperature setpoint range width	K	1.0	1-4
Enable room temperature control (room temp. - supply temp. cascade control)	-	1	2-4
Room temp. control master controller gain	-	4	2-4
Room temp. control master controller integral action time	h	0.5	2-4
Room temp. control measurement selection (0: all rooms, 1: meeting rooms only)	-	0	2-4
Enable mechanical night-time ventilation	-	1	2-4
Mech. night-time ventilation availability start	h	23	2-4
Mech. night-time ventilation availability stop	h	6	2-4
Mech. night-time ventilation low limit of maximal predicted outside air temperature	degC	28	2-4
Mech. night-time ventilation switch-on temp. diff. room - outside	K	5	2-4
Mech. night-time ventilation switch-off temp. diff. room - outside	K	3	2-4
Mech. night-time ventilation switch-on temp. diff. room - setpoint heating comfort	K	2	2-4
Treat adiabatic cooling as completely free (apply same rules as for ERC)	-	0	2-4

4.3 Model Predictive Control

4.3.1 Overview

This section describes the implementation of the Model Predictive Control (MPC) on the industry PC in the demonstrator building. It extends the report given in [16].

MPC is a promising alternative to standard strategies for building control. It uses a mathematical model of the building and predictions of disturbances (e.g., outside air temperature) over a given prediction horizon (e.g., two days) for defining an optimization problem that is solved such as to maintain thermal comfort for the occupants while minimizing some objective (e.g., energy use or monetary cost).

Measurements of the building enter the problem as the initial state of the model. The result of the optimization problem is an optimal control input *trajectory* over the prediction horizon. The first step of this trajectory is applied to the building, setting all actuators related to heating, cooling, ventilation and blinds control. At the next time step, the procedure is repeated. This *receding horizon* approach is what introduces feedback into the system, since the new control problem solved at begin of the next time step will be a function of the new state at that point in time and hence of any disturbances that have meanwhile acted on the building.

In contrast to most conventional building control approaches, MPC makes it possible to integrate all available actuators and their interactions as well as predictions of weather, internal gains and electricity prices into a coherent, mathematically founded control framework that can handle constraints on control inputs and room temperatures.
See [17] for a standard book on MPC.

4.3.2 MPC Implementation

As described in Section 4.1.2, the control was implemented in a hierarchical way that allowed us to keep the original low-level (LL) control essentially unchanged. The MPC controlled all setpoints given in Table 4-1 with the exception of the static heating that was set to automatic mode.

For solving of the optimization problem the specialized CPLEX software was called from within MATLAB. The execution time of the algorithm was less than 2 minutes.

The MPC fallback strategy consisted of two parts: (i) If the optimization fails to produce a new control input, the corresponding element of the last successfully computed control trajectory is applied. (ii) If either (i) is applied for 8 consecutive steps (i.e., 2 hours), or the HL controller does not send any new setpoints for at least one hour, HL control is switched off and the built-in LL control solution takes over.

4.3.3 MPC Control Algorithm

Figure 4-14 shows the flow of information in an individual MPC iteration. The following subsections detail the individual steps a)–g).

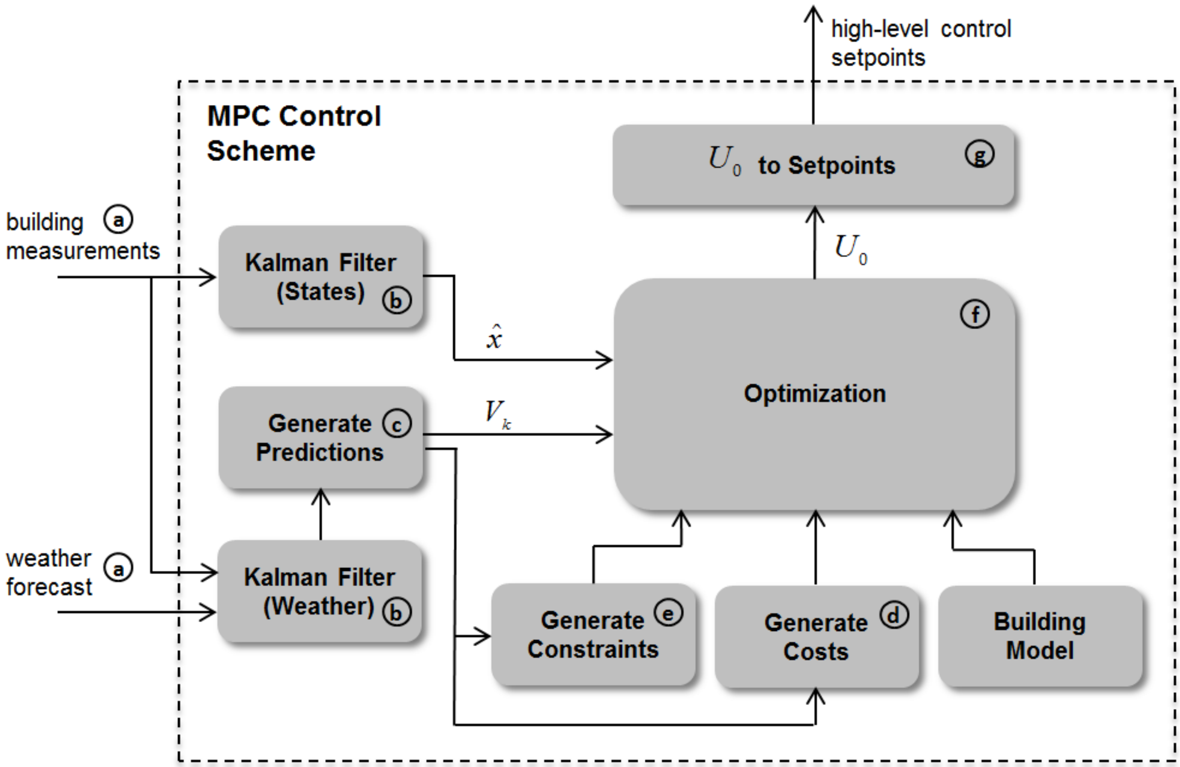


Figure 4-14: Flow of information in a single MPC iteration

4.3.3.1 Step f) – Optimization

Clearly, the optimization is the central part of the MPC algorithm and most of the other steps prepare data to set it up. To reference its individual components in the following subsections, step f) described here first.

The goal of the MPC was to minimize total actuation cost (either monetary cost, or usage of Non Renewable Primary Energy [NRPE]) over the next N time steps (indexed with k) while maintaining thermal, air quality and illumination comfort as defined in Section 4.1.5.

The resulting optimization problem was bilinear in control inputs u and states x, as well as in the inputs and predicted disturbances v:

$$\min_{U_k} \sum_{k=0}^{N-1} c_k^T u_k \tag{4.1}$$

such that

$$x_{k+1} = Ax_k + B_u u_k + B_v v_k + \sum_{i=1}^{n_u} \left[\left(B_{vu,i} v_k + B_{xu,i} x_k \right) u_{k,i} \right] \tag{4.2}$$

$$y_k = Cx_k + D_u u_k + D_v v_k + \sum_{i=1}^{n_u} \left[\left(D_{vu,i} v_k + D_{xu,i} x_k \right) u_{k,i} \right] \tag{4.3}$$

$$y_{\min,k} \le y_k \le y_{\max,k} \tag{4.4}$$

$$Fx_k + Gu_k \le g_k \tag{4.5}$$

$$\forall\, k = 0,1,\ldots,N-1$$

$$x_0 = \hat{x} \tag{4.6}$$

with the output vector y consisting of the averaged room temperatures for various zones groups (see also Table 3.8).

Equation (4.1) gives the total cost that is computed as a linear function of the actuation signals u using coefficients c_k which are determined in Step d). Expressions (4.2) and (4.3) constrain the system to evolve according to the modeled dynamics that are described by the matrices $A, B_u, B_v, B_{vu}, B_{xu}, C, D_u, D_v, D_{vu}, D_{xu}$ (see also Section 3.3.1). The room temperature comfort is enforced by the time-varying constraints (4.4). The physical limits on the actuators, the air quality comfort constraint and the limits on the ventilation supply air temperatures are encoded by (4.5). All constraints are generated in Step e). Equation (4.6) finally states that the initial state of the dynamic model (4.2) used in the optimization is given by the estimate $\hat{x}$ that is determined in Step b).

For the disturbances v we substituted the numerical values generated by Step c). To solve the bilinear optimization problem without having to rely on nonlinear solvers, we used a sequential linear programming approach as described in [1]. It solves the problem by iteratively linearizing around the state trajectory computed in the last iteration until convergence is achieved. The prediction horizon was 58h, which implied N = 232.

4.3.3.2 Step a) – Reading of New Measurements and Obtaining Weather Forecast

The current measurements from the building are gathered via the OPC interface (Section 4.1.2) and their quality is checked. The latest available 72 hour MeteoSwiss forecast (see Section 4.1.5.4) for outside air temperature and global radiation is downloaded if not already done so. The forecast is updated three times a day. If unavailable, we calculate a persistence forecast by assuming the weather of the next three days to be the same as that of the previous day.

4.3.3.3 Step b) – Kalman Filtering

A Kalman filter is a standard algorithm to estimate imperfectly measured states from measurements using some model. Informally, at every iteration the estimate of the state at the last time step is predicted ahead using the previously applied control inputs to generate a preliminary estimate of the system's state at the current time step. This preliminary estimate is then refined using the current measurements. Two different Kalman filters are applied for estimating the current state of the building and improving the weather forecast.

- *Estimation of the building model's current thermal state*. The current measurements from the building are processed to obtain the MPC model's measured control inputs, disturbance inputs and outputs of the last time step. Since convergence of the Kalman filter deteriorates with increasing number of states to be estimated, this step was a main reason for applying the model reduction described in Section 3.3.1.4. The resulting state estimate is used to initialize the optimization (Equation (4.6)).
- *Weather forecast filtering*. The available weather forecasts did not apply to the exact location of the controlled building and they also did not account for shadowing by neighbouring buildings or other local climatic effects. To account for such local influences we therefore fused the predicted data with radiation and temperature measurements from the roof of the target building. This Kalman filter was based on an autoregressive model for the local correction coefficients and is described in more detail in [1] and [18].

4.3.3.4 Step c) – Generation of Predictions

This step first generates the predictions for the disturbance inputs V_k, and then computes intermediate predicted values for the generation of the costs and constraints vectors.

The predicted values of the outside air temperature $v_{\mathrm{T\,ambient}}$ are simply obtained by resampling the Kalman-filtered weather forecast time series. The internal gains by people and equipment v_{IG} are predicted by the same hourly and weekly schedules that were used in EnergyPlus.

The MPC algorithm requires two kinds of predictions related to solar radiation: (i) the global solar radiation incident on the facades, $v_{\mathrm{solar,\ \{N,E,W,S\}}}$, to be used for construction of the V_k; and (ii) the expected heat gains due to transmitted solar radiation through the windows, $u_{\mathrm{transm\ solar,\ \{N,E,W,S\}}}$. The latter quantity is required for each zone as a function of blind position.

To obtain these values, the Kalman-filtered forecast for the global radiation (on a horizontal surface) is processed in several steps. First, the radiation values are split into their direct and diffuse components based on the work by Perez [13]. Second, the direct and diffuse components incident on every window *j*, $v_{\mathrm{solDirWin,j}}$ and $v_{\mathrm{solDiffWin,j}}$, are computed by taking into account the sun's elevation and azimuth angles, window position and the shadowing by the building and the neighboring buildings. Third, the global radiation on each facade, $v_{\mathrm{solar,\ \{N,E,W,S\}}}$, is obtained by summing the two components and then averaging over all respective windows. Finally, for every window j the heat gains due to transmitted solar radiation as a function of the blinds position bPos, $Q_{\mathrm{transm\ solar,\ win}\,j}(\mathrm{bPos})$, is computed according to

$$Q_{win,j}(\mathrm{bPos}) = \alpha v_{\mathrm{solDirWin,j}} + \beta v_{\mathrm{solDirWin,j}} + \gamma v^2_{\mathrm{solDirWin,j}} + \delta$$

Here $\alpha,\beta,\gamma,\delta$ are functions of the calendar month, the facade orientation and the blinds position, and δ is in addition a function of the hour of day. The parameters $\alpha,\beta,\gamma,\delta$ were estimated by a multivariate linear regression based on quarter hourly outputs $Q_{\mathrm{transm\ solar,\ win}\,j}(\mathrm{bPos})$, $v_{\mathrm{solDirWin,j}}$ and $v_{\mathrm{solDiffWin,j}}$ from a year-long EnergyPlus simulation.

4.3.3.5 Step d) – Generation of the Costs

The MPC procedure supported time-varying cost vectors c_k. This functionality was introduced, firstly, because the cooling tower's efficiency (and hence the cost of cold production) depended on the predicted outside air temperature. Secondly, we wanted to be able to experiment with time-varying energy costs, e.g. in order to simulate the case of heat production with a heat pump that is operated under a dynamic electricity tariff.

4.3.3.6 Step e) – Generation of the Constraints

The used comfort requirements are defined in Section 4.1.5.3. The thermal comfort constraints were enforced in a straightforward manner by limiting the room temperature outputs (Equation (4.4)) and the Air Handling Unit's supply air temperature according to the comfort requirements. Constraining the supply air temperature is possible since the total ventilation heat flux added to the building can be bilinearly represented (Section 3.3.1.3) and hence constrained by the product of the corresponding temperature limit, the ventilation mass flow rate input and the heat capacity of air. Indoor air quality requirements were considered by specifying a minimum supply air mass flow rate during office hours.

As mentioned in Section 4.1.4.5, the building's blind automation system supports only four possible blinds position setpoints. This translated at any given point in time into four achievable heat gain values due to transmitted solar radiation pro facade. The exact representation of these so-called integer constraints would have increased the computational effort for MPC by several orders of magnitude. We therefore relaxed the constraint by allowing continuous variation of the heat gains while respecting some lower and upper bounds $u_{\text{transm solar, \{N,E,W,S\}}}$, as described below. Then we determined in Step g) the blinds positions that resulted into the heat gains closest to the calculated optimal ones.

The bounds on $u_{\text{transm solar, \{N,E,W,S\}}}$ were determined according to the following procedure: First we computed for every time step in the prediction horizon the allowed subset of blinds positions. These were determined by allowing only non-closed positions during working hours, by allowing positions that provide some minimum shading in the afternoon in case of high solar radiation at noon, and by considering that during working hours the blinds can be moved only twice, in the morning and at noon, respectively.

Then, using the predicted heat gains due to window-transmitted solar radiation from Step c), we computed for each time step in the prediction horizon the lower and upper bounds $Q_{\text{transm solar}}(\text{bPos}_{\text{maxShading},fac},\ldots)$, $Q_{\text{transm solar}}(\text{bPos}_{\text{minShading},fac},\ldots)$ as in Equation (3.18) as the heat fluxes that corresponded to the maximum and minimum allowed shading positions for that step, respectively.

4.3.3.7 Step g) – Post-processing of Results

As described in Section 3.3.1.3, the actuators (TABS, blinds, AHU) could not be conveniently modeled in a bilinear manner as a function of their corresponding setpoints. Hence we modeled the actuators' influence by the associated heat fluxes. The task of the post-processing Step g) was to compute the setpoints from the optimal heat fluxes as determined in the optimization procedure.

4.3.4 Control Settings

The performance of the MPC algorithm can be modified by the following settings:

Model. The model lies at the core of the MPC and most effort in setting up the MPC controller goes into constructing a good model rather than into tuning/specifying thresholds and rules as in RBC. We consider the physical constraints on the actuators also as part of the model. The modeling is described extensively in Section 3.3.

Internal gains predictions. The internal gains predictions directly influence the heating and cooling demand calculated by MPC. They were in our case based on standard schedules that were adjusted according to electricity measurements as described in Section 3.2.2.10.

Control horizon and sampling time. A sampling time of 15 minutes proved sufficient to match the building's slow dynamics, while still leaving enough time for the MPC problem to be solved on the local Industry PC. The chosen control horizon of 58 hours was motivated by the prediction horizon of the available forecasts. Sampling time and control horizon determine the size of the optimization problem which also influenced the aforementioned decisions

Settings for weather and state estimation Kalman filters. The settings for the weather filtering were investigated and optimized in the OptiControl-I project, see [18]. The settings for the state estimation Kalman filter showed not to be very delicate in our experience and were chosen by manual tuning.

Comfort constraints. The comfort constraints are determined by the specifications described in Section 4.1.5. To account for variability across the individual rooms of the various zone groups considered in MPC the thermal comfort constraints were tightened by 0.1°C.

Cost functions. An important feature of MPC in building control is the fact that it is straightforward to change the control objective. This allows flexible switching between NRPE and monetary optimization, and also the implementation of time-varying costs or the encoding of incentives such as the limitation of peak electrical power demand.

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5 Controller Assessment

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The Rule Based Control (RBC) and Model Predictive Control (MPC) strategies described in Chapter 4 were applied to the target building starting in November 2011. Here we report on the newly developed strategies' control performance and on their acceptance by the building owner, facility manager, and end users. The analysis covers three out of ten evaluation criteria considered in the overall benefit-cost analysis reported in Chapter 7.

Due to its obvious importance, control performance is considered here in particular detail. In contrast to all other evaluation criteria it can be assessed quantitatively in an objective and precise manner based on appropriately defined performance indices.

The comparability and representativity of the field experimental results was however limited by several factors: The various control strategies could only be tested sequentially, they could only be applied for a few weeks each, and, moreover, each test period was characterized by a different set of (partially unknown) disturbances acting on the system. To enable a more systematic assessment of controller performance we therefore also employed whole-year simulations with a detailed, validated model of the target building (see Chapter 3.2).

Section 5.1 details the quantitative indices used to assess control performance. Sections 5.2 and 5.3 report the results from the field experiments and simulations, respectively. Section 5.4 finally gives an evaluation of user acceptance, as assessed by means of a questionnaire and two web-based surveys.

5.1 Performance Indices

5.1.1 Control Costs

We considered two kinds of control costs: Non-Renewable Primary Energy usage (NRPE, expressed in kWh) and Monetary Cost (MC, expressed in Swiss Francs, CHF).

NRPE usage accounted for the two sources of energy available to the control system and the occupants in the target building: gas consumed by the gas boiler and electricity consumed by the Heating, Ventilation and Air Conditioning (HVAC) system, and by lighting and equipment. Table 5-1 summarizes all considered energy consumers and their type.

Table 5-1: Energy consumers in the target building

Energy	Type	Description
Non-offices lighting / equipment	Electricity	Lighting and equipment energy of all non-office zones
Offices equipment	Electricity	Equipment energy of all office zones
Offices lighting	Electricity	Lighting energy of all office zones
Water transport	Electricity	Pump energy of all heating and cooling distribution groups
Air transport	Electricity	Ventilation fan energy
Cooling ventilation	Electricity	Energy of adiabatic cooler
Heating ventilation	Gas	Gas energy required by the ventilation heating
Heating radiators	Gas	Gas energy required by the radiators heating
Heating TABS	Gas	Gas energy required by the TABS heating

NRPE was computed by multiplying the consumed energy with the following factors: 1.2 for gas and 3.32 for electricity [1].

For MC we considered only the variable costs associated to energy consumption. Other costs, such as costs related to the (dis)comfort and work productivity of the occupants, or effects on equipment maintenance cost were not considered within the control costs. Thermal comfort was treated as a separate performance indicator, see Section 0.

MC was computed in three parts: MC during high tariff times (Monday–Friday 06:00–21:00, Saturday 06:00–12:00), MC during low tariff times (otherwise) and peak electric power demand costs. The latter were computed on a monthly basis, according to the power company's billing convention: they were proportional to the maximum mean electrical power consumption over a 15 minutes interval in a given month. For the generation of daily time series the peak power costs were distributed uniformly to all days of the respective month.

Table 5-2 shows the used MC cost figures. They were based on historical billing costs from the year 2012.

Table 5-2: Energy to costs conversion factors

Description	Value	Unit
Monetary costs natural gas	0.075	CHF/kWh
Monetary costs electrical energy low tariff	0.097	CHF/kWh
Monetary costs electrical energy high tariff	0.145	CHF/kWh
Monetary costs electrical energy peak load	5.82	CHF/kW

5.1.2 Thermal Comfort

Thermal (dis)comfort was assessed in terms of room temperature setpoint range violations. Considered was the time-integral of the room temperature comfort range violations during working hours (defined as Monday–Friday 08:00–19:00), measured in Kelvin-hours (Kh).

The thermal comfort assessment showed large variation across rooms, respectively zones, in both, measurements and simulations. We focused on the most extreme rooms by considering the following quantities:

- Maximum comfort violation "too cold": Number of Kelvin-hours for the "coldest" office or meeting room over the time interval under consideration.
- Maximum comfort violation "too warm": Number of Kelvin-hours for the "warmest" office or meeting room over the time interval under consideration.

The "too warm" violations were evaluated depending on the outside air temperature. We distinguished between "low" and "high" outside air temperature depending on whether the latter is below or above the room temperature upper setpoint, respectively. The occurrence of "too warm" violations under "low" outside air temperature indicates potential for lowering of the room temperature due to manual window opening by the building users.

5.1.3 Further Performance Indices

A series of further performance indices could have been considered to assess controller performance. Below follows a non-comprehensive list, together with the reasons why we omitted these indices in the present study:

- Air quality. We did not consider any air quality indices because all controllers used the same ventilation air flow rate, i.e. the same amount of fresh air was supplied to the rooms/zones throughout all control experiments (see Section 4.1.5.2)
- Number and/or timing of blind movements. Blind movements were restricted equally for all controllers, to once per day at exactly 12:30 (in the real building) or 13:00 (in the simulations) during working days (see Section 4.1.5.1).
- Illuminance. Both in the real building and in simulations, a lower luminance level was maintained by constant light control. For all controllers, the same blind control restrictions were applied in terms of glare protection and allowed blind positions during working hours. Therefore, we did not include any luminance control performance indices in our analysis.
- Supply air temperature. A too low or too high supply air temperature may cause discomfort for the room users due to draught or poor mixing of air in the room, respectively. The lower supply temperature setpoints and the room temperature setpoints differed slightly between simulations and the real building (but not between simulations), because we had to comply with a few occupant requests. However, we generally did not consider supply air temperature (dis)comfort, because in all cases the controllers managed to maintain the prescribed lower and upper limits without any problems.

5.2 Field Experiments

In this section we report measured costs and comfort indices for the reference control strategy that was running in the building prior to the start of the project, RBC-0, plus the newly developed strategies RBC-1, RBC-2, RBC-4 and MPC.

The measurement setup was operational since October 7th, 2011. The data reported here comprise the whole period until April 2nd, 2013, with the exception of a few days where we conducted open-loop experiments (see Section 3.2.3), and a 22-day interval in December 2011 where some of the measurements were corrupted.

Table 5-3 summarizes the field experimental timeline, i.e. either which controller was active or what experiment was conducted. It can be seen that the five different controllers were operational during fourteen distinct periods.

Table 5-3: Timeline of field experiments.

Ident	Period	Controller/ Experiment	Comment
P01	Oct 7 – Nov 4, 2011	RBC-0	Reference (original) control
P02	Nov 4 – Nov 6, 2011	EXP-1	First open-loop control experiment (ventilation response)
P03	Nov 6 - Nov 8, 2011	RBC-0	Reference control, not considered in assessment
P04	Nov 8 – Dec 2, 2011	RBC-1	Application of new non-predictive, but integrated RBC
P05	Dec 2 – Dec 23, 2011	RBC-1	Some corrupted measurements, not considered in assessment
P06	Dec 23, 2011 – Jan 1, 2012	EXP-2	Second open-loop control experiment (TABS response)
P07	Jan 1 – Jan 20, 2012	RBC-0	Reference control, not considered in assessment
P08	Jan 20 – Apr 20, 2012	RBC-2	First application of new predictive and integrated RBC
P09	Apr 20 – Aug 17, 2012	MPC	First application of new MPC strategy
P10	Aug 17 – Nov 10, 2012	RBC-2	Second application of new predictive and integrated RBC
P11	Nov 10 – Dec 22, 2012	MPC	Second application of new MPC strategy
P12	Dec 22 – Dec 25, 2012	EXP-3	Third open-loop control experiment (TABS response)
P13	Dec 25, 2012 – Feb 25, 2013	MPC	Third application of new MPC strategy
P14	Feb 26 – Apr 02, 2013	RBC-4	Application of new predictive, integrated and model-based RBC

RBC-n: Rule Based Control, variant n; EXP-n: Open-loop experiment number n; MPC: Model Predictive Control

In the following subsections we first present the energy signatures from the various RBC and MPC operation periods, and then we report the measured control cost and comfort indices.

5.2.1 Comparison of Energy Signatures

Figure 5-1 summarizes the weekly total NRPE usage for heating (by TABS, ventilation and radiators) and cooling (by TABS and ventilation) as a function of weekly mean outside air temperature. Equipment, lighting and air transport costs were not considered here as these costs do not depend directly on outside air temperature.

As can be expected, NRPE consumption roughly shows a "V" shape with a minimum at an approximate outside air temperature of 17°C. Heating and cooling operation are responsible for the shown increases in NRPE usage when outside air temperature was below or above this minimum point, respectively. Note that the slopes of possible trend lines (not shown) representing the change in heating/cooling energy usage as a function of outside air temperature measure a given controller's energy-efficiency (the smaller the slope, the more energy efficient the controller).

No clear differences between the various controllers can be discerned from Figure 5-1. At least two reasons contributed to this result: Firstly, Figure 5-1 accounts for but one disturbance, the outside air temperature. Other disturbances acting on the building were solar heat gains (influenced by manual blind positioning), internal heat gains (by equipment and persons), natural air change (influenced by the outdoor wind field and manual window opening) and manual settings on room thermostats in the corner rooms. These disturbances were in large parts unknown. Moreover, several of them varied strongly across the relatively short measurement intervals available for each control strategy. Secondly, the thermal comfort settings had to be modified somewhat during and across different experimental phases due to occupant requests.

In summary, without resorting to rigorous statistical testing, the energy signature analysis suggests a comparable performance for all newly developed controllers. The original control strategy RBC-0 seems to have a somewhat higher NRPE use than the new controllers, but based on only four weeks data for RBC-0 no firm conclusions can be drawn.

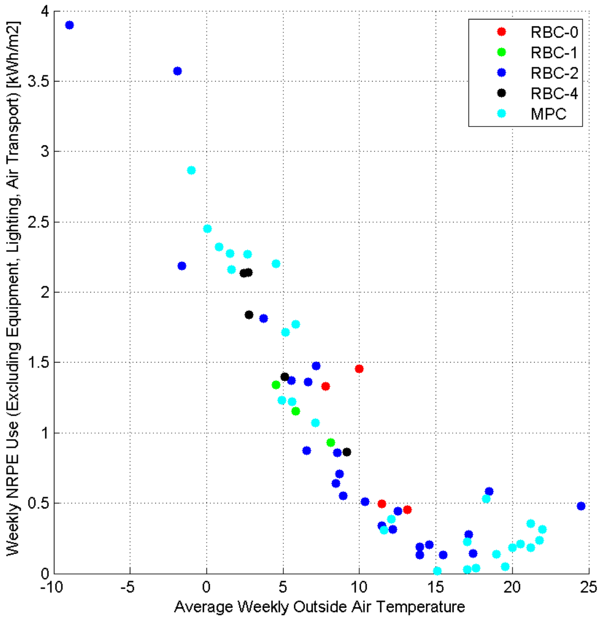


Figure 5-1: Energy signatures for closed loop field experiments

5.2.2 Assessment of Individual Control Strategies

In this section, we show measurement results for eight selected periods (cf. Table 5-3) covering the reference control strategy and all novel strategies.

Data for each single period are reported in one separate figure consisting of four panels.

The left panel in each figure contains a scatter plot of measured office room temperatures versus filtered outside air temperatures (see Section 4.1.5.3). The solid lines denote the upper and lower bounds of the target thermal comfort range as a function of the filtered outside air temperature. Hourly mean values from measurements of the 2nd floor offices during working hours were considered. Figure 5-2 shows the legend for these plots.

The topmost and middle panels at the right side of each figure show the daily NRPE consumption in kWh/m^2 and the MC in CHF, respectively. All data were scaled such as to refer to the 2nd floor only, and this floor's net floor area was also used as the reference area.

Figure 5-3 shows the colors used to encode the energy cost contributions listed in Table 5-1 in the cost figures.

The bottom-right panel in each figure shows the outside air temperature during the respective measurement period.

The rightmost data points in each of the NRPE, MC, and outside air temperature panels show the corresponding average values over the entire analysis interval (denoted with 'A').

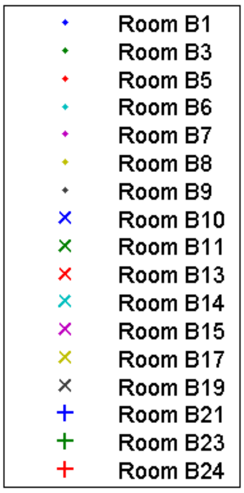


Figure 5-2: Legend for room temperature scatter plots

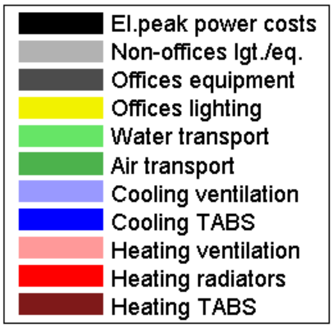


Figure 5-3: Legend for cost plots

As can be seen in Figure 5-4 to Figure 5-11, the office room temperatures were distributed within a range of about 3K. One reason for this is because room temperatures tend to rise during the day due to external and internal heat gains. This behavior can also be observed during the main TABS operation seasons winter and summer. The slow TABS heating and cooling system is not capable to completely equalize the diurnal variation in heat gains (this was anyway not the goal, since allowing room temperatures to fluctuate within the comfort range was at the core of all control cost minimization). Another reason is because there are room temperature differences between the rooms. These can also not be prevented because there is only one TABS zone for the entire building.

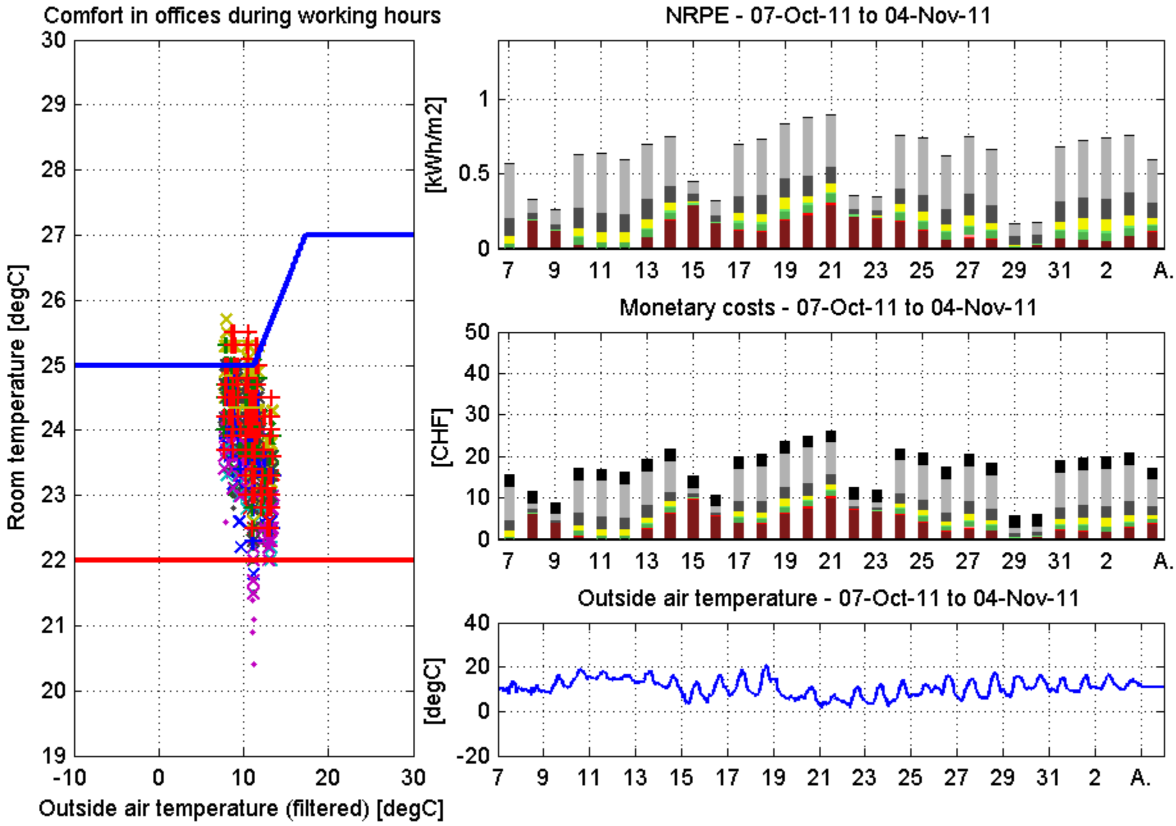


Figure 5-4: Measured room temperatures, costs and outside air temperature for period P01 and control strategy RBC-0. NRPE: Non-Renewable Primary Energy usage.

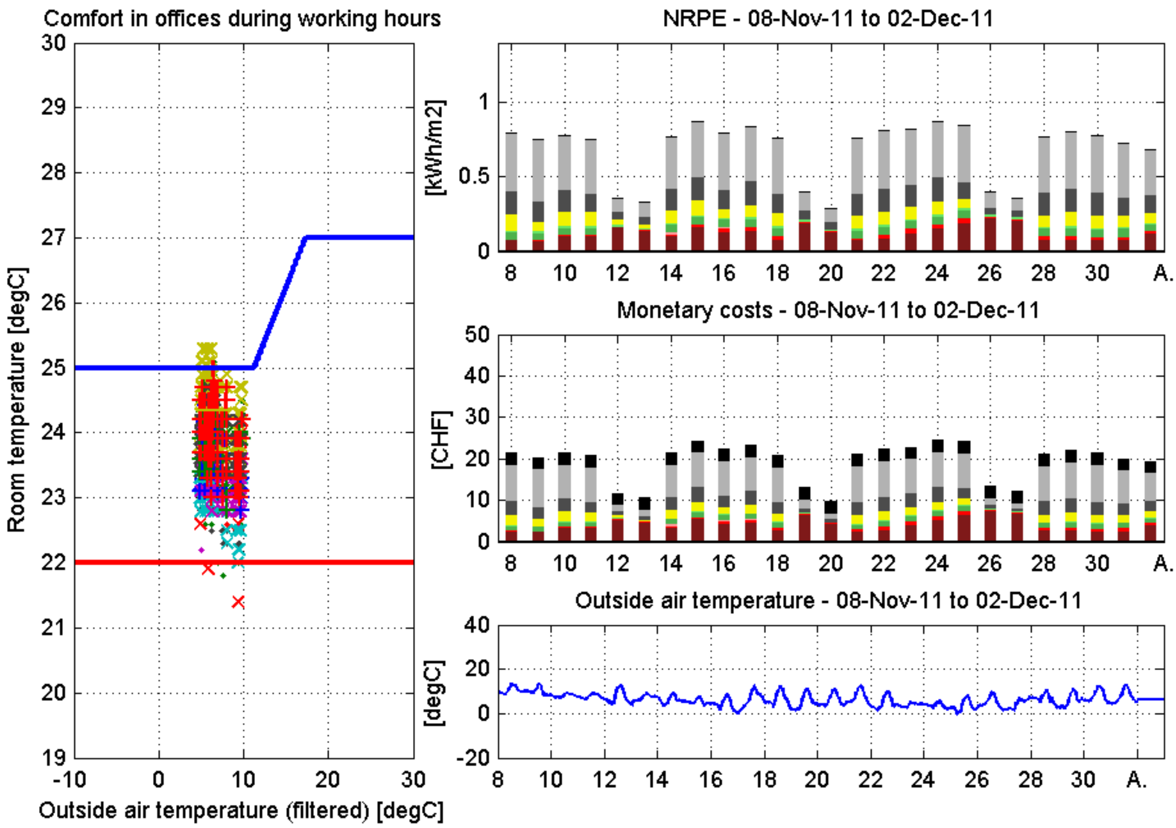


Figure 5-5: Same as previous figure, but for period P04 and control strategy RBC-1.

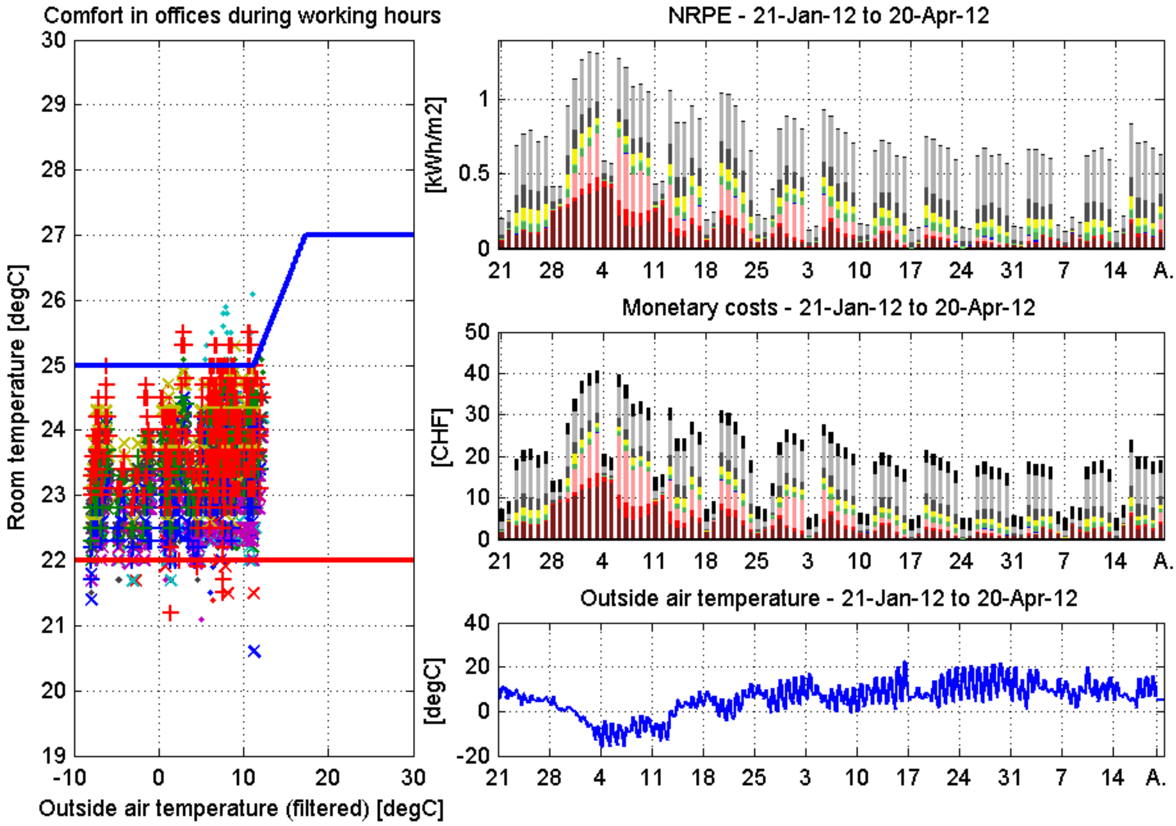


Figure 5-6: Same as previous figure, but for period P08 and control strategy RBC-2.

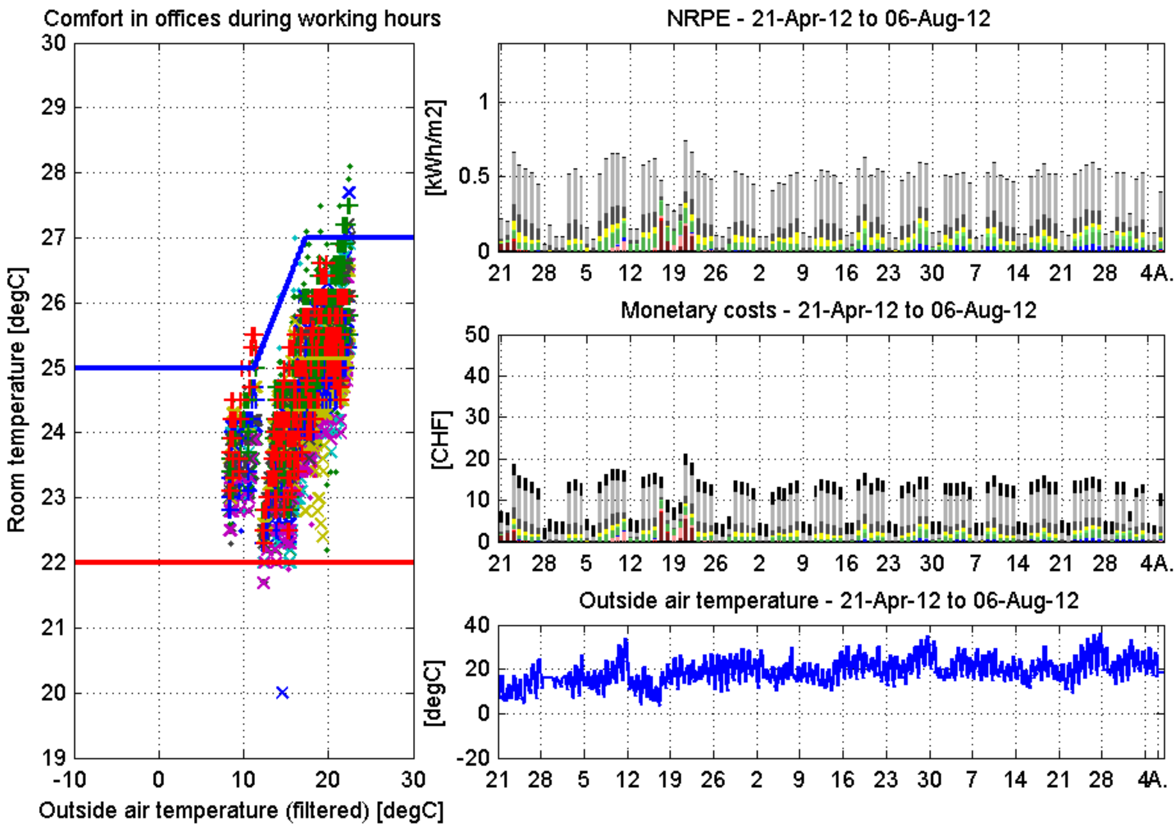


Figure 5-7: Same as previous figure, but for period P09 and control strategy MPC.

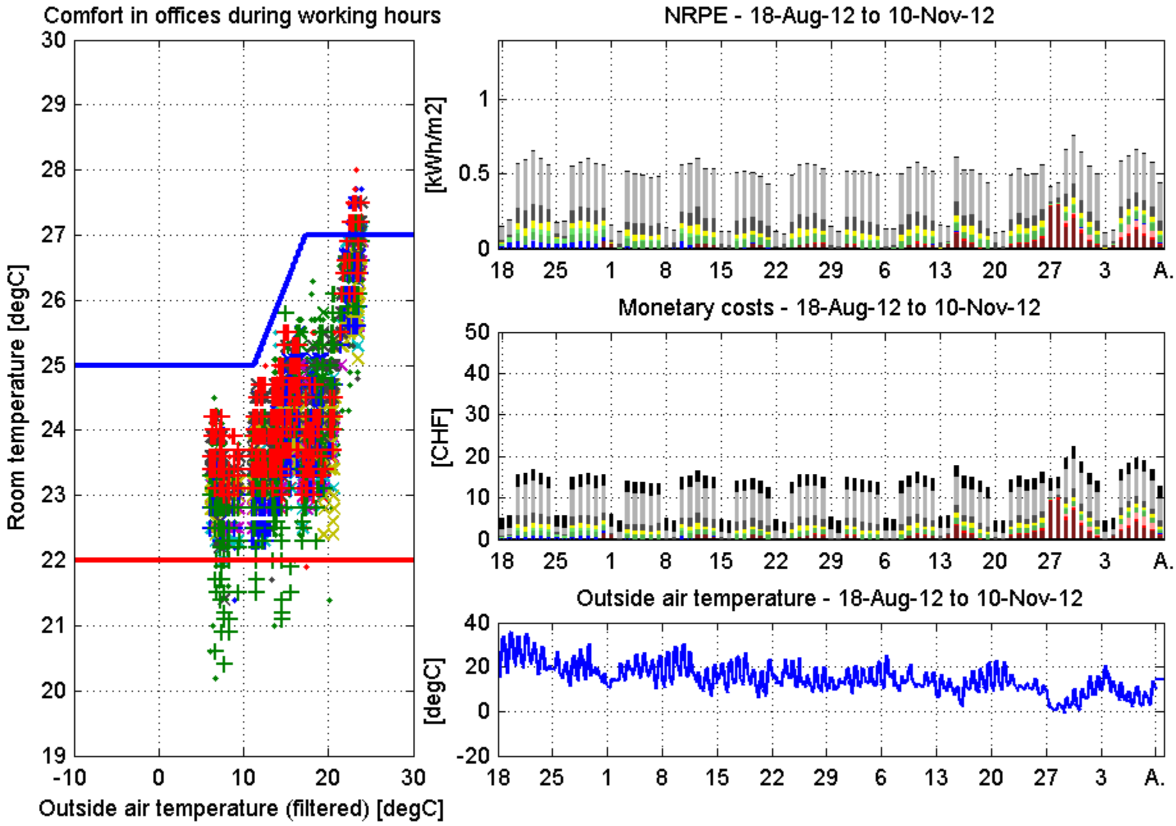


Figure 5-8: Same as previous figure, but for period P10 and control strategy RBC-2.

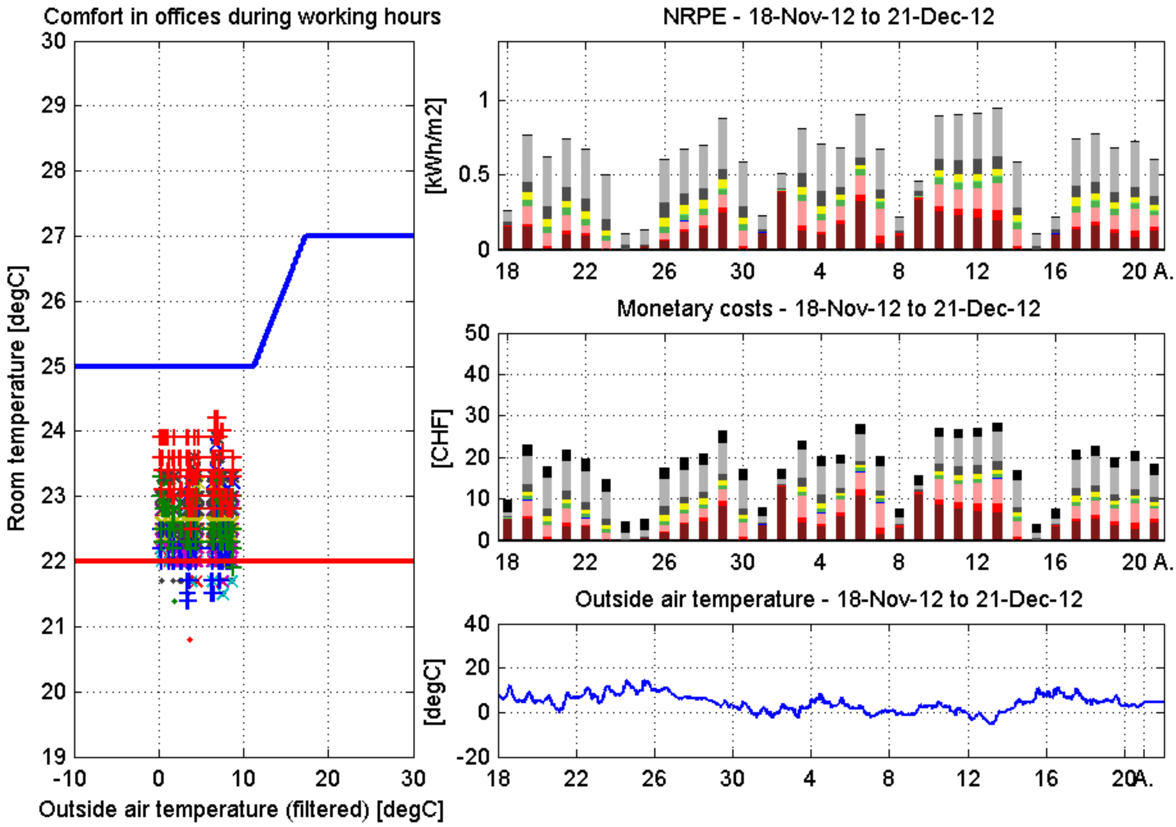


Figure 5-9: Same as previous figure, but for period P11 and control strategy MPC.

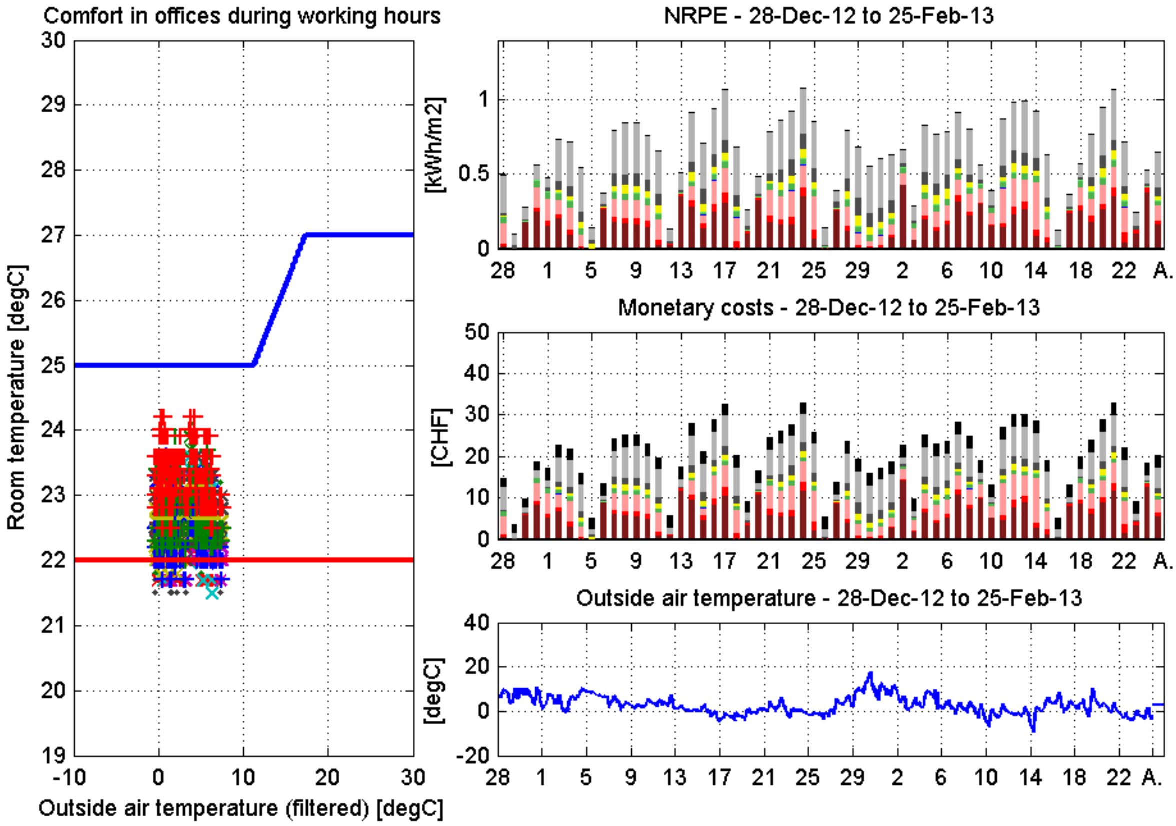


Figure 5-10: Same as previous figure, but for period P13 and control strategy MPC.

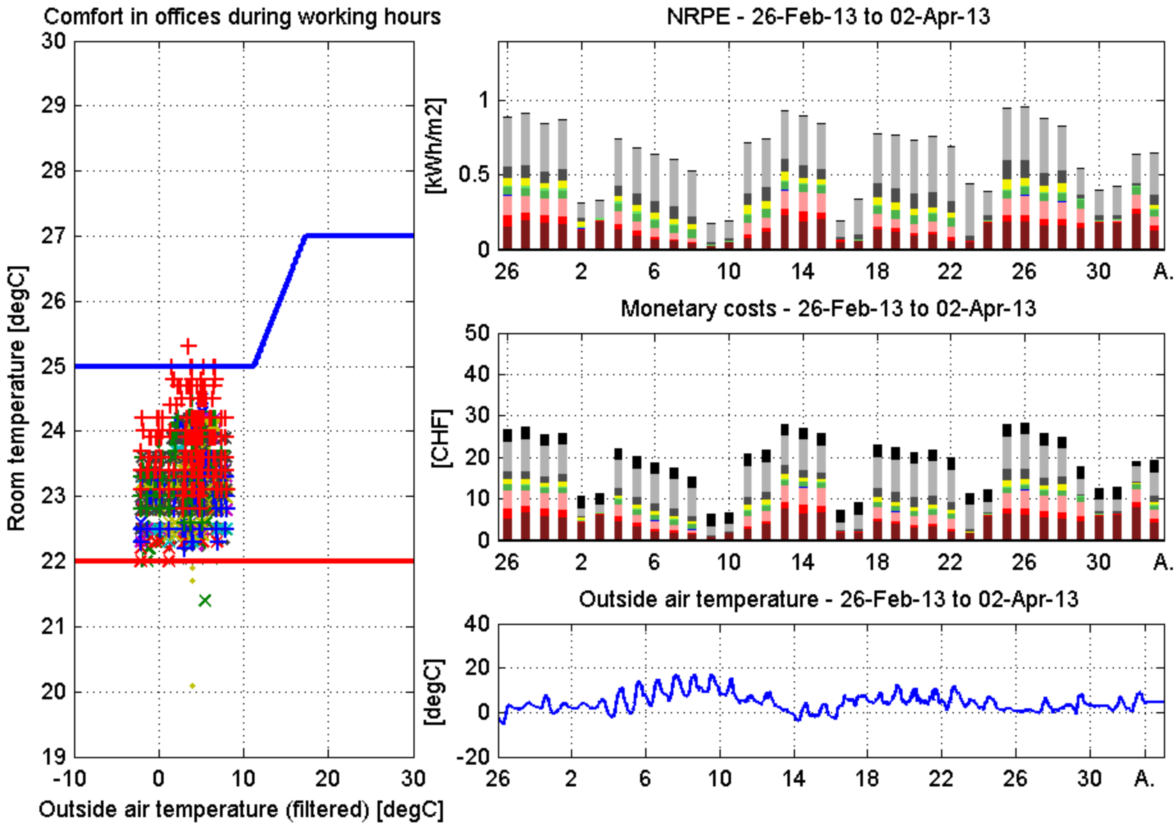


Figure 5-11: Same as previous figure, but for period P14 and control strategy RBC-4.

Overall, it can be seen that all control strategies managed to keep room temperature trajectories well within the prescribed thermal comfort range. A closer analysis (not shown) revealed that all outlier values at the lower bound of the comfort range during winter were actually caused by manual window opening. The violations of the upper comfort range in midsummer (filtered outside air temperature > 20°C) were due to the limited cooling power of the free cooling system.

Control costs depended for all control strategies directly on the cost components for heating, cooling and air/water transport. The control also had an indirect, limited impact on lighting energy usage through the blind control. The remaining cost components were essentially not affected by control: equipment cost could not be controlled at all, and peak electric power demand costs could hardly be influenced since heating in the target building was based on gas, not electricity, and cooling had to be accomplished due to operational constraints exclusively by night-time TABS operation while peak electric loads tend to occur during daytime.

From Figure 5-4 to Figure 5-11 can be seen that for cold winter days the energy costs (NRPE and MC) were dominated by heating operation. During summer, the dominant cost factor was electrical equipment usage (grey parts of the bars in the cost panels). This cost does not depend on the season and could not be influenced by the control strategies.

Costs for cooling were very low compared to all other cost components. This was due to the use of a free cooling system (with the cooling tower being operated exclusively in dry mode) and of a ventilation return air washer/cold recovery system. In particular the air washer was operated but at working hours and caused only very low additional cost.

A further observation is that the MPC strategy (Figure 5-7) showed lower TABS heating costs and somewhat higher ventilation heating costs as compared to the RBC strategies. This was due to two reasons. First, in contrast to all RBC strategies, MPC reduced TABS heating during weekends to minimize transmission heat losses through the building's envelope. Second, all RBC strategies were set up in such a way that heating was done mainly by TABS, with passive support by the ventilation system. In contrast, MPC actively used heating by ventilation on workday mornings for faster warm-up of the rooms.

5.3 Simulation Experiments

The use of simulation experiments enabled efficient and encompassing comparisons of controller performance under precisely determined conditions. Here we report results obtained with a detailed EnergyPlus model, model "M3-B" (see Section 3.2.3.3).

Whole-year simulations were executed for all RBC and MPC strategies for the year 2010 using hourly weather data from the MeteoSwiss [2] weather station Basel Binningen close to the building's location. For the predictive control strategies RBC-2, RBC-3, RBC-4 and MPC we used in addition archived weather predictions by the "COSMO-7" numerical weather prediction model [3] that were also made available by MeteoSwiss.

For the RBC simulation experiments we used exactly the same control algorithms with exactly the same control parameter values as employed in the field experiments. For MPC we used slightly different controllers in the field experiments and in the simulations. The field experimental controller was based on a thermal resistance capacitance model (see Section 3.3) that accounted for the fact that supply air ducts in the target building were partially embedded in the slab (see Section 3.2.3.3). For the simulation experiments the MPC model was adjusted to match the used EnergyPlus model by omitting all direct heat fluxes between the ventilation supply air and the slab. The sensitivity of MPC control performance to this adjustment was investigated, see Section 5.3.3.

5.3.1 Controller Comparison

5.3.1.1 NRPE and Monetary Costs

Table 5-4 shows the simulated NRPE and monetary HVAC, lighting and equipment costs for all controllers; results are given for default control parameter settings (Sections 4.2.6 and 4.3.4 for RBC and MPC, respectively) and for the 2nd floor only. Table 5-5 gives a similar overview restricted to the HVAC costs. A graphical representation of the same data is shown in Figure 5-12. Figure 5-13 shows the various costs disaggregated by month.

It can be seen that the integrated control strategy RBC-1 performs considerably better than the reference strategy RBC-0, mainly thanks to reductions in the heating and lighting cost. The integrated and predictive strategy RBC-2 further reduces energy costs. The model based, predictive and integrated strategy RBC-4 allows for even lower cost than RBC-2, while RBC-3 is the least cost-efficient of all newly developed RBC strategies.

MPC shows the best cost performance: compared to RBC-0 annual total costs are lowered by 16.6 % (NRPE) and 16.9 % (MC). Compared to the non-model based RBC-2, MPC gave lower costs by 4.4 % (NRPE) and 3.1 % (MC).

As already observed in the field experimental results, MPC was found to reduce TABS heating drastically (to almost no TABS heating) while using more heating by ventilation. In the simulations this behaviour was even more pronounced because the omission of embedded air ducts in the simulation model allowed for faster heating by ventilation than this was actually possible in the real building.

Table 5-4: Simulated annual total Non-Renewable Primary Energy (NRPE) usage and monetary costs (MC) for the various RBC and MPC control strategies in the year 2010. Shown are results for HVAC, lighting and equipment for the 2nd floor using default control parameter settings.

	NRPE			MC		
	Relative [%]	Abs. (2nd floor) [MWh/a]	Specific [kWh/(m2a)]	Relative [%]	Abs. (2nd floor) [CHF/a]	Specific [CHF/(m2a)]
RBC-0	100	130	243	100.0 (0.0)	6625 (0.0)	12.40 (0.0)
RBC-1	88.0 (-12.0)	114 (-16)	214 (-29)	87.6 (-12.4)	5804 (-821.3)	10.86 (-1.5)
RBC-2	86.7 (-13.3)	113 (-17)	211 (-32)	85.8 (-14.2)	5686 (-938.5)	10.64 (-1.8)
RBC-3	88.5 (-11.5)	115 (-15)	215 (-28)	88.6 (-11.4)	5873 (-751.9)	10.99 (-1.4)
RBC-4	85.9 (-14.1)	112 (-18)	209 (-35)	85.6 (-14.4)	5674 (-951.1)	10.62 (-1.8)
MPC	83.4 (-16.6)	108 (-21.6)	202.99 (-40.4)	83.1 (-16.9)	5506 (-1118.5)	10.31 (-2.1)

Table 5-5: Same as Table 5-4, but for HVAC costs only.

	NRPE			MC		
	Relative [%]	Abs. (2nd floor) [MWh/a]	Specific [kWh/(m2a)]	Relative [%]	Abs. (2nd floor) [CHF/a]	Specific [CHF/(m2a)]
RBC-0	100.0 (0.0)	46 (0.0)	85.58 (0.0)	100.0 (0.0)	2463 (0.0)	4.61 (0.0)
RBC-1	82.5 (-17.5)	38 (-8.0)	70.64 (-14.9)	78.5 (-21.5)	1934 (-529.1)	3.62 (-1.0)
RBC-2	81.4 (-18.6)	37 (-8.5)	69.64 (-15.9)	77.9 (-22.1)	1917 (-545.5)	3.59 (-1.0)
RBC-3	87.0 (-13.0)	40 (-6.0)	74.42 (-11.2)	85.8 (-14.2)	2114 (-348.5)	3.96 (-0.7)
RBC-4	79.7 (-20.3)	36 (-9.3)	68.22 (-17.4)	77.4 (-22.6)	1906 (-557.1)	3.57 (-1.0)
MPC	74.7 (-25.3)	34 (-11.6)	63.93 (-21.6)	69.4 (-30.6)	1709 (-753.8)	3.20 (-1.4)

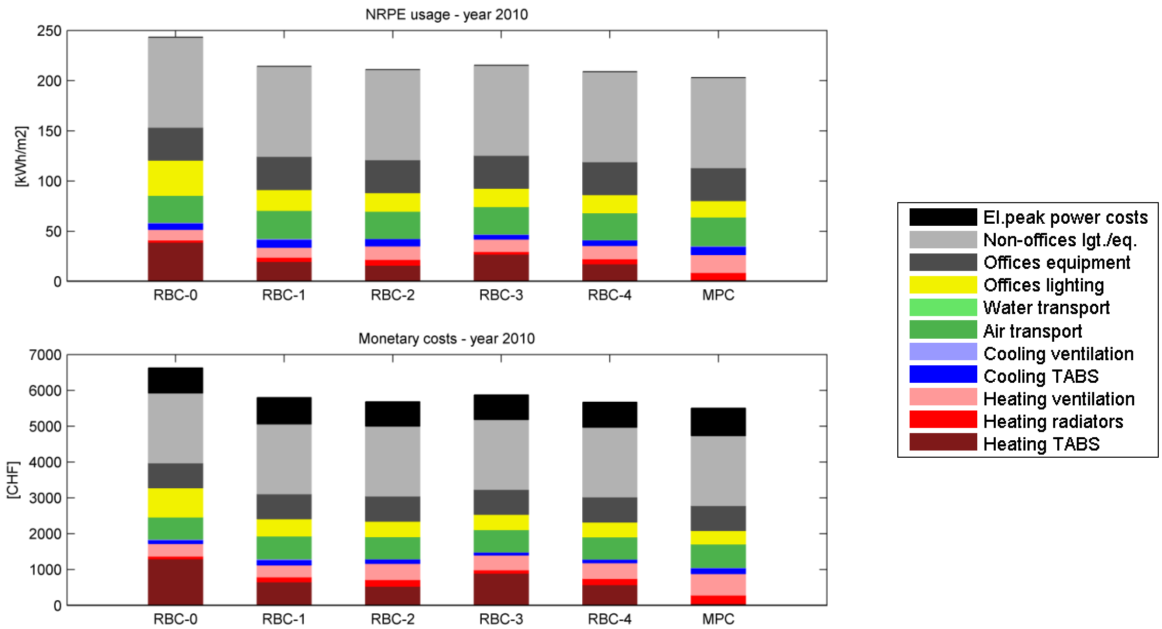


Figure 5-12: Simulated annual total Non-Renewable Primary Energy (NRPE) usage and monetary costs for the different control strategies.

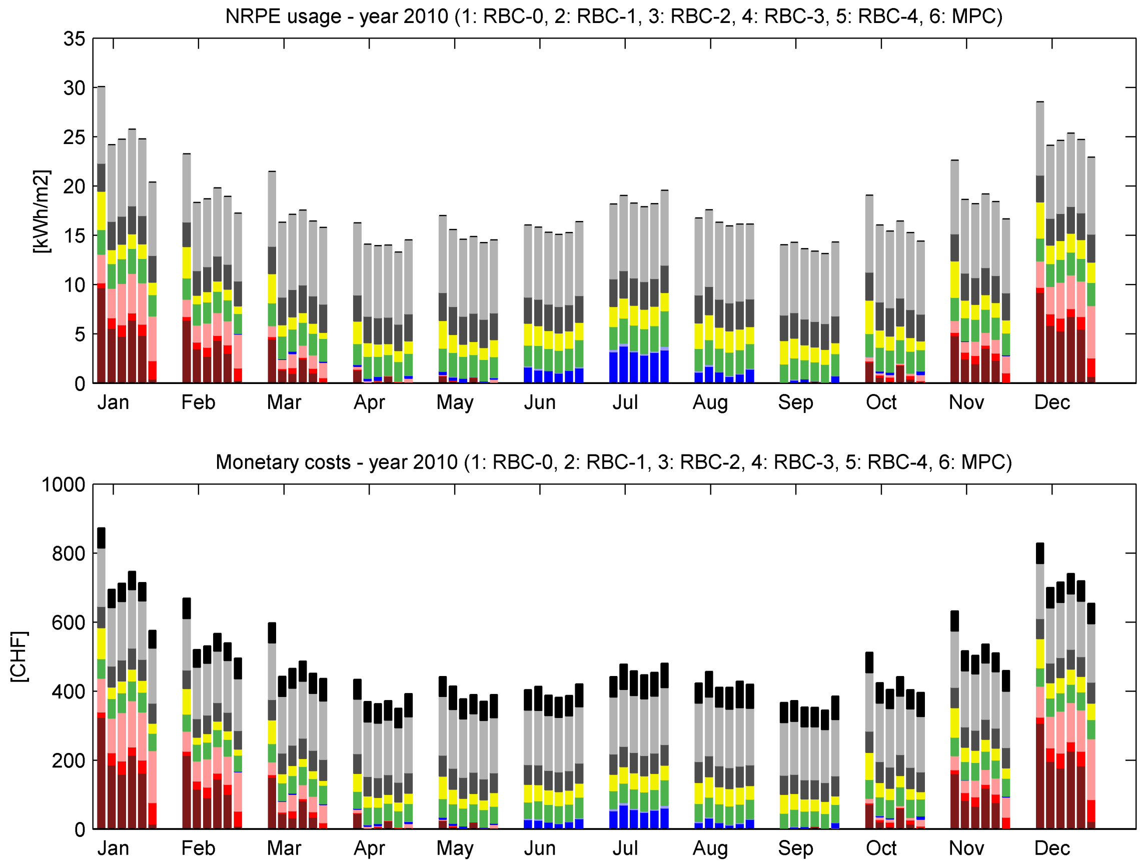


Figure 5-13: Same as Figure 5-12, but for monthly total costs. Each group of bars reports the monthly data from the six cases shown in Figure 5-12.

5.3.1.2 Thermal Comfort

Table 5-6 reports the simulated annual thermal comfort violations for the various control strategies, as obtained using the default control parameter settings. The data refer to the 13 office zones of the 2nd floor. Figure 5-14 gives a graphical representation of the simulated annual total violations for the zones with the largest thermal discomfort, whereas Figure 5-15 shows the associated monthly comfort violation figures. Monthly total comfort violation figures per office zone are shown in Figure 5-16. Figure 5-17 finally shows the frequency distributions of the simulated quarter-hourly average operative room temperatures from all office zones and working hours.

The results show that with some minor differences all six control strategies satisfied the thermal comfort requirements very well. With regard to overheating RBC-0 performed worse than RBC-1 to RBC-4, whereas MPC performed clearly better than all RBC strategies. Regarding too low room temperatures, RBC-0 showed the lowest violation numbers due to strong heating during most of the heating season (cf. Figure 5-13). The RBC-1 to RBC-4 simulations featured higher violation numbers, with the meeting room (zone "07_SW") being by far the coldest room, see Figure 5-16. However, when the "too cold" violations were only counted in case the meeting room was occupied, the total violations amounted to only 25–50 Kh, which was about the performance of MPC.

The room temperature frequency distributions (Figure 5-17) depended strongly on the control strategy. RBC-3 yielded the most symmetric distribution with the majority of room temperatures clustering around the center of the thermal comfort range. The distributions from the RBC-1, RBC-2 and RBC-4 simulations were all quite similar, indicating average room temperatures somewhat below the center of the thermal comfort range.

Quite differently, for RBC-0 most room temperatures lay in the upper half of the comfort range, whereas MPC even showed a distinct bimodal distribution. The bimodality was due to the fact that MPC typically operates close to the comfort bounds in order to minimize actuation cost. In our case this was in particular accomplished by using ventilation heating for fast warm-up in winter, which made it possible to reduce heating and cooling costs as compared to RBC.

All distributions, and most prominently the one from the MPC simulation, showed a spike at the lower bound of the comfort range. This was due to the simulated radiator heating that kept the corner rooms close the lower setpoint value.

Table 5-6: Simulated annual total thermal comfort violations for the various RBC and MPC control strategies in the year 2010. Shown are totals for all 13 office zones of the 2nd floor plus the largest single office annual total. All results were produced using the default control parameter settings.

	Too cold [Kh]		***Too warm [Kh]***	
	Total from 13 office zones	*Maximum office zone value*	*Total from 13 office zones*	*Maximum office zone value*
RBC-0	16	16	786	116
RBC-1	223	204	325	42
RBC-2	186	131	184	30
RBC-3	126	122	197	33
RBC-4	196	168	157	27
MPC	143	34	40	15

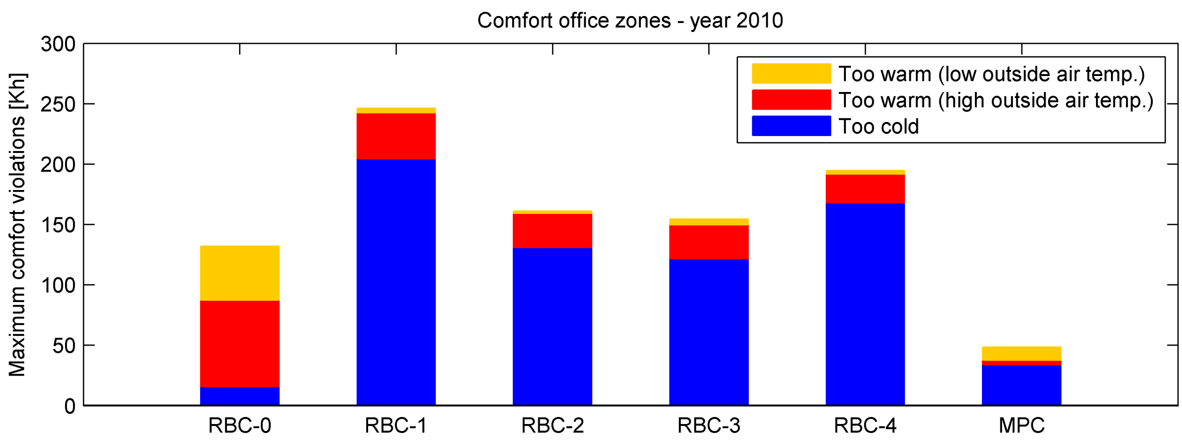


Figure 5-14: Simulated annual total thermal comfort violations for the different control strategies. Shown are for each control strategy the maximum simulated annual violations values from all 13 office zones.

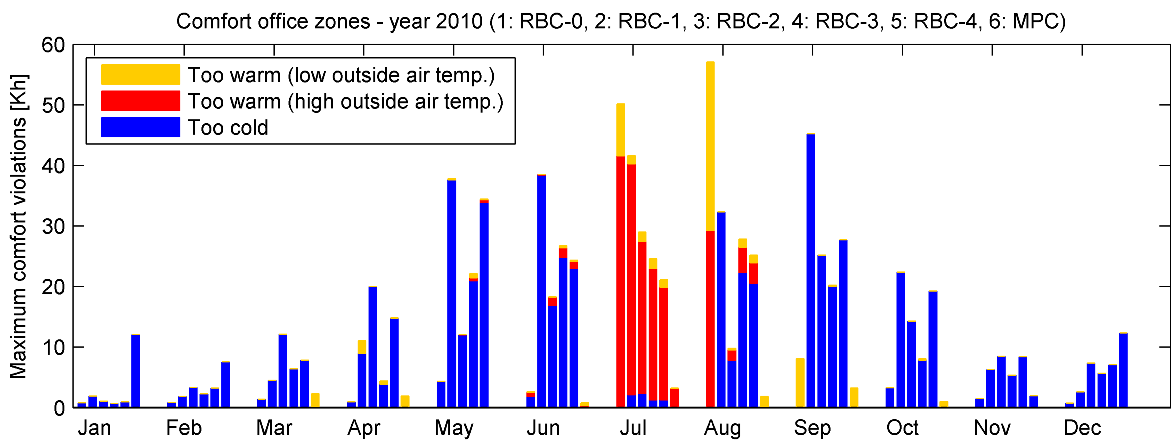


Figure 5-15: Same as Figure 5-14, but for monthly total maximum comfort violations.

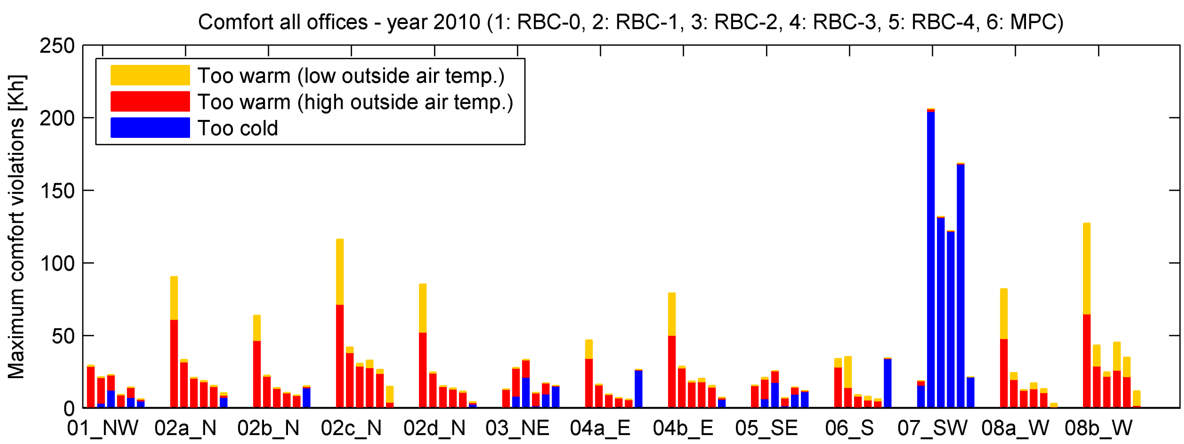


Figure 5-16: Simulated annual total thermal comfort violations for the different control strategies by office zone.

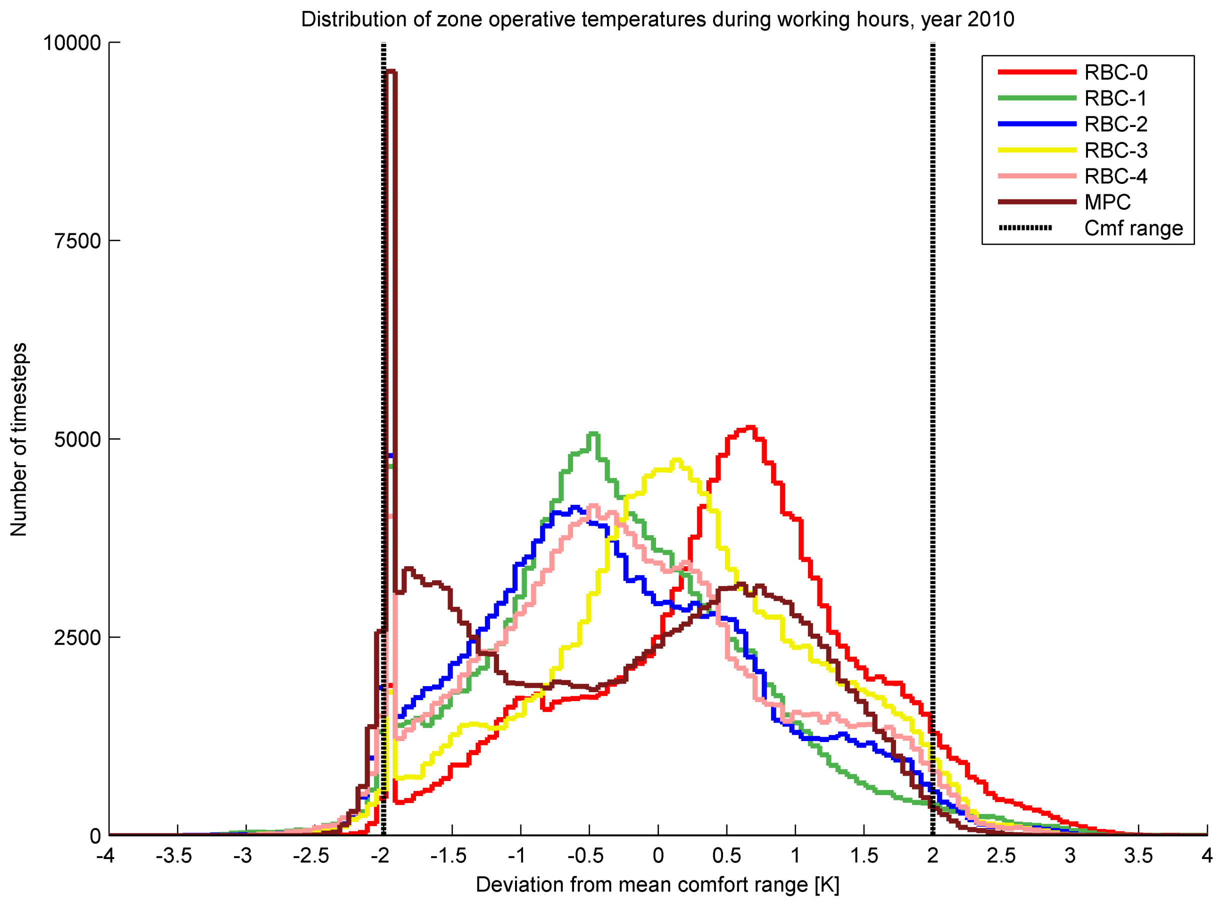


Figure 5-17: Frequency distributions of the simulated quarter-hourly office room temperatures during all working hours of the year 2010 for the different control strategies.

5.3.2 RBC Sensitivity Studies

In the process of RBC strategy development, several sensitivity studies on control parameter variation were executed. The focus was to identify good control parameter values and to get indications on how robust the controllers are against “non-optimal” settings.

The design of an example variant study targeting controller variants RBC-0, RBC-1 and RBC-2 is presented in Table 5-7. The various considered variants addressed differences in simulated year, comfort range settings, ventilation air flow rate, high-level blind control restrictions and settings, TABS heating restriction, and type of weather forecast used.

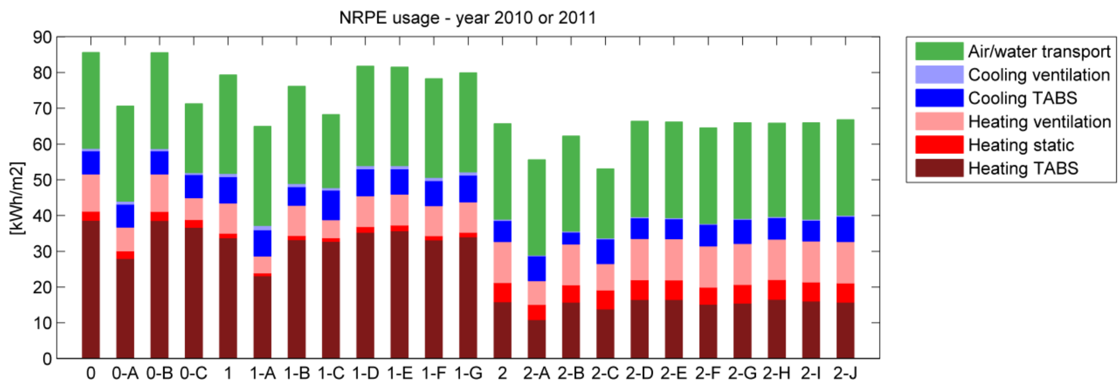
Results are shown in Figure 5-18 for the control costs and Figure 5-19 for maximum thermal comfort violations. The following main observations can be made:

- For the year 2011 – which had a warmer winter compared to the year 2010 – the simulated costs are reduced considerably.
- Raising of the upper thermal comfort range limit reduced the simulated “too warm” violations due to the less restrictive comfort requirement and increased free cooling potential; in particular for RBC-0 and RBC-1, violation numbers became very low.
- Reduction of the ventilation air rate lowered air transport energy, as could be expected. For RBC-0, however, this energy saving was accompanied by a strong worsening of thermal comfort: heavy overheating resulted due to the lower air flows supplied.

- The various changes in blind control parameters had no significant impact on control performance.
- The restriction of employing TABS heating during night-time only did not worsen control performance – in particular, comfort violation numbers were not increased considerably.
- For RBC-2, control performance was not sensitive to the type of weather prediction or the length of the prediction horizon.

Table 5-7: Simulated variants of example RBC variant study.

Variant	RBC Strategy (RBC-n)		
	0	**1**	**2**
–	Reference case using default control parameter settings, simulated year 2010		
A	Simulated year 2011 instead of 2010		
B	Upper comfort range limit set higher than default value		
C	Ventilation air flow rate reduced from default flow rate		
D	n.A.	Three blind control HL commands per day during working hours	
E	n.A.	No blind control HL command time restrictions at all	
F	n.A.	No blind control HL command position and time restrictions at all	
G	n.A.	Threshold values for shading applications set higher than default values	
H	n.A.	n.A.	TABS heating only allowed from 9 p.m. to 6 a.m.
I	n.A.	n.A.	Used weather prediction lead time 48 h instead of 24 h
J	n.A.	n.A.	Using “persistence” instead of “COSMO-7” weather forecast



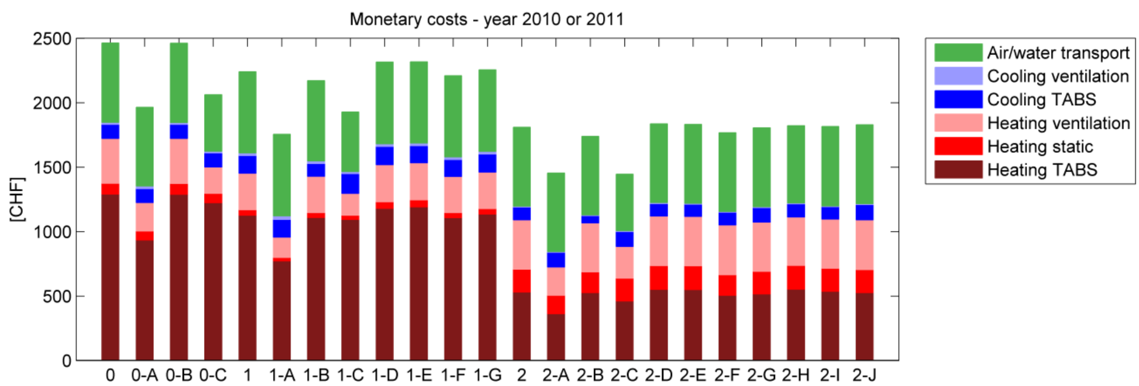


Figure 5-18: Simulated annual total Non-Renewable Primary Energy (NRPE) usage and monetary costs for heating, ventilation and air conditioning by selected RBC control strategies and variants (cf. Table 5-7); 0: RBC-0; 1: RBC-1; 2: RBC-2.

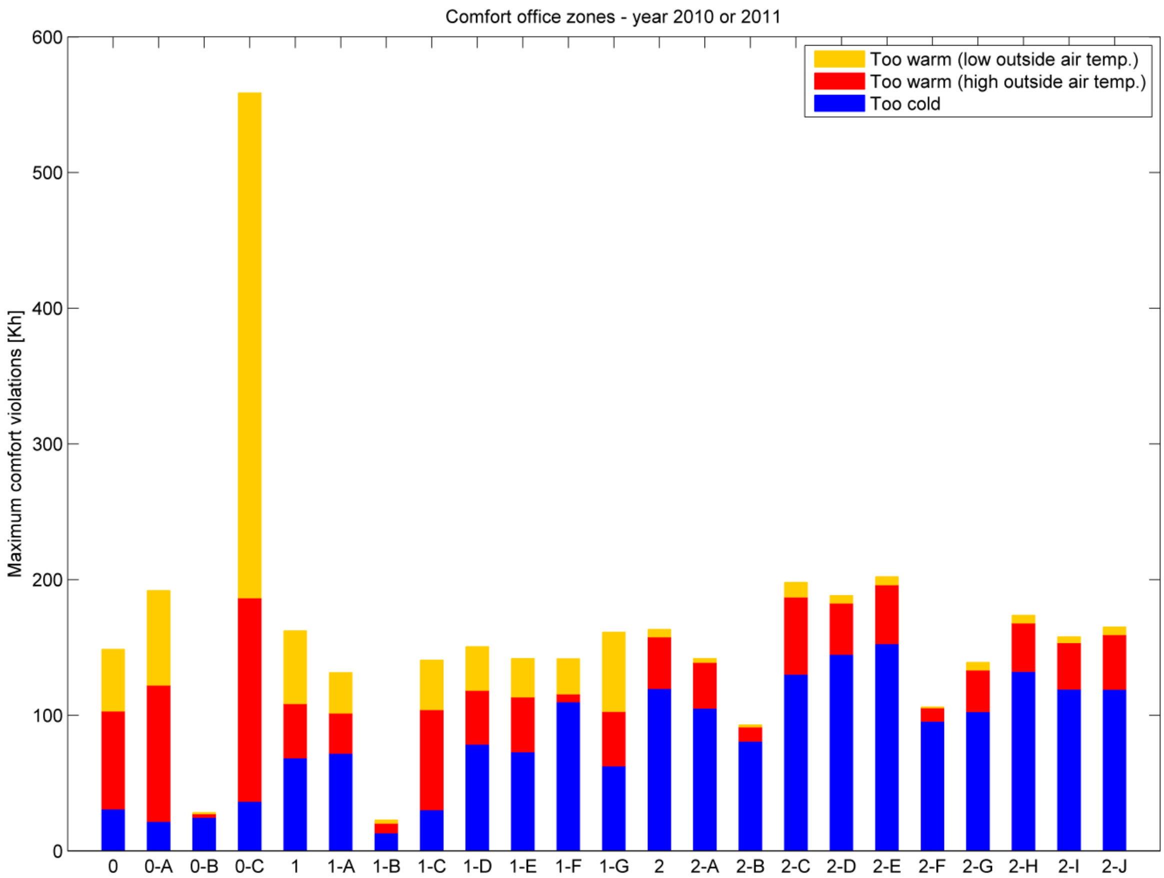


Figure 5-19: Simulated annual total thermal comfort violations by selected RBC control strategies and variants (cf. Table 5-7). Shown are for each control strategy the respective maximum simulated annual violations values from all 13 office zones.

Another study of RBC control variants exclusively dealing with high-level blind control is presented in Section 6.2. There, different control parameter settings were investigated to assess the importance of different blind types, blind integration approaches, and room user preferences.

For all executed simulation sensitivity studies, the newly developed RBC strategies – and in particular RBC-2 and RBC-4 – showed good robustness with regard to control parameter settings. For the simulation of our target building, a priori settings for the control parameter values that had been derived from basic building data yielded control performances close to the best achievable RBC performances as determined later by means of systematic simulation studies. This indicates that the estimation of control parameter values is simple and feasible without detailed knowledge of the building and its HVAC/lighting/blind systems.

It must be noted, however, that the sensitivity of controller performance to different building types and HVAC systems was investigated only to a very limited extent, i.e. only by simulating the RBC strategies with the various EnergyPlus models (Section 3.2.3.3) that were developed in the course of the project. Nevertheless, these simulations also suggested good robustness for the RBC controllers (results not shown).

Much more extensive simulation studies have been carried out in the forerunner project OptiControl-I [1]. They showed that controller performance and sensitivities to control parameter settings can vary strongly across basically different building types and HVAC system configurations. In that sense our results need to be interpreted with care.

5.3.3 MPC Model Mismatch Sensitivity Study

The EnergyPlus model used in all above simulation based controller assessments was the model M3-B. As described in Section 3.2.3.3, it did not incorporate the heat exchange between supply air and the office ceilings' concrete slabs that was present in the real building. The heat exchange was also not taken into account in the MPC model used for the simulations. However, it was incorporated in the model used to run MPC on the building.

In this section we evaluate the sensitivity of our MPC simulation results to different levels of supply air / concrete slabs interaction, including the interaction level used on the building. The critical interaction parameter was named *AhuSlabExch* and it appears in the model as

$$T^{i}_{\mathrm{AHU,sup}}(u,v,x) = AhuSlabExch \cdot T^{i}_{slab}(x) + \left(1 - AhuSlabExch\right) \cdot T_{\mathrm{AHU,sup}}(u,v,x))$$

where *u*, *v* and *x* denote control inputs, disturbances and system states, respectively (see Equation 3.8); the time indices "(t)" have been omitted for brevity. The used supply air temperature into zone *i,* $T^{i}_{\mathrm{AHU,sup}}(u,v,x)$*,* was thus the weighted mean of the concrete slab temperature of zone *i,* $T^{i}_{slab}(x)$, and the controlled AHU supply air temperature, $T_{\mathrm{AHU,sup}}(u,v,x)$ Of course, the model considered not only the effect of the slabs on the zone supply air temperatures, but also any opposite heat fluxes to the slabs (not shown).

To analyse the sensitivity of MPC performance to changes in the *AhuSlabExch* value, we simulated the EnergyPlus model M3-B with five different MPC controllers using *AhuSlabExch values* $\in \{0,\ 0.2,\ 0.4,\ 0.6,\ 0.8\}$. Note that the EnergyPlus model M3-B implemented a situation corresponding to *AhuSlabExch* = 0, the value that had also been used by MPC in all simulations reported in Section 5.3. The value used for MPC on the building had been determined from a two-week special monitoring phase (see Section 3.2.3.3) and it was 0.6.

Figure 5-20 and Table 5-8 report the simulated annual NRPE and monetary costs. The baseline simulation (with *AhuSlabExch* equal to 0) showed the lowest cost, followed by slightly increased costs in the 0.2 to 0.6 simulations, and a particularly large cost increase in the 0.8 simulation. The found increases in costs with increasing *AhuSlabExch* values reflected the increasing degree of mismatch between the MPC model and the controlled EnergyPlus model.

As can be seen from Figure 5-20 the perturbed simulations gave an increase in TABS heating. This was because the baseline MPC made heavy use of the AHU to rapidly heat up the building in the morning hours. Apparently, when part of the AHU heat was specified to go into the concrete slabs this actuation was determined to be less appropriate by the MPC.

Figure 5-20 shows the simulated maximum thermal comfort violations. There is a clear trend towards higher comfort violations with increasing values of *AhuSlabExch.* Even though comfort deteriorated heavily as compared to the baseline simulation, for the 0.6 simulation it was in the range of the comfort provided by the RBC-1 strategy (Figure 5-14). A closer analysis revealed that almost all additional thermal comfort violations occurred during spring or autumn, when MPC expected the concrete to heavily cool or heat the supply air – an interaction that was not present in the EnergyPlus model. The violations were most frequent in the intermediate seasons because then the temperature gradient between the supply air and the concrete slabs is largest.

These results demonstrate the importance of correct modeling of energy flows for efficient MPC operation. The performance deterioration due to a wrongly modeled AHU-slab heat exchange using the best guess value of 0.6 for the *AhuSlabExch* parameter was not very large. However, if that heat exchange would have gone undetected, MPC could hardly have been expected to perform better than the non-model based RBC strategy RBC-2 for our target building (Table 5-4 vs. Table 5-8).

Since MPC relies so heavily on the AHU, the model mismatch investigated here probably had a particularly large impact on control performance as compared to many other parameter or input uncertainties. Nevertheless, this result motivated us to investigate ways to make MPC more robust to (unavoidable) plant-model mismatch, as reported in Section 6.4.

Table 5-8: Simulated annual total Non-Renewable Primary Energy (NRPE) usage and monetary costs (MC) for the MPC control strategy in the year 2010 using different values for the supply air / concrete slabs interaction parameter AhuSlabExch. Shown are results for HVAC, lighting and equipment for the 2nd floor.

	NRPE			***MC***		
	Relative [%]	Abs. (2nd floor) [MWh/a]	Specific [kWh/(m²a)]	Relative [%]	Abs. (2nd floor) [CHF/a]	Specific [CHF/(m²a)]
AhuSlabExch 0	100.0 (0.0)	108 (0.0)	202.75 (0.0)	100.0 (0.0)	5506 (0.0)	10.27 (0.0)
AhuSlabExch 0.2	100.1 (0.1)	108 (0.1)	202.99 (0.2)	100.3 (0.3)	5506 (18.7)	10.31 (0.0)
AhuSlabExch 0.4	100.8 (0.8)	109 (0.9)	204.44 (1.7)	101.0 (1.0)	5540 (52.5)	10.37 (0.1)
AhuSlabExch 0.6	103.8 (3.8)	112 (4.1)	210.38 (7.6)	104.1 (4.1)	5711 (223.1)	10.69 (0.4)
AhuSlabExch 0.8	114.0 (14.0)	123 (15.2)	231.12 (28.4)	115.5 (15.5)	6337 (849.4)	11.86 (1.6)

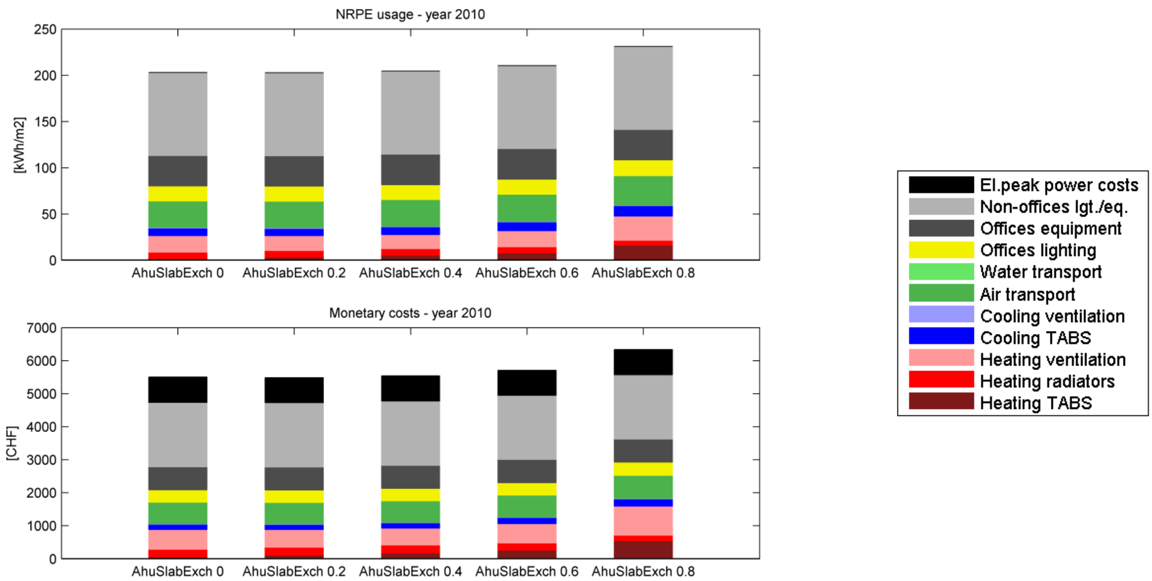


Figure 5-20: Simulated annual total Non-Renewable Primary Energy (NRPE) usage (top) and monetary costs (bottom) for the MPC control strategy in the year 2010 using different values for the supply air / concrete slabs interaction parameter AhuSlabExch.

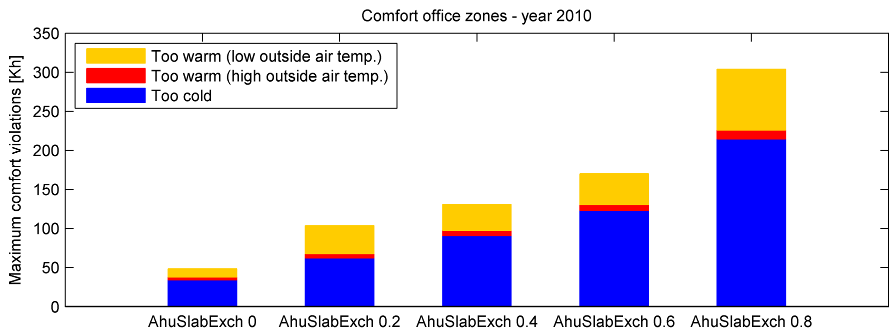


Figure 5-21: Simulated annual total thermal comfort violations for the MPC control strategy in the year 2010 using different values for the supply air / concrete slabs interaction parameter AhuSlabExch. Shown are for each case the maximum simulated annual violations values from all 13 office zones of the 2nd floor.

5.4 Evaluation of User Acceptance

5.4.1 Building Owner and Facility Manager

Acceptance by the building owner and facility management is crucial for the success of a building automation system. The building owner typically decides with the aid of experts on the building automation system and its functionality, while the facility management people have to be able to operate and work with the system efficiently.

To assess the acceptance and expectations by the target building's owner and facility manager, a questionnaire was elaborated and answered by them at the beginning of the project. This provided the starting point for a series of further discussions and feedbacks during the course of the project.

From the facility manager we learned how he had tuned and optimized the RBC-0 control strategy prior to the beginning of our research project: The most important settings were supply air temperature setpoints that were changed around 4 to 6 times a year, depending on the outside air temperature (season). During the first phase of building operation he had also to adapt the original settings for the TABS heating curve and for the TABS cooling control rules. Changes were often triggered by complaints of the office room users. The facility manager reported that he dedicated around 20% of his working time to building automation tasks (maintenance, operation and monitoring). He pointed out that he had not been trained sufficiently on the building automation system and that his options for adapting the system were too limited.

The building owner stated at the beginning of the project the following objective: to have buildings that do not only provide a very high comfort level, but that also can be operated in an energy efficient manner. Regarding the project OptiControl-II, the building owner expressed a strong interest to support this research, and also further research beyond the present project. The building owner also made clear that a more detailed monitoring of the building would be beneficial in order to be able to take actions that would improve the target building's performance, and for being able to take better informed decisions when planning new buildings.

During the execution of our field experiments we learned that keeping the facility manager well informed about our activity was of paramount importance for the acceptance of our work. This was understandable since our experimental design did not give him any authority to modify the high-level control settings. The only option available to him was to completely turn off the experimental high-level control, an event that never occurred during the course of the project. Of course, a final high-level control product would have to include a simple and understandable interface for building operators.

All in all, both the building owner and the facility manager reacted very positively to our work and were fully satisfied by the performance of *all* high-level control strategies applied to the target building in the course of the project. Their feedback proved also very helpful as an input to the cost/benefit analysis, see Chapter 7.

5.4.2 Room Users

In order to assess acceptance by the office room users, a web-based survey was designed based on [5], [6], [7] and was implemented in Actelion's Intranet. The survey included 38 questions on personal data, workspace & satisfaction, lighting, thermal comfort, air quality and general comments on the building and its control.

The main goal was to get from the occupants feedback on the acceptance of our high-level control strategies, in particular regarding thermal comfort and automatic blind control. Figure 5-22 shows an illustration example of how the survey presented to the room users.

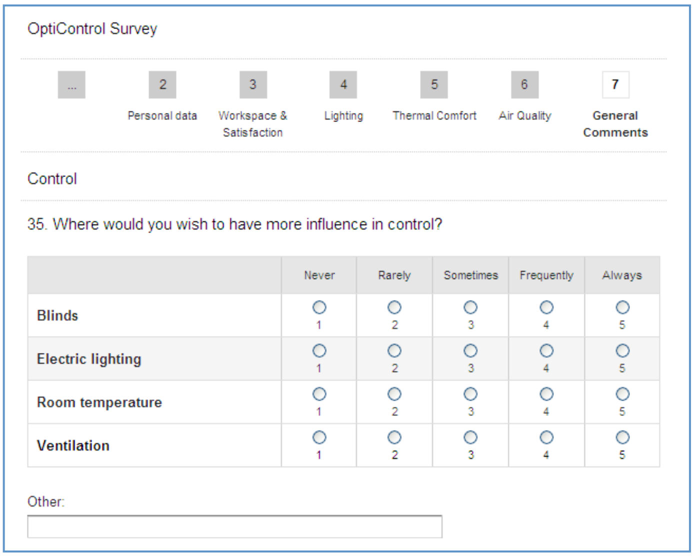


Figure 5-22: Example of an entry form used in the web-based room user survey.

The survey was carried out for the first time between October 24th and November 7th 2011, i.e. before the start of the first field experiment, with the original control RBC-0 being still in operation. Of the total number of 123 building users at this point in time, 78 participated in the survey.

A second, identical occupant survey was carried out between March 29rd and April 20th 2012, at the end of a ca. three-monthly phase where the RBC-2 high-level control strategy was in operation. A total of 48 occupants participated in the second survey.

The general questions from both surveys revealed that the building usage is typical for office buildings with Personal Computer work being dominant. Room users were found to move quite often between workspaces; most of them reported having worked only for a few months at their current workspace. Roughly 60 % of the room users were women.

The surveys showed that the **general satisfaction** with the building was high; both shortly before the first control experiment took place and after several weeks of RBC-2 control, see Figure 5-23. The general satisfaction was on average higher in the second survey. Note the different scales in Figure 5-23 and all subsequent figures (shown are always absolute numbers of responses).

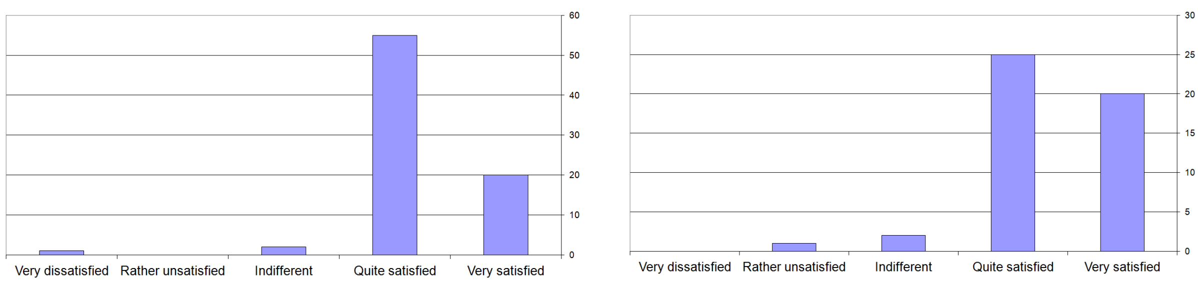


Figure 5-23: Responses to question "How satisfied where you with the building overall?"; results from survey 1 (left) and survey 2 (right).

Regarding **lighting**, protection against daylight by means of blinds proved important to the majority of the users, see Figure 5-24. Figure 5-25 further indicates that the daylight level is just right for most users. Some users think that their room is too bright and very few think that it is too dark. The results were nearly identical for both surveys. There were no negative feedbacks or complaints regarding the automatic blind control that was introduced after the first survey took place. It seems that the novel automatic blind control that restricted high-level blind operation to only once at 12:30 during working hours was accepted well by the room users.

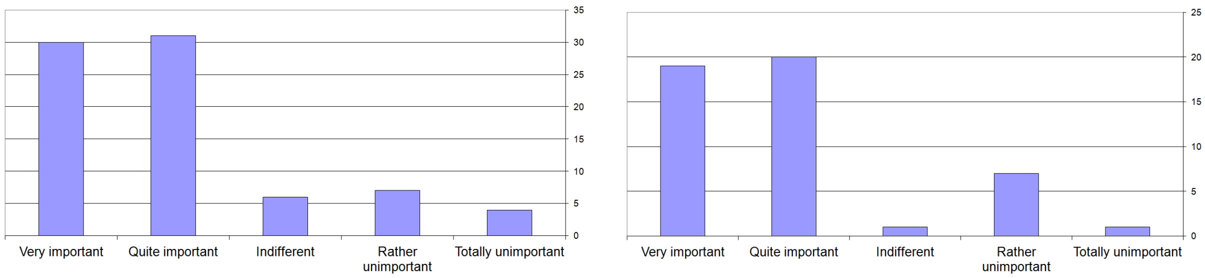


Figure 5-24: Response to question "How important is for you protection against daylight, glare or heat?"; results survey 1 (left) and survey 2 (right).

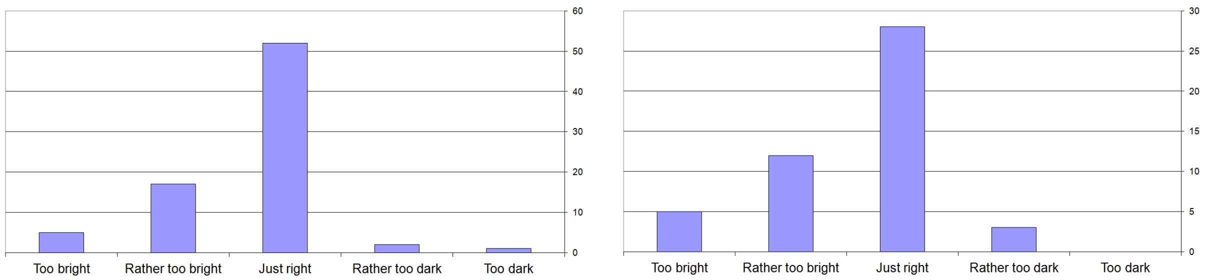


Figure 5-25: Response to question "How satisfied are you with the daylight level in the whole room?"; results survey 1 (left) and survey 2 (right).

To help interpret answers on **thermal comfort,** Figure 5-26 and Figure 5-27 show weather and thermal comfort (in 2nd floor offices only) during the execution of survey 1 and survey 2, respectively. It can be seen that due to overheating by the RBC-0 control strategy during the first survey the measured room temperatures in the 2nd floor offices were somewhat higher than during the second survey.

This difference however did not leave any marks in the users responses – room users gave very similar responses in both surveys. In particular, they reported more frequently too warm room temperatures in the afternoon (Figure 5-29) as compared to the morning (Figure 5-28). This result reflected the diurnal rise in room temperatures due to internal and external heat gains, an effect that can hardly be prevented by the slowly reacting TABS system.

From Figure 5-30 can be seen that the room users were generally satisfied with the thermal comfort. Thermal comfort satisfaction also remained more or less unchanged between surveys, as this was the case for the overall satisfaction with the building (Figure 5-23).

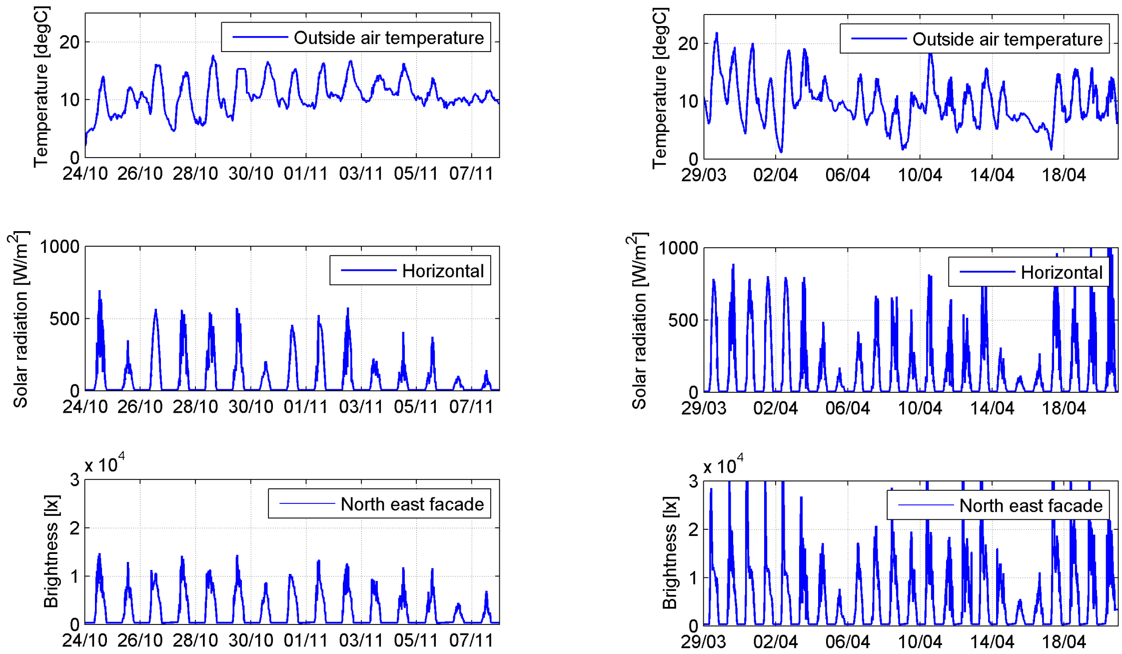


Figure 5-26: Weather data during the execution of survey 1 (left) and survey 2 (right).

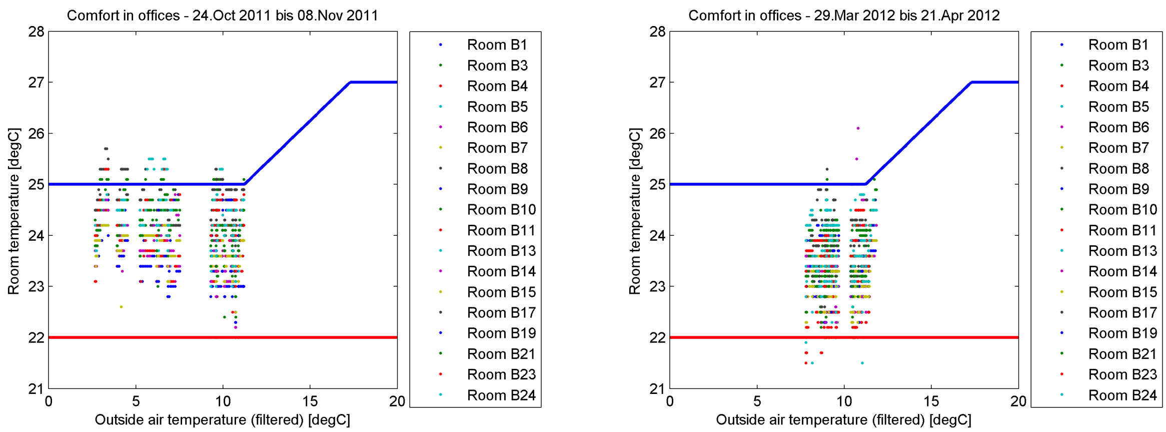


Figure 5-27: Thermal comfort evaluation during the execution of survey 1 (left) and survey 2 (right).

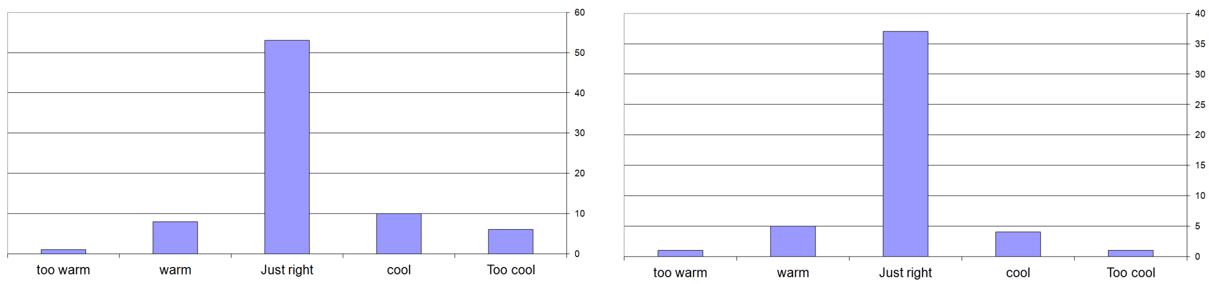


Figure 5-28: Response to question "During the last two weeks temperature at your work space in the morning was … ?"; results survey 1 (left) and survey 2 (right).

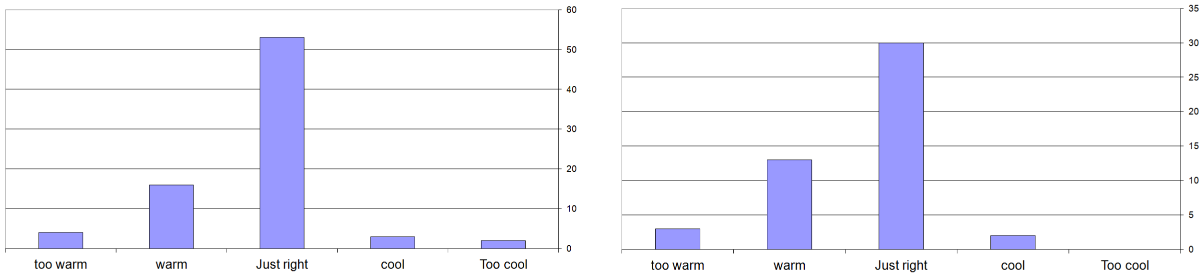


Figure 5-29: Response to question "During the last two weeks temperature at your work space in the afternoon was … ?"; results survey 1 (left) and survey 2 (right).

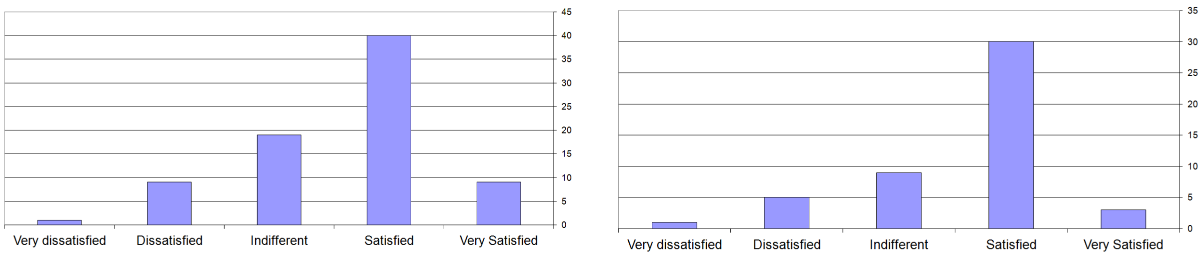


Figure 5-30: Response to question "How satisfied have you been with the temperature in your workspace in the last two weeks?"; results survey 1 (left) and survey 2 (right).

The target building is designed such that it does not allow for individual room control, and that only the users of the corner rooms have some possibility to interact with the heating system (by changing the room temperature setpoint of the radiators). All other users have no possibility for interaction with the heating system. Moreover, none of the room users may interact with the cooling system. The surveys revealed that most room users would like to exert more control over room temperatures than this is currently possible, a result that remained stable across the two surveys, see Figure 5-31.

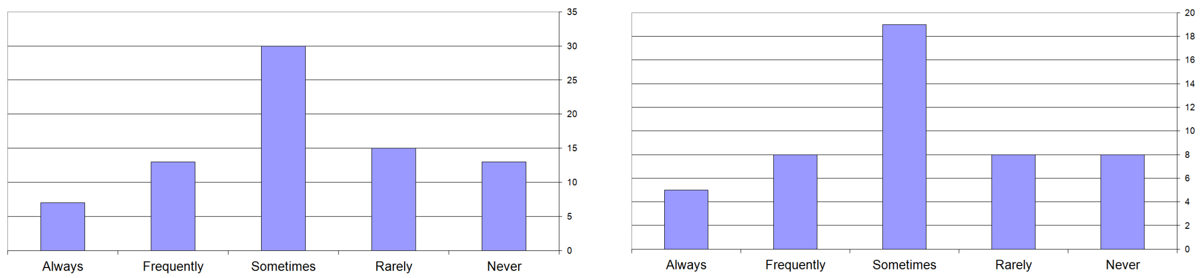


Figure 5-31: Response to question "How often do you wish that you had more control over room temperature?"; results survey 1 (left) and survey 2 (right).

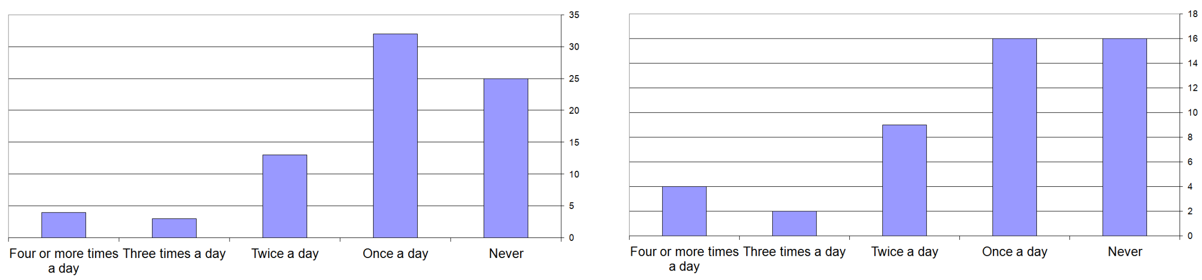


Figure 5-32: Response to question "How often do you open a window in order to change the temperature in your office?"; results survey 1 (left) and survey 2 (right).

The most important option available to room users for manipulating room temperatures is the opening of windows. The responses to the corresponding question (see Figure 5-32) showed a wide spectrum of window usage patterns by the different users: some users reported to never open windows, while other users apparently open them several times a day. This results was confirmed by our analysis of the window contact measurements in the building (results not shown).

In summary, room users were satisfied with the building and building automation already prior to the start of the project. The general response from the second survey (after a novel high-level control had been operating for three months) was nearly identical to the first one. Therefore, we conclude that there was no significant negative impact of the introduced high-level controller. At the same time, we also could not detect any significant positive effect.

5.5 References

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6 Further Control-Related Studies

D. STURZENEGGER, M. GWERDER, D. GYALISTRAS & R.S. SMITH

6.1 Load Shifting

Electrical load shifting and electrical peak load reduction in buildings are expected to become more and more important in the future. This is because of increasing electricity demand and the increasing use of renewable, intermittent energy sources.

Buildings equipped with the capability for energy storage are particularly suited for load shifting tasks. Storage devices for *thermal* energy are particularly attractive because they are technically comparatively easy to implement, safe and robust. They include warm/cold water storages, ice storage, ground storage, and heat/cold storage in the building's structure.

The latter option was available in the OptiControl-II target building thanks to the presence of Thermally Activated Building Systems (TABS). TABS employ a network of pipes embedded in the building's concrete core that is actively conditioned by circulating hot and cold water.

The various control strategies presented in Chapters 4 and 5 used the TABS to exploit time-varying environmental energy fluxes: by taking advantage of low night-time outside air temperatures to pre-cool the building by means of free cooling, and by using solar heat gains to pre-heat the building by means of appropriate blinds control.

TABS however also offer the possibility to optimize the active production of heat and cold. In the OptiControl-II target building this option is currently irrelevant, because a gas boiler provides all heating energy, and gas is for the time being abundantly available at a more or less constant price. However, in many other TABS buildings heat is generated by means of heat pumps. Their operation strongly impacts the building's electrical consumption profile and, depending on electricity tariff, also the operation cost.

Below we report on two studies that explored the feasibility and possible benefits of load shifting for the target building. For this hypothetical study we assumed that a heat pump is used to produce heat instead of a gas boiler. To simplify matters, we assumed throughout a constant heat pump coefficient of performance (COP) of 4.

6.1.1 Load Shifting Using RBC

Current tariffs for electrical energy in Switzerland typically favor load shifting from day-time to night-time, as this was also the case for the target building (see Table 5.2). In [1] we assumed presence of a heat pump operated according to this tariff structure to assess load shifting by means of Rule Based Control (RBC). To this end we performed two whole-year simulations with the following control strategies:

- RBC-2, as described in Section 4.2.4
- RBC-2P, a modified version of RBC-2. This strategy restricts TABS heating to the low tariff phase from 21:00 until 06:00 of the following day. It was implemented based on a Pulse Width Modulation (PWM) procedure, similar to the one used for the night-time free cooling control.

We found that RBC-2P was able to reduce both, monetary costs (MC) as well as electrical peak load, as compared to RBC-2. Thermal comfort and Non-Renewable Primary Energy (NRPE) usage were almost equal for both cases. MC for TABS heating were lowered by

24% and MC for electrical peak power by 4% (>10% for winter months). These savings reflected a relatively modest high/low tariff rate ratio of 1.5. Much larger MC savings can be expected to occur under a higher ratio.

We concluded that by combining TABS with an appropriate RBC strategy it is possible to efficiently shift heat (as well as cold) generation to within low cost phases, without having to compensate for storage losses, and with no negative impact on thermal comfort.

6.1.2 Load Shifting Using MPC

The above RBC load shifting study assumed a very simple and regular tariff structure. In the future it is likely that building owners and operators will be increasingly confronted with time-varying pricing, including dynamic price forecasts. Handling of more complex load shifting requirements pushes however the RBC approach to its limit, since simple rules that can deal with arbitrary scenarios are very difficult to develop and tune.

Quite differently, Model Predictive Control (MPC) by design flexibly supports easy inclusion of complex tariff structures, or, more generally, predictions of time-varying price signals in the optimization task (see Section 4.3.3). To test the practicability of this feature we conducted a field experiment where the target building was controlled during two different periods by MPC using two distinct cost functions. The experiment has also been reported in [1].

The first period extended over almost 3 months, from November 11, 2012 to February 4, 2013. During this period we used throughout a constant actuation cost for all actuators. The second period extended from February 5 to February 14, 2013. Here we prescribed a diurnally varying price signal for electricity with two low-price windows extending over 04:00–06.30 and 21:00–01:30, respectively.

During both periods MPC operated under the assumption that heat for the TABS, the conditioning of the supply air and the radiators was produced by a heat pump. Electricity usage by fans was also considered in the MPC cost function.

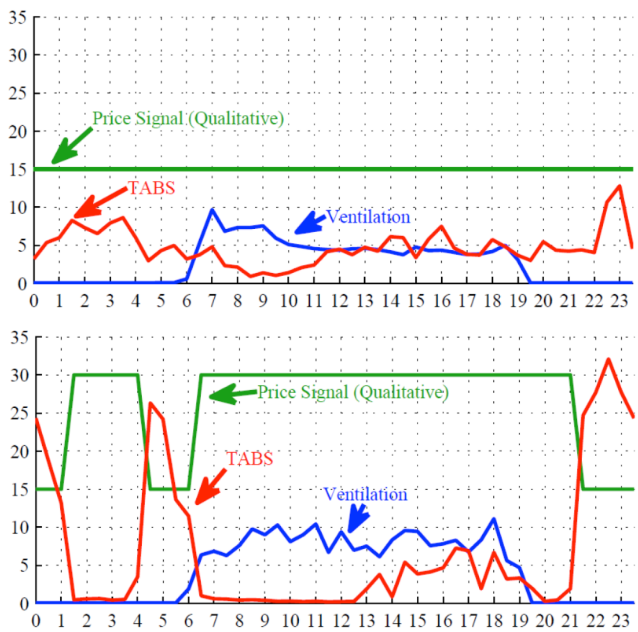

Figure 6-1: Average diurnal cycles of imposed MPC price signals and of measured average specific heating power (in [W/m2]) for TABS and ventilation from the target building. The horizontal axis shows the hour of day. Top: reference case (November 11, 2012 to February 4, 2013); bottom: load shifting experiment (February 5 to 14, 2013).

Figure 6-1 compares the diurnal cycles of the imposed price signals together with the average daily cycles of the measured specific heating power used by the TABS and the Air Handling Unit (AHU) for the two experimental periods, respectively.

From the top panel of Figure 6-1 can be seen that during the first experimental period ventilation heating was only used during the day, when the AHU was on, while TABS heating largely happened during the night. This reflected the MPC planning for the compensation of transmission losses during the night and early morning hours (the coldest time of day) in order to ensure thermal comfort in workday mornings.

Figure 6-1 (bottom) shows that in the second experimental period most of the TABS power delivery was shifted into the two low-price windows. Such a shift was not possible for ventilation due to the specified minimum supply air temperature constraints during working hours. On average, some TABS heating proved still necessary during afternoons to satisfy thermal comfort towards the end of working days.

Comparing absolute numbers from the two experimental periods in Figure 6-1 one can see that, on average, in the second period more heating energy was consumed. This was due to lower outside air temperatures as compared to the first period. Thermal comfort was maintained in both periods equally well (results not shown).

Our experiment clearly demonstrates the capability of MPC to take into account time-varying price signals. It also shows that depending on thermal comfort requirements MPC may be able to allocate some portion of the actuation power demand to low-price windows.

Overall, it can be stated that the ease and flexibility with which cost functions and comfort (and other) constraints can be modified in MPC opens up entirely new possibilities for the adjustment of the trade-off between energy usage, monetary cost and thermal comfort in building control.

6.2 Importance of Integrated Blind Control

From an energetic point of view blind operation presents a highly efficient device to control the harvesting of solar energy in the heating season and the cooling demand in summer.

In this section we present a simulation study where we compared the control performance of several different blind control strategies for the OptiControl-II target building. Our focus was to assess the value of so-called integrated blind control, i.e. control that coordinates the blind operation with the actuation of all other HVAC system components.

A comprehensive assessment of integrated control strategies for other buildings and HVAC/blinds/light applications was done in the forerunner project OptiControl-I, see [2], [4]. The present comparison of integrated and non-integrated strategies is to our knowledge novel and unique.

6.2.1 Simulation Study Set-Up

6.2.1.1 Control Strategies

All investigated control strategies were based on the newly developed strategy RBC-2, see Section 4.2.4 and [5]. The various strategies differed only in the blind control part. The control of TABS, ventilation, and radiator heating was in all cases exactly the same as defined in the baseline strategy RBC-2.
Table 6-1 gives an overview of the control strategies investigated.

The different control strategies analyzed were:

- The default control Strategy **DEF**. This was strategy RBC-2 with standard control parameter values, as described in Section 4.2.4 and [5].
- Strategy **NTR**. The same strategy as DEF, but with no restrictions related to the timing and frequency of blind movement. However, as for strategy DEF, during working hours, blinds cannot be in the closed position, i.e. they must be either open, or in one of the two predefined shading positions with a blind slat angle of 45° or 70°, respectively.
- Strategy **NTROC**. It uses a modified algorithm for determining the high-level control blind operating mode: operating modes SHADE_MIN and SHADE_MAX in strategy DEF are replaced by LOAD and UNLOAD, respectively. These modes imply but fully opened or fully closed blinds. The NTROC strategy provides maximum energetic support for the HVAC system by reducing heating and cooling load as far as possible, regardless of the consequences for lighting costs or visual user comfort.
- Strategy **NTAR**. It is the same strategy as NTR, but in addition blind slat angles can be varied continuously within the range 45°–90°. As for DEF and NTR, during working hours, blinds are not allowed to be in the closed position. In case of direct solar radiation on the facade, both operating modes SHADE_MIN and SHADE_MAX are specified such as to set the blind slat angle to the cut-off angle (limited to within the range 45° and 90°), under overcast conditions they both set the angle to 90°.
- Strategy **DEF NI**. It is the same strategy as DEF, but with blind control integration removed, i.e. the high-level control blind operating mode is determined independently of the blind and HVAC control. Instead of relying upon historical heat/cold demand signals, the operating mode of all blinds of a given façade is solely determined based on the measured incident solar radiation on that façade: if the measured value is below a given threshold the blind control mode is set to LOAD, otherwise to UNLOAD. Prior to phases with restricted blind movement, MeteoSwiss predictions are analyzed in addition, as for strategy DEF.
- The control strategy **NTR NI** is the same strategy as NTR, but using the high-level control blind operating mode calculation of strategy DEF NI.
- The control strategy **NTROC NI** is the same strategy as NTROC, but using the high-level control blind operating mode calculation of strategy DEF NI.
- The control strategy **NTAR NI** is the same strategy as NTAR, but using the high-level control blind operating mode calculation of strategy DEF NI.
- The control strategy **DEFNF NI** is the same strategy as DEF NI except that no weather forecasts are used.

Table 6-2 gives some information on why they were selected and their field of application.

Table 6-1: Overview of the investigated control strategies

Name	Control strategy	Integrated control	Angle restrictions	Time restrictions	Using MeteoSwiss weather forecast
DEF	**DEF**ault strategy	✓	✓	✓	✓
NTR	**N**o **T**ime **R**estrictions	✓	✓	×	×
NTROC	**N**o **T**ime **R**estrictions, **O**pen/**C**lose positions only	✓	✓	×	×
NTAR	**N**o **T**ime and **A**ngle **R**estrictions	✓	×	×	×
DEF NI	**DEF**ault strategy, **N**ot **I**ntegrated	×	✓	✓	✓

NTR NI	**N**o **T**ime **R**estrictions, **N**ot **I**ntegrated	×	✓	×	×
NTROC NI	**N**o **T**ime **R**estrictions, **O**pen/**C**lose positions, **N**ot **I**ntegrated	×	✓	×	×
NTAR NI	**N**o **T**ime and **A**ngle **R**estrictions, **N**ot **I**ntegrated	×	×	×	×
DEFNF NI	**DEF**ault strategy, **N**o Weather **F**orecast, **N**ot **I**ntegrated	×	✓	✓	×

The different control strategies analyzed were:

- The default control Strategy **DEF**. This was strategy RBC-2 with standard control parameter values, as described in Section 4.2.4 and [5].
- Strategy **NTR**. The same strategy as DEF, but with no restrictions related to the timing and frequency of blind movement. However, as for strategy DEF, during working hours, blinds cannot be in the closed position, i.e. they must be either open, or in one of the two predefined shading positions with a blind slat angle of 45° or 70°, respectively.
- Strategy **NTROC**. It uses a modified algorithm for determining the high-level control blind operating mode: operating modes SHADE_MIN and SHADE_MAX in strategy DEF are replaced by LOAD and UNLOAD, respectively. These modes imply but fully opened or fully closed blinds. The NTROC strategy provides maximum energetic support for the HVAC system by reducing heating and cooling load as far as possible, regardless of the consequences for lighting costs or visual user comfort.
- Strategy **NTAR**. It is the same strategy as NTR, but in addition blind slat angles can be varied continuously within the range 45°–90°. As for DEF and NTR, during working hours, blinds are not allowed to be in the closed position. In case of direct solar radiation on the facade, both operating modes SHADE_MIN and SHADE_MAX are specified such as to set the blind slat angle to the cut-off angle (limited to within the range 45° and 90°), under overcast conditions they both set the angle to 90°.
- Strategy **DEF NI**. It is the same strategy as DEF, but with blind control integration removed, i.e. the high-level control blind operating mode is determined independently of the blind and HVAC control. Instead of relying upon historical heat/cold demand signals, the operating mode of all blinds of a given façade is solely determined based on the measured incident solar radiation on that façade: if the measured value is below a given threshold the blind control mode is set to LOAD, otherwise to UNLOAD. Prior to phases with restricted blind movement, MeteoSwiss predictions are analyzed in addition, as for strategy DEF.
- The control strategy **NTR NI** is the same strategy as NTR, but using the high-level control blind operating mode calculation of strategy DEF NI.
- The control strategy **NTROC NI** is the same strategy as NTROC, but using the high-level control blind operating mode calculation of strategy DEF NI.
- The control strategy **NTAR NI** is the same strategy as NTAR, but using the high-level control blind operating mode calculation of strategy DEF NI.
- The control strategy **DEFNF NI** is the same strategy as DEF NI except that no weather forecasts are used.

Table 6-2: Application fields of the investigated control strategies

Name	When/why to apply the strategy
DEF	During building usage (Mo-Fr, 07:00–19:00), only one high-level control blind command at 13:00 is allowed. This shall ensure high user acceptance. The control still aims at an energy efficient operation while taking this constraint into account. The strategy is favorable if - there is only unidirectional communication, from high-level to low-level control - recent user interactions are overridden by high-level control commands - blind movement presents a high disturbance to the room users

	- the control can command but a limited number of shading positions (here: 2 shading angles)
NTR	The strategy enables more energy efficient operation and better glare protection since blind control commands can be issued without time restrictions. This strategy is expected to lead to a lower user acceptance than the strategy DEF. The strategy is favorable if - there is bidirectional communication between high-level and low-level control - recent user interactions are not overridden by high-level control commands - the control can command but a limited number of shading positions (here: 2 shading angles) - blind movement does not present a high disturbance to the room users
NTROC	The strategy operates the blinds only to the positions open or close. Blinds are commanded without time restrictions to maximally support the HCAV system's heating and cooling actions. Impact on lighting energy consumption is not considered. The strategy serves estimating the theoretically possible savings in heating and cooling energy demand if the blinds were controlled such as to minimize energy usage only.
NTAR	The strategy creates the possibility for an even more energy efficient operation and improved glare protection compared to NTR since blind control commands can be issued without any time or angle restrictions. This strategy is expected to lead to a lower room user acceptance than the strategy DEF. The strategy is favorable if - there is bidirectional communication between high-level and low-level control - recent user interactions are not overridden by high-level control commands - control can command many different shading positions - blind movement does not present a high disturbance to the room users
DEF NI	Same motivation as for DEF, but in case that integrated control is not possible. This strategy uses weather forecasts.
NTR NI	Same motivation as for NTR, but in case that integrated control is not possible.
NTROC NI	The strategy is considered for comparison with NTROC only. Its application is otherwise not recommended.
NTAR NI	Same motivation as for NTAR, but in case that integrated control is not possible.
DEFNF NI	Same motivation as for DEF NI, but in case that no weather forecast is available for blind control.

6.2.1.2 Assumptions on User Behavior

The following assumptions regarding user behavior and interactions with the control system were made for all simulations:

- It was assumed that all offices are occupied from 07:00–18:00 during working days. The assumed heat gains by persons and equipment are given in Section 3.2.2.10.
- During occupancy, the simulations implemented instantaneous constant lighting control with a minimal luminance level of 500 lx on a reference point (working desk). The artificial light efficiency was assumed to be 59.5 lm/W, i.e. in the absence of daylight the electrical energy required to provide 500 lx was 8.4 W/m^2.
- The room users were assumed to not manually override lighting control commands.
- The room users were assumed to not manually override high-level blind commands.
- The windows were assumed to be always closed. The room users were assumed to never open them.

The validity of the above assumptions is discussed later in Section 6.2.3.

6.2.1.3 Simulation Environment and Analysis of Results

All simulations were conducted with the co-simulation environment described in Section 3.2.2.1. The used building model was an EnergyPlus model of the target building's second floor, model version M3-B, see Section 3.2.3.3.

Each investigated controller variant was simulated for the entire year 2010 using MeteoSwiss weather data from the station Basel Binningen.

The simulation results were evaluated in terms of annual Non-Renewable Primary Energy usage (NRPE, see Section 5.1.1), annual Monetary Cost (MC, Section 5.1.1), thermal comfort (Section 5.1.2), and luminance comfort as one key aspect of visual comfort.

NRPE usage and MC were evaluated for the following consumers: heating, cooling and offices lighting. Energy usage and/or costs related to the operation of fans and pumps, the operation of office equipment, and peak power demand were neglected.

With regard to luminance comfort we distinguished between so-called over- and under-shading. Over-shading in a given office room was defined to occur in a simulation time step where all of the following conditions applied: (i) the room was occupied; (ii) the blinds were in shading position; (iii) the luminance level in the room's reference point without artificial lighting being switched on would have been below the comfort minimum setpoint of 500 lx; and (iv) no glare would occur if the blinds were fully opened. Under-shading in a given office room was defined to occur in a simulation time step where (i) the room was occupied, (ii) the luminance level was above 2000 lx, and (iii) the controller had not commanded a shading position.

Note that "under-illumination" actually never occurred in the simulations, since the artificial lighting was by definition operated such as to satisfy the minimum setpoint. This increased the electric energy consumption in the simulations. While over-shading is not expected to cause any discomfort other than limited vision to the outside, under-shading is indicative of conditions with glare. Users would in reality apply shading, eventually causing lighting costs. This effect was however not considered in the simulations.

6.2.2 Results

6.2.2.1 Energy Usage and Monetary Costs

Figure 6-2 and Table 6-3 summarize the simulated annual NRPE usage and MC for all considered control strategies. It can be seen that the integrated control strategies yielded throughout lower NRPE usage and monetary costs than their non-integrated counterparts.

For the default strategy DEF, lack of integration (strategy DEFNF NI, no weather forecasts available for blind control) increased NRPE usage by 8.8% and MC by 7.2%. With the use of weather forecasts (strategy DEF NI) the surplus still amounted to 6.0% for NRPE and 5.0% for MC, respectively.

For the NTR strategy lack of integration resulted into a deviation of +6.4% for NRPE and +6.0% for NC. For the strategy NTROC the corresponding numbers were +2.3% for NRPE, and +4.2% for MC. For NTAR they were +4.1% for NRPE and +4.4% for MC.

Figure 6-2 further shows that the various integrated control strategies resulted into considerably lower NRPE and MC for heating and cooling than the respective non-integrated strategies. The opposite was the case for lighting. This result was due to the fact that the integrated control strategies used during summer more often shading positions in order to reduce cooling effort.

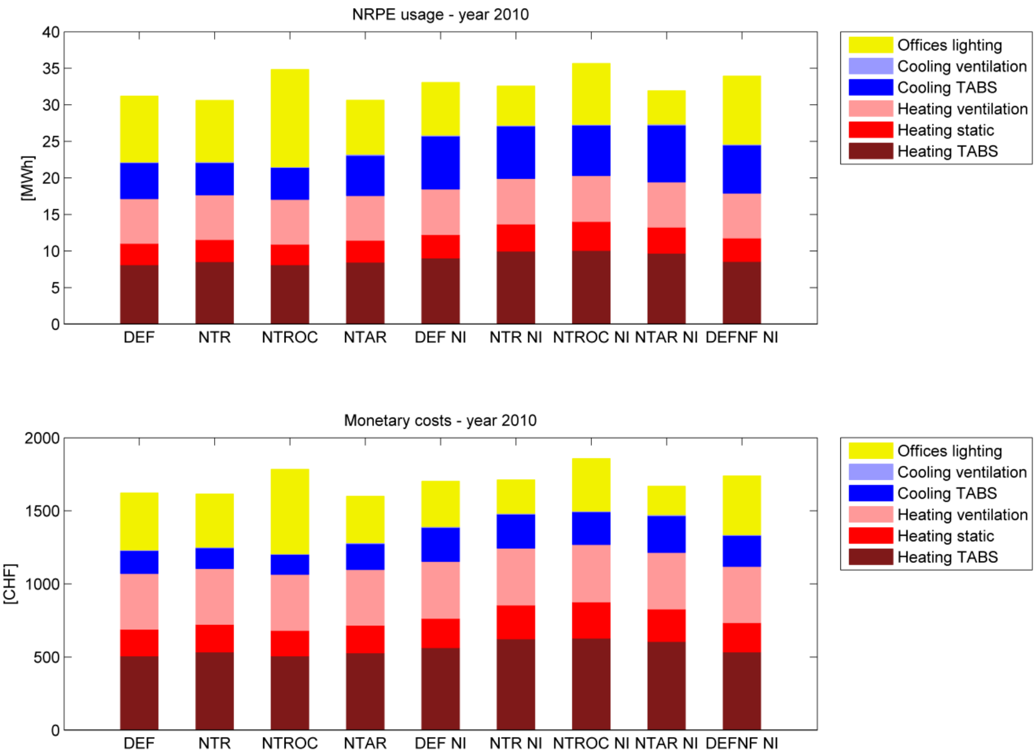

Figure 6-2: Simulated annual total Non-Renewable Primary Energy (NRPE) usage and monetary costs (MC) by different control strategies for the 2nd floor of the target building. Shown are selected HVAC and lighting costs only. For control strategies see Table 6-1.

Table 6-3: Simulated annual total Non-Renewable Primary Energy (NRPE) usage and monetary costs (MC) by different control strategies for the 2nd floor of the target building. For control strategies see Table 6-1.

	NRPE			MC		
	Relative [%]	Abs. (2nd floor) [MWh/a]	Specific [kWh/(m²a)]	Relative [%]	Abs. (2nd floor) [CHF/a]	Specific [CHF/(m²a)]
DEF	100.0 (0.0)	31 (0.0)	58.42 (0.0)	100.0 (0.0)	1623 (0.0)	3.04 (0.0)
NTR	98.1 (-1.9)	31 (-0.6)	57.32 (-1.1)	99.5 (-0.5)	1615 (-7.5)	3.02 (-0.0)
NTROC	111.7 (11.7)	35 (3.6)	65.23 (6.8)	109.9 (9.9)	1784 (161.1)	3.34 (0.3)
NTAR	98.2 (-1.8)	31 (-0.6)	57.35 (-1.1)	98.6 (-1.4)	1601 (-22.2)	3.00 (-0.0)
DEF NI	106.0 (6.0)	33 (1.9)	61.92 (3.5)	105.0 (5.0)	1703 (80.4)	3.19 (0.2)
NTR NI	104.4 (4.4)	33 (1.4)	60.97 (2.6)	105.5 (5.5)	1713 (90.0)	3.21 (0.2)
NTROC NI	114.3 (14.3)	36 (4.5)	66.76 (8.3)	114.5 (14.5)	1858 (235.3)	3.48 (0.4)
NTAR NI	102.3 (2.3)	32 (0.7)	59.78 (1.4)	102.9 (2.9)	1669 (46.3)	3.12 (0.1)
DEFNF NI	108.8 (8.8)	34 (2.7)	63.55 (5.1)	107.2 (7.2)	1740 (116.9)	3.26 (0.2)

6.2.2.2 Thermal Comfort

Figure 6-3 and Table 6-4 show the simulated annual total thermal comfort violations for all investigated control strategies. Violations are given in Kelvin-hours and refer to working hours only. The analysis distinguishes between the cases too cold, too warm when outside air temperature is lower than upper room temperature setpoint, and too warm when outside air temperature is higher than upper room temperature setpoint (see also Section 5.1.2).

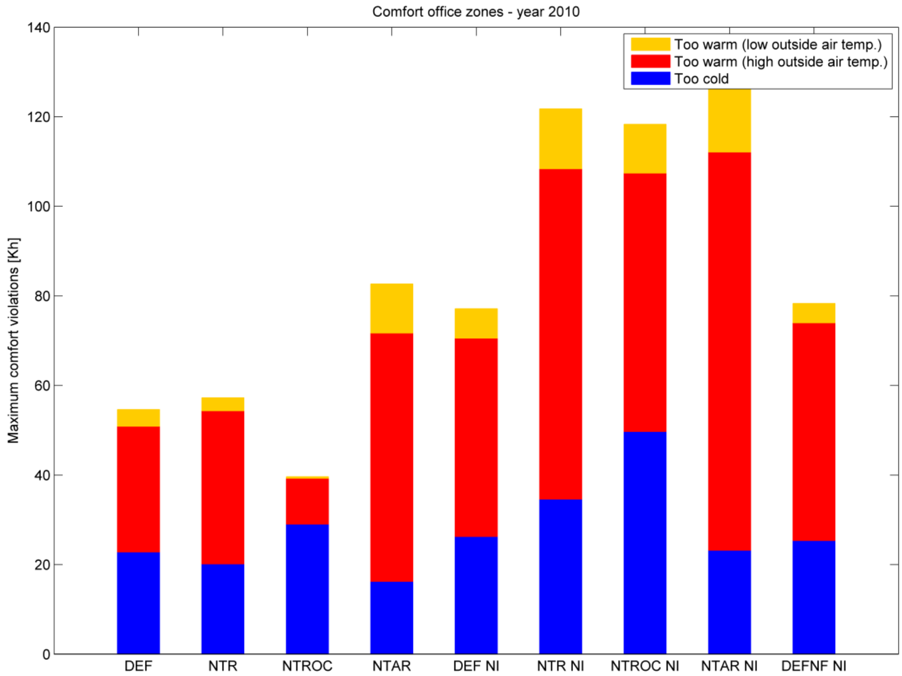

Figure 6-3: Simulated annual total maximum (from 13 outside-facing zones) thermal comfort violations by different control strategies for the 2nd floor of the target building. For control strategies see Table 6-1.

Table 6-4: Simulated annual total and annual total maximum (from 13 outside-facing zones) thermal comfort violations by different control strategies for the 2nd floor of the target building. For control strategies see Table 6-1.

	Too cold [Kh]		Too warm [Kh]	
	All office zones	Zone with max. value	All office zones	Zone with max. value
DEF	58	23	222	32
NTR	52	20	237	37
NTROC	82	29	238	11
NTAR	52	16	399	66
DEF NI	62	26	256	51
NTR NI	60	35	465	87
NTROC NI	79	50	290	69
NTAR NI	53	23	701	106
DEFNF NI	61	25	284	53

It can be seen that all strategies simulated a good thermal comfort. The integrated control strategies however systematically showed fewer violations than their non-integrated counterparts.

6.2.2.3 Visual Comfort

Figure 6-4 compares the simulated luminance comfort for all investigated control strategies. Shown are the annual total simulated hours of under-shading and over-shading from all 13 outside-facing zones of the used model of the target building's 2nd floor.

It can be seen that the integrated control strategies caused more over-shading hours than the corresponding non-integrated strategies (the only exception being the non-integrated strategy DEFNF NI). With regard to under-shading hours the two kinds of strategies gave roughly similar results.

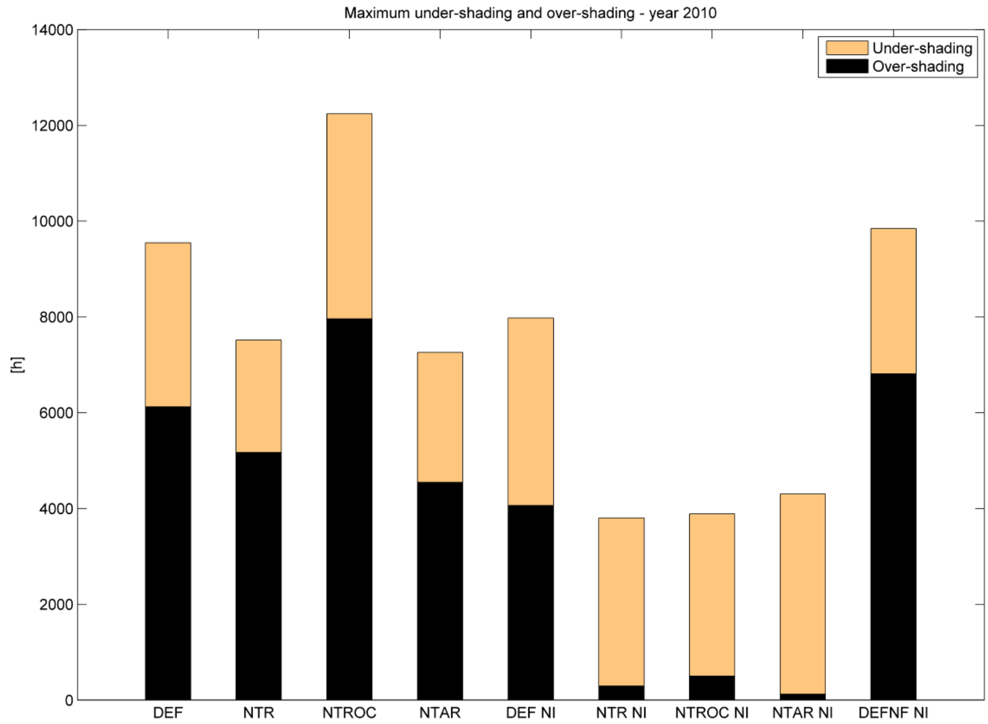

Figure 6-4: Simulated annual total (from 13 outside-facing zones) over-shading and under-shading hours by different control strategies for the 2nd floor of the target building. For control strategies see Table 6-1.

6.2.2.4 Blind Positions and Electrical Lighting

Figure 6-5 and Figure 6-6 show whole-year carpet plots of the blind positions and electrical lighting power for all control strategies except DEFNF NI. Shown are data for the south-east façade and a selected office room with that façade orientation, respectively.

The most conspicuous difference between the integrated and non-integrated control strategies in Figure 6-5 (left vs. right panels, respectively) is the night-time blind operation by the integrated control. It reflects the following HVAC system support by the integrated blind control: In operating mode LOAD, blinds are closed at night in order to increase the thermal resistance of the building envelope, i.e. to decrease transmission losses and heating energy demand; in operating mode UNLOAD, blinds are opened at night to support heat emission from the building and reduce cooling demand.

The annual patterns of the simulated lighting power (Figure 6-6) were found to vary more strongly with control strategy, rather than between integrated and non-integrated control. A closer look reveals however the somewhat higher artificial lighting usage by integrated control (cf. Figure 6-2).

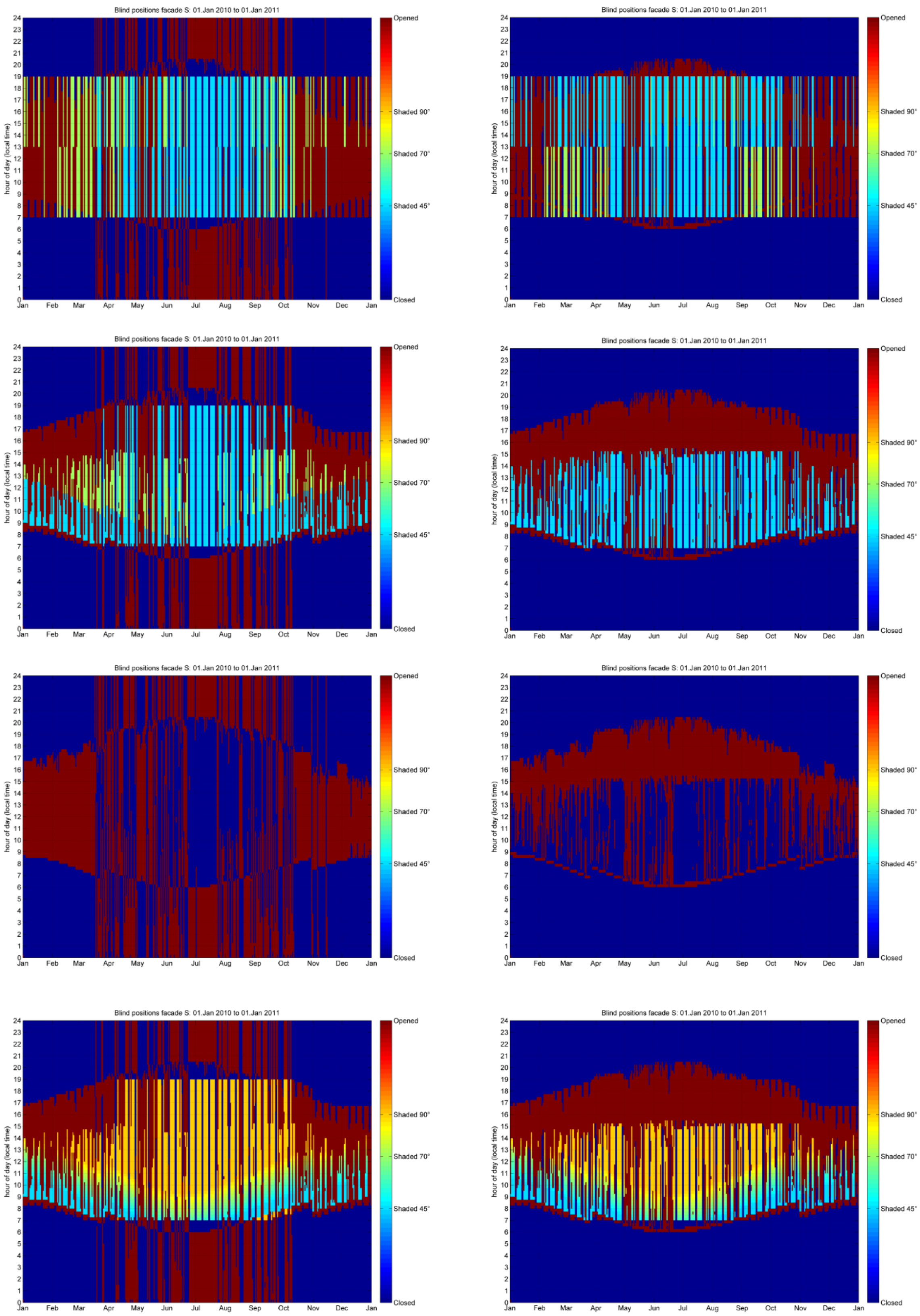

Figure 6-5: Simulated blind positions for the target building's south-east façade as a function of day of the year (x-axis) and time of day (y-axis). Left (top to bottom): results by the integrated control strategies DEF, NTR, NTROC, NTAR; right (top to bottom): results by the non-integrated control strategies DEF NI, NTR NI, NTROC NI, NTAR NI. For control strategies see Table 6-1.

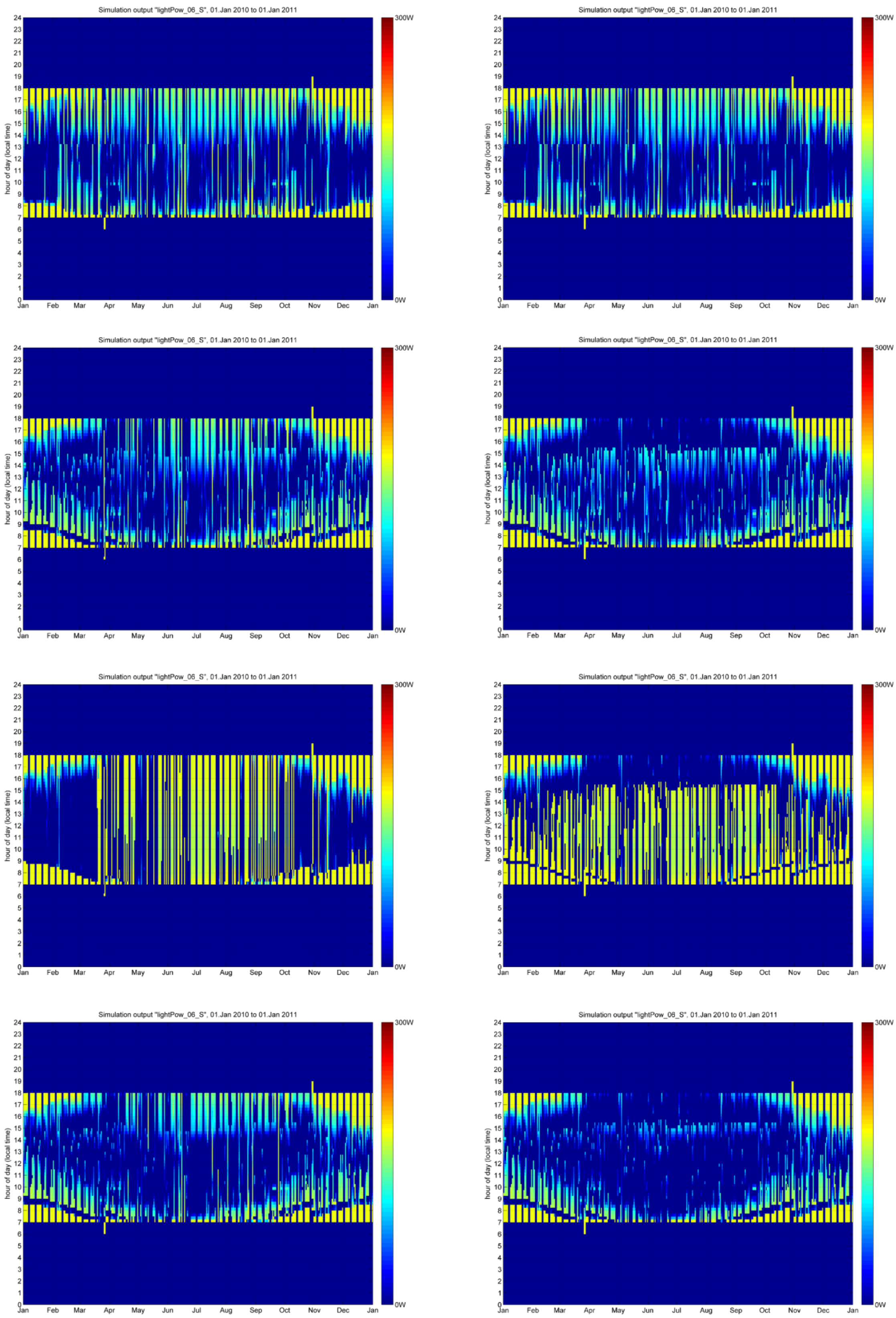

Figure 6-6: Electrical lighting power for the south-east facing zone no. 6 of the target building as a function of day of the year (x-axis) and time of day (y-axis). Left (top to bottom): results by the integrated control strategies DEF, NTR, NTROC, NTAR; right (top to bottom): results by the non-integrated control strategies DEF NI, NTR NI, NTROC NI, NTAR NI. For control strategies see Table 6-1.

6.2.3 Discussion and Conclusions

Our simulations employed specific assumptions about user behavior (Section 0) that cannot be considered very realistic. In reality, the frequency and form of interactions with the building control system will vary widely with situation and across user groups. In order to increase the realism of our simulations we would thus have needed to resort to a carefully parameterized stochastic simulation approach. This was however far beyond the scope of the present study.

We nevertheless believe that the inclusion of realistic occupant interactions with the control system would have not much affected our overall results. This is for two reasons: Firstly, all control strategies yielded a high thermal (Figure 6-3), air quality (not shown) and visual (Figure 6-4) comfort in the simulations. This minimized the scope for user interactions with the control system. Secondly, we were mainly interested in assessing long-term average differential effects between control strategies rather than in the realistic representation of individual situations. Due to the averaging over many different cases and operating conditions in our post-analysis of the simulation results we believe that the obtained differences between control strategies are quite trustworthy.

The control of shading and artificial lighting are the key to visual comfort in buildings. Here we analyzed over-shading and under-shading to account for two selected aspects of visual comfort, namely luminance and risk of glare, respectively. Additional parameters that could have been considered are illumination, brightness, luminous spectrum, and the possibility to look outside. The combined effect of all these parameters on occupant satisfaction is known to vary strongly between individuals and depends on a range of physiological and psychological factors. Our simple comparative assessment of visual comfort (Figure 6-4) should therefore be interpreted with caution. Two surveys for our target building (see Section 5.4.2) suggested at least for the default blind control strategy DEF good acceptance by the room users.

All integrated blind control strategies yielded higher electrical lighting costs than their non-integrated counterparts (Figure 6-2). We expect that our study overestimated this additional energy use because the artificial lighting costs scale with average occupancy time, and this time is in the target building actually lower than was assumed in our simulations. Moreover, in the simulations artificial lighting was controlled on a per room/zone basis. The target building has however a much more individualized electrical lighting system with one lighting source per work place, and this more fine-grained control also leads to lower artificial lighting costs. Smaller occupancy times than the ones assumed in the present study and workplace-specific lighting control also apply to many other Swiss office buildings. We therefore believe that our results (Figure 6-2 and Table 6-3) give a quite conservative estimate for the likely energy savings thanks to integrated blind control.

In summary, our simulation study suggests that for buildings similar to our target building

- the investigated integrated blind control strategies can be expected to save around 5%–10% NRPE and MC for heating, cooling and lighting compared to non-integrated strategies while providing improved thermal comfort
- the integrated strategies can be expected to provide an equal or higher room user acceptance than the non-integrated strategies, since integrated blind control plausibly supports heating and cooling in a manner that can be easily understood by the user

Besides these benefits, an integration of blind control typically also allows for better tuning as well as better monitoring of blind control because these activities can be executed via a central building management system.

6.3 Analysis of Energy Fluxes

Due to the increasing share of renewables in today's electricity generation and their inherent intermittency, the need for temporary storage of electrical energy is increasing. Buildings are more and more considered for that purpose by integrating and exploiting both active and passive storage systems such as water or ice storages, the thermal mass of the building structure or phase changing materials. In particular, preheating and precooling of the building structure can be used to manage the building's total electricity demand.

To get a feeling for the energy storage capacity of a building, it is interesting to analyse the energy fluxes to and from the building and its overall energy balance over time. This analysis was easily possible for our target building thanks to the availability of a reasonably accurate thermal Resistance Capacitance model (RC model, Section 3.3). This model allowed for the exact calculation of all energy fluxes (after defining appropriate outputs in the various involved heat flux submodels), alongside with the total stored energy (the time derivative of which should equal the net sum of all energy fluxes at any point in time).

We simulated the year 2010 using the full scale RC model of the second floor (fRC, enhanced by various extra heat flux outputs) under the control of a Model Predictive Control procedure (MPC, Section 4.3) that minimized total Non-Renewable Primary Energy usage. The MPC was implemented based on a reduced order RC model (rRC). We used measured weather data, and Kalman-filtered (Section 4.3.3.3), archived weather forecasts as predictions. Internal gains were set accordingly to the schedules reported in Section 3.2.2.10, and they were perfectly predicted.

All energy and power values were computed for the simulated second floor of the target building. The floor's area was 543 m^2, and the total heat capacity of all its walls, floors, ceilings and air volumes amounted to 273 kWh/K.

We considered nine different heat fluxes to the second floor: TABS, AHU heating/cooling, AHU heatflux due to airflow, Radiators, Internal Gains, Windows Solar Gains, Windows Conduction, Infiltration, Infiltration and Building Hull (Without Windows).

The heat flux due to the AHU was split in two components to better illustrate the actuation: the "AHU heating/cooling" component measured the supplied heat by the heating coil and the (sensible) cold supplied by the evaporative cooler, while the "AHU heat flux due to airflow" quantified the heat flux difference between heat provided to the building by AHU outside air flow and heat removed from the building by AHU exhaust air flow. Due to linearity, both fluxes add to the total AHU heat flux.

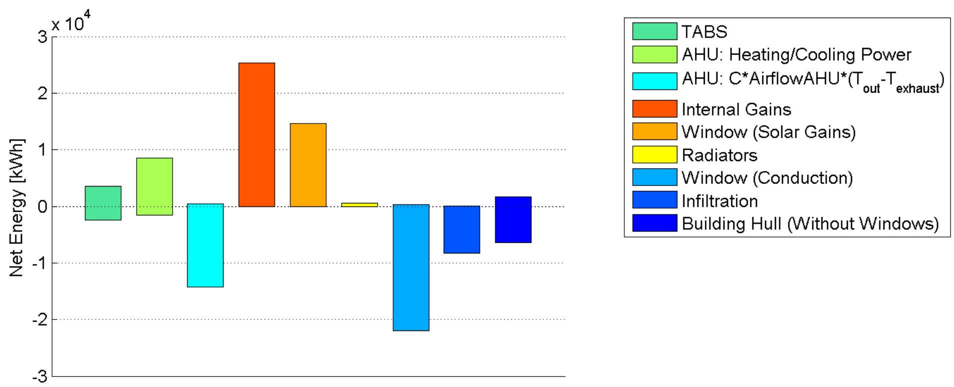

Figure 6-7: Simulated annual total heat fluxes for the target building's second floor and the year 2010.

The TABS and radiators were considered as closed systems, such that their heat fluxes directly corresponded to the applied heating/cooling power.

Figure 6-7 shows the annually integrated positive and negative contributions by all nine heat fluxes. As could be expected, the internal and solar window gains were found to dominate on the positive side, while the window losses contributed the largest negative heat fluxes. Also to be noted are the rather large losses due to forced ventilation, even though the building includes an air energy recovery system. The energy fluxes delivered by the TABS, AHU and radiators were significantly smaller than most of the remaining fluxes.

Figure 6-8 and Figure 6-9 give two views of the integrated values of the simulated heat fluxes for every month together with the monthly net heat energy flux to the building (i.e. the sum of the monthly integrated heat flux values).

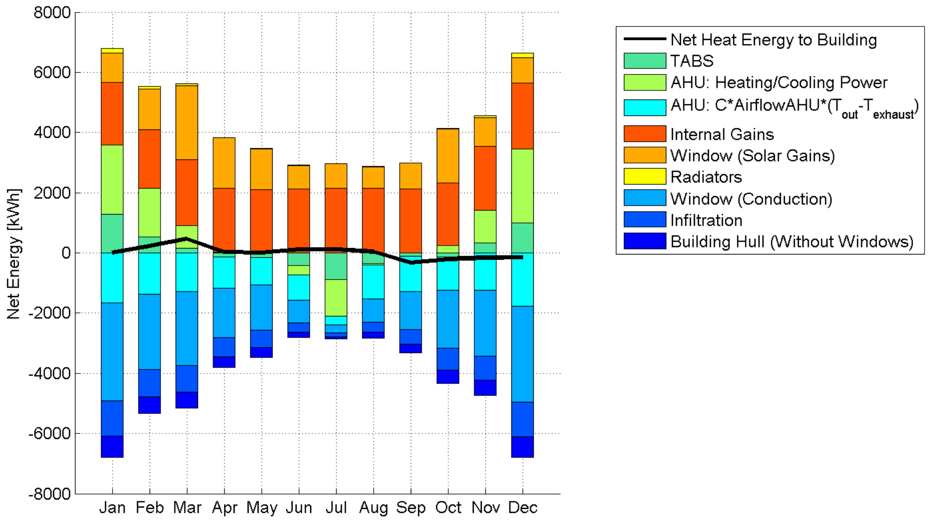

Figure 6-8: Simulated monthly total heat fluxes (bars) and net heat energy flux to the target building's second floor (black line) for the year 2010.

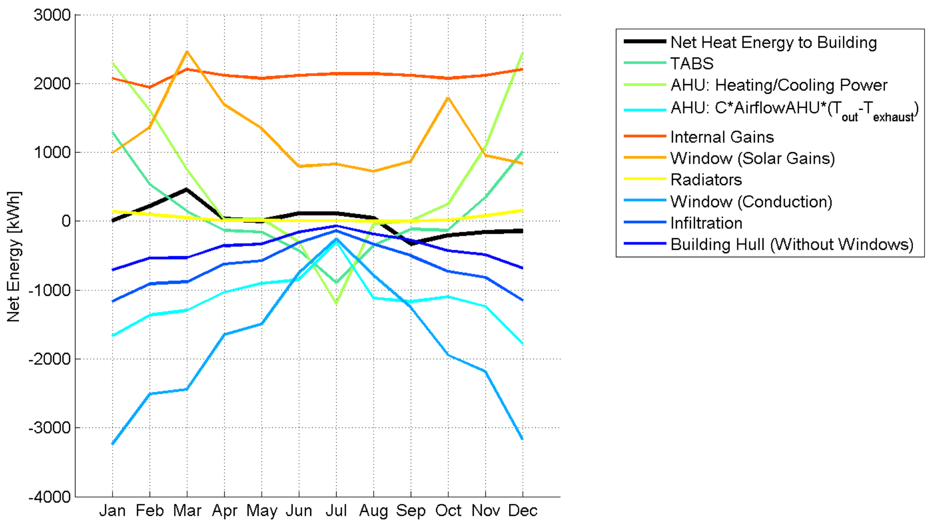

Figure 6-9: Simulated monthly heat fluxes (colored lines) and net heat energy flux to the target building's second floor (black line) for the year 2010.

It can be seen that the simulated monthly total positive and negative heat fluxes ranged in magnitude from 3500-5000 kWh. Their monthly balance was in the range -200 to 500 kWh, corresponding to the energy that was released from, respectively stored in, the building's structure over a given month.

The internal gains were the largest positive heat flux to the building and, by definition, quite constant over the year. The shown variations reflect the number of working days in a given month.

The second largest positive heat flux was found to be the solar gains through the windows. This flux peaked in the transition seasons when there was still significant solar radiation compared to winter, and also some need for heating which the MPC controller accomplished to the maximum possible extent by opening the blinds. In winter the achievable solar heat gains were limited by the availabilty of solar radiation. In summer, the controller closed the blinds to minimize cooling energy usage.

Except in the summer months, the largest negative heat fluxes to the target building's second floor were found to be the conduction losses through the windows. Infiltration and building hull losses followed a similar profile but were generally smaller.

With regard to the actuation heat fluxes it was found that the radiators contributed the smallest amount of energy, followed by the TABS and the AHU.

Figure 6-10 details the simulated daily total stored energy (offset to 0 kWh at the beginning of the simulation) as well as the capacity weighted average temperature of all walls, floors, ceilings and air volumes of the target building's second floor (right and left axis, respectively).

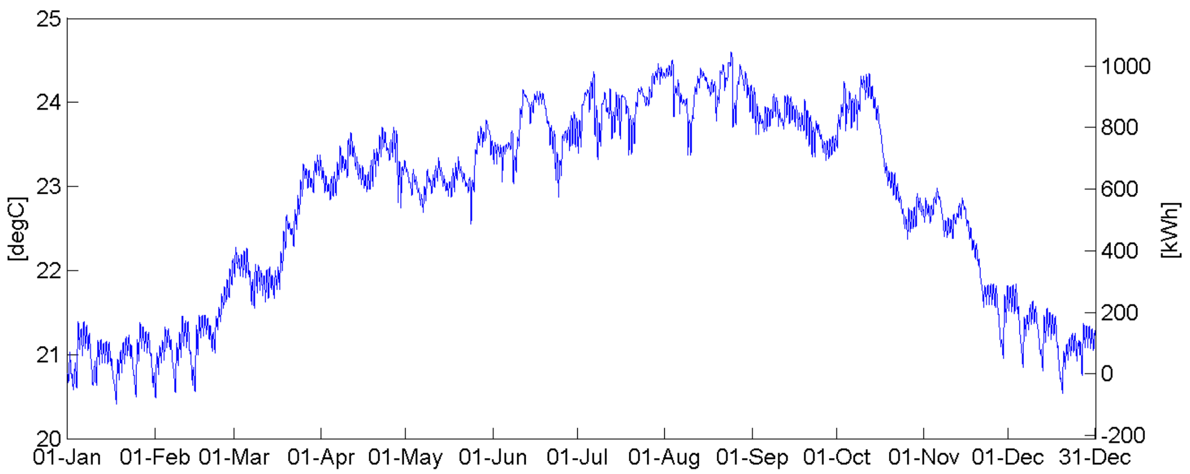

Figure 6-10: Simulated capacity weighted average temperature (left axis) and total stored energy (right axis, offset to 0 [kWh] on Jan 1st) for the target building's second floor in the year 2010.

It can be discerned that the simulated average temperature changed by about 4°C throughout the year, which corresponds to about 1000 kWh. The annual cycle was modulated by diurnal variations and the MPC-imposed weekend temperature setbacks. The annual average and the standard deviation of the daily peak-to–peak value of the stored energy were 78 kWh and 38 kWh, respectively. Towards the end of the year, the simulated energy content of the building was almost the same as initially.

6.4 Model Mismatch: Performance Sensitivity and Adaptations

As discussed in Section 3.3 on modeling for MPC we advocate the use of physically based building models built from geometry and construction data. In practical application, this data will usually not be exact, since the particular construction may not be known in detail, or the actual material parameters may not coincide with the assumed values. Further common sources of uncertainty in building energy modeling are the estimation of solar and internal heat gains.

Modeling imprecisions result into so-called MPC plant-model mismatch and a deterioration of MPC control performance, i.e. higher control cost and/or enhanced thermal comfort violations. An example of the implications of plant-model mismatch for our target building was provided in Section 5.3.3.

Here we investigate the sensitivity of MPC to plant-model mismatch in more detail and consider possible measures to limit its impact on control performance. The results presented summarize the semester thesis [6] that can be consulted for more detail.

6.4.1 Method

Due to the large number of dimensions and parameters involved, plant-model mismatch can only be assessed on a case study basis. Here we attempted to gain first insight based on the use of the relatively simple, realistic 12-state bilinear thermal resistance capacitance (RC) model of a single office zone that had been developed in the forerunner project OptiControl-I (see [7]).

Note that as shown in [4], MPC performance can be expected to vary widely between building cases, zones and locations. Hence the *quantitative* results reported here are valid for the investigated case only and may not be readily extrapolated to the OptiControl-II target building.

We considered a building zone with the following characteristics: light construction, Swiss average thermal insulation level, south oriented façade with a window area fraction of 20%, and a low internal gains level (cf. [4]).

The subsystems controlled by means of MPC were blinds, electric lighting, radiator heating, and a cooled ceiling (as System "S1" in [4], [1] but with "free cooling" disabled). The prescribed room temperature comfort range was 22°C–25°C during working hours and 12°C–35°C otherwise. No restrictions were imposed on blinds movements. We performed annual simulations with a time step of one hour using weather data from Vienna and the year 2007.

The investigation was twofold. First, we looked at how the performance of MPC deteriorates when one uses a model that is based on imperfect parameter values, i.e. values that deviate from those found in the controlled system (plant). Second, we investigated the extent to which the resulting loss in performance could be recovered by two different procedures that employed an online adaptation of the MPC model.

In a real application, when MPC is newly implemented on a given building, the adaptation approach would correspond to the following procedure: first, an initial "best-guess" model is constructed and used in a conservatively tuned MPC. Then the model is improved in online operation with the aid of measurements, gradually allowing for less conservative settings and thus improving the control performance in the process.

In the original study [6] we considered two kinds of feedbacks to the MPC controller: state feedback and output feedback. Here, we show results only for the more realistic case of output feedback. Furthermore, we did not consider the presence of any low-level control (see [4] for information on low-level control): MPC was used to directly control the building model, without any further control actions taking place. The presence of low-level control will typically reduce the performance sensitivity on MPC model mismatch.

Figure 6-11 shows the used simulation setup. M(**P**) denotes a building model based on parameter vector **P**, and $\mathbf{P_0}$ and **dP** denote the nominal parameter values vector and a corresponding deviations vector, respectively. C denotes the controller variant, J_e and J_c are measures of the control performance for energy and thermal (dis)comfort, respectively, and u, y are the system inputs and outputs, respectively.

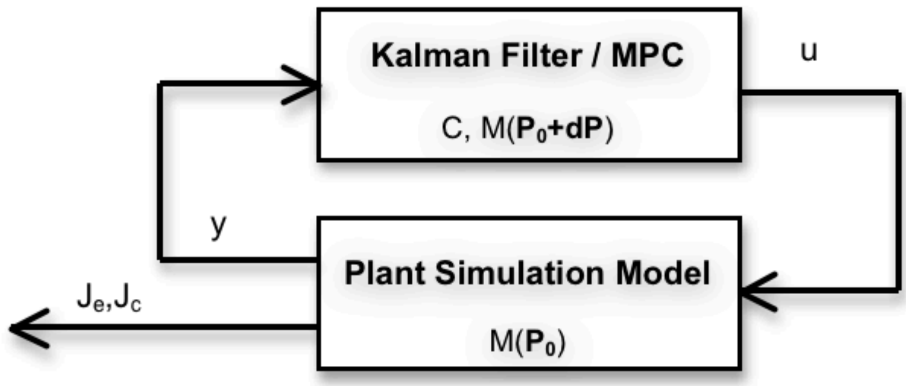

Figure 6-11: Simulation setup used for the investigation of Model Predictive Control (MPC) plant-model mismatch. For explanation of symbols see text.

In all simulations we kept the parameters of the plant simulation model fixed to $\mathbf{P_0}$ and always applied to it the same disturbance inputs (weather, internal gains, etc.). Hence any simulated variations in control performance were only a function of the parameter mismatch **dP** and the controller variant C.

The following parameters were considered:

- *Heat capacities (C_r):* The specific heat capacities of all materials
- *Inner thermal resistances (R_{inner}):* The thermal resistances of all thermal connections to the room node (including window U-values, convective coefficients etc.)
- *Outer thermal resistances (R_{outer}):* The values of all non-inner thermal resistances
- *Solar gains (solG):* The solar heat gain coefficient of the windows
- *Radiator gain (hPowRad):* The heat gain of the radiator heating system.
- *Chilled ceiling gain (cPowSlab):* Cold gain of the cooling system mounted just below the ceiling.
- *Internal Gains (IG):* Level of internal gains during occupancy as assumed by the MPC.

The following three controller variants were investigated:

- *Regular MPC:* Model predictive controller with no adaptations
- *MPC with disturbance estimation:* In this variant, the control model was enhanced by a state corresponding to a constant disturbance acting on the room node. The value of this disturbance was estimated by the Kalman filter and subsequently taken into account in the MPC internal predictions.

- *MPC with regression based model adaptation:* At each time step the differences of the Kalman filter state estimates at a particular time i and the one-step ahead prediction from the state estimate at time i-1 were computed for the last 100 time steps. On this vector of differences a linear regression was performed to find the best linear combination of the following predictor variables: i) +1 during workday nights and weekends, 0 otherwise; (ii) +1 during workday mornings, zero otherwise; (iii) +1 during workday afternoons, 0 otherwise; (iv) solar radiation; (v) radiator power; (vi) cooling slab power. The regression coefficients were then – thanks to linearity, straight-forwardly – incorporated in the MPC internal predictions of office room temperatures. The overall procedure was repeated at every control time step.

A reference simulation using the regular MPC and perfect predictions for weather and internal gains was used to define the control performance baseline. Due to the use of a perfect control model (i.e., a model that was identical to the plant simulation model) the result was energy optimal and showed no violations of thermal comfort ($J_c = 0$). The found, minimal annual Non-Renewable Primary Energy (NRPE) use we denote as J_e*.

Various **dP** vectors were obtained by varying each parameter by -50%, -25%, +25% and +50% of its nominal value, one parameter at the time. This yielded 7 x 4 = 28 simulations per controller variant C. We employed two performance measures, the relative annual NRPE cost difference (J_e-J_e*)/ J_e* in [%], and the annual amount of thermal comfort violations J_c in Kelvin-hours [Kh].

6.4.2 Results

Figure 6-12 (top) summarizes the deterioration of MPC performance when using regular MPC for all considered **dP**. For each of the seven investigated parameters shown are four points connected by straight lines. The points correspond to the four considered deviations from the respective nominal parameter values, with the box markers denoting the +50%, and the filled circle markers the -50% results.

All lines exhibit a similar “c” shape with the upper end indicating few thermal comfort violations but increased control cost (more than necessary control action), and the lower end indicating high comfort violations and decreased control cost (too little control action). The maximum found increase in total costs amounted to around only 1.4%. Quite differently, the thermal comfort violations showed significant increases.

The small change in control costs probably reflects the fact that the investigated system reacted very fast to the actuations, such that no major planning errors were introduced due to the plant-model mismatch. Note that the total costs included next to heating and cooling typically also very significant lighting costs.

The highest sensitivities to ill-known parameter values were obtained for the inner resistances and solar gains. Model mismatch due to imperfect knowledge of thermal capacitance, cooling gain and “outer” resistances parameter values showed a much smaller impact.

The middle and bottom panels of Figure 6-12 summarize the results obtained for the two controllers that included online adaptation of the MPC model. It is apparent that the MPC with a very simple disturbance estimation already is able to cancel out most of the negative effects. The MPC with the regression based adaptation performs even better. In terms of implementation, however, the first approach is cheaper, since most MPC controllers implemented in practice usually include a Kalman filter.

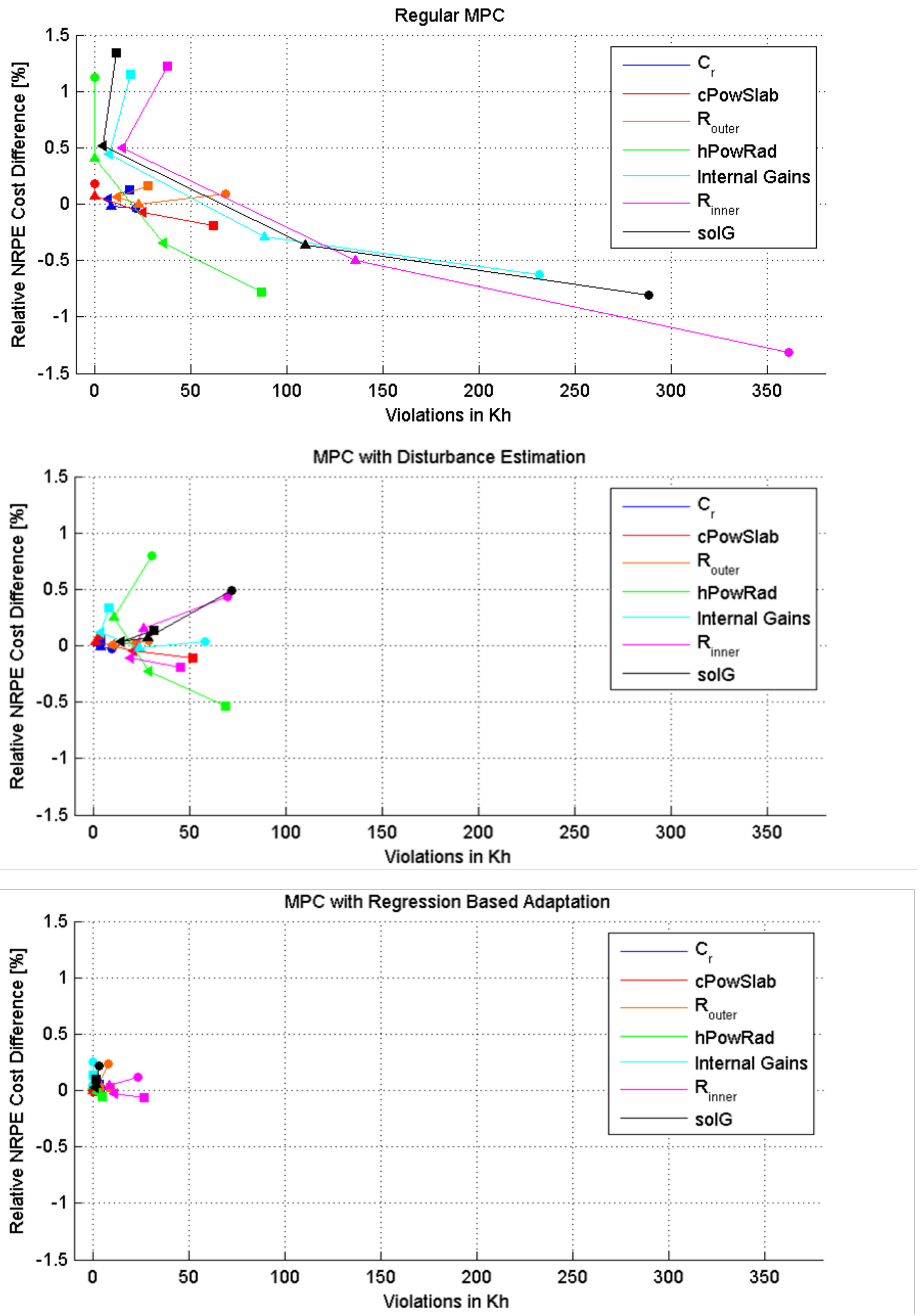

Figure 6-12: Relative changes in simulated annual Non-Renewable Primary Energy (NRPE) usage versus simulated annual amount of thermal comfort violations due to plant-model mismatch in Model Predictive Control (MPC). Reference for NRPE is the energy usage by perfect MPC. Shown are results due to perturbation of seven different parameters (see legend), one at a time, by -50%, -25%, +25% and +50% of their nominal value. Circles denote -50% and boxes +50% changes relative to the nominal parameter values. Top: regular MPC controller; middle: MPC with disturbance estimation; bottom: MPC with regression based model adaptation.

6.4.3 Concluding Remarks

The study demonstrates that in the presence of MPC plant-model mismatch the two investigated MPC modifications lead to major performance improvements as compared to straightforward MPC application.

Here we investigated a system with fast reaction to disturbances and control actions. Slower reacting setups (involving heavy constructions, such as thermally activated building systems, TABS) can be expected to show even higher sensitivity to model mismatch.

More investigations are necessary to assess the performance of the proposed adaptive MPC procedures under more realitic set-ups. This includes cases where the model mismatch does not encompass just one parameter and/or is nonlinear, cases with low-level control being present, and of course the application to a real building.

6.5 References

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7 Benefit-Cost Analyses

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The OptiControl project deals exclusively with non-standardized control solutions, i.e. solutions where control is tailored to a specific building. This is typically the case for mid-sized to large non-residential buildings such as office buildings, warehouses, shopping malls, hospitals etc.

The main challenge for any control strategy to be employed in the context of non-standardized control solutions consists in having to accommodate tremendous variation across buildings in terms of construction, equipment, usage and disturbances. Moreover, the control strategies should be able to handle widely varying, building-specific combinations of different Heating, Ventilation and Air Conditioning (HVAC), light and blind applications.

Application of a non-standardized control solution to a given building consists of several steps: the definition of the requirements, the choice of the control strategy, the design of the control solution, its implementation and commissioning, and its possible adaptation to changing requirements throughout the building's life cycle. According to current practice engineers will try to base the solution as far as possible on the adaptation of existing building automation control programs and libraries. However, specific program modules have often to be implemented from scratch.

From this, it becomes clear that although good *control performance* in terms of energy usage and occupant comfort is essential, the applicability and suitability of a given control strategy for use in non-standardized control solutions also depends on a range of other factors.

In Chapter 5 we assessed the *control performance* and the *user acceptance* of the newly developed Rule Based Control (RBC) and Model Predictive Control (MPC) strategies based on field experiments, questionnaires and simulations. Here we extend the evaluation by considering additional criteria, in particular also the inflicted cost.

Section 7.1 first presents the set of criteria used for the cost-benefit analyses. In Sections 7.2–7.11 we apply them to the various control strategies. Our summary and conclusions are given in Section 7.12. The analysis centers on the OptiControl-II target building, but we try to keep it as generic as possible in order to make the results applicable also to other buildings.

7.1 Criteria Used for Benefit-Cost Analyses

A comprehensive list of criteria to assess the benefit and cost of non-standardized control solutions was elaborated in the predecessor project OptiControl-I [1]. Originally, the criteria were defined for the very general control application "Integrated Room Automation" (see Introduction to Chapter 1). Table 7-1 lists them together with a short description and the assessment method used within the OptiControl-II project.

Table 7-1: Criteria for the assessment of non-standardized control solutions in the Building Automation sector, cf. [1].

No.	Criterion	Description	Assessment based on
1	Achievable control performance	Maximum performance that can be attained for a correctly functioning and well-tuned system. The benefit and cost of different control solutions can be quantified quite exactly – albeit with	Field experiments (Section 5.2) and simulation studies

No.	Criterion	Description	Assessment based on
		considerable effort – by simulation studies. For example, energy or monetary costs as well as comfort indices can be calculated and compared.	(Sections 5.3 and 6.2)
2	Robustness with respect to control parameter settings	In practice, the control parameter settings will be far from perfect due to missing information or incomplete understanding of the controlled system, and limited knowledge of the disturbances acting upon it. Therefore, it is essential that the control performance is satisfactory for a broad range of control parameter settings.	Simulation sensitivity studies (Sections 5.3.2 and 5.3.3) and experience from control experiments
3	Robustness with respect to building system, disturbances, and user interactions	A control solution should perform well for all kinds of building systems, disturbances (e.g. weather developments, internal gains patterns) and user interactions. Typical user interactions are light switching, blind positioning or the shifting of temperature set points. Their frequency and form may vary considerably across different occupants or occupant groups.	Estimation from experience, control experiments, and from evaluation of user acceptance (Section 5.4)
4	Flexibility and tuning effort in the engineering process	Besides to being applicable to different building types and climatic conditions good control solutions should also support different control applications. These may differ in terms of HVAC equipment, blind and lighting systems, automation level, control requirements etc. Moreover, a given application may change during the building's lifetime (e.g., due to changing room usage or the rearrangement of interior walls). Therefore, there is a need for flexible solutions that support as many control application variants as possible with low engineering effort. The tuning effort, i.e. the effort required for determining control parameter values that lead to a good control performance, should also be low. Tuning may occur in the pre-commissioning, the commissioning, and/or the service phase of a control solution.	Control program characteristics and simulation sensitivity studies (Section 5.3)
5	User acceptance for engineering, commissioning and service	Non-standardized control solutions are engineered for each building individually. To be well received by the involved technical personnel they should be designed such that they can be adapted, commissioned and serviced with as much ease and as little effort as possible. The engineer in charge of adaptation should be able to quickly get to a good understanding of the control solution's basic functionality and properties. The personnel responsible for tuning and servicing should be able to rely on clear, simple and efficient procedures. Moreover, the training effort for correct engineering, commissioning and servicing should be kept low.	Estimation from experience
6	User acceptance by the end user	This is an essential prerequisite for the commercial success of a control solution. For the OptiControl-II target building the following relevant aspects were identified: (i) Desired comfort can be achieved; (ii) Possibility and ease of manual interaction; (iii) Plausibility of automatic control actions – in particular blind movement; (iv) Minimization of disturbances by automatic control actions (e.g. noise of blind movement, lighting control).	Estimation from experience, control experiments, and from evaluation of user acceptance (Section 5.4)
7	Suitable as an extension option	The possibility to use a new control solution as an "add-on" is generally valued as an advantage. The control solution then presents an element in an incrementally extendable solution portfolio. The overall control solution should be based on as many conventional components as possible; the new components can then be introduced selectively to increase performance or provide additional functionality.	Control program characteristics
8	Investment and maintenance costs	The costs associated with the application of the control solution. Investment costs can be costs for extra needed computing infrastructure, provision of tailored software components, training costs for engineers etc. Maintenance costs include costs for service activities, and for purchasing of weather forecasts or other input data relevant to control.	Control equipment, software development and data needs, training effort
9	Development effort	The smaller the development effort, the higher the chances for a control solution to be fully developed and introduced to the market. A control solution with low development effort can be typically easily investigated in field tests at low financial risk. Quite differently, high development effort often correlates with the need for thorough and expensive tests by means of simulations and/or the investigation of prototypes.	Estimation from experience
10	Innovativeness and selling arguments	Besides potential benefits in terms of improved comfort and energy efficiency, the offer of an innovative control solution can be exploited for marketing purposes: additional selling arguments are generated.	Actual and estimated future selling arguments

7.2 Achievable Control Performance

A thorough assessment of achievable control performance based on whole-year simulations with a validated model of the target building's second floor is reported in Section 5.3.1. Here we summarize and comment the main results.

7.2.1 NRPE and Monetary Costs

Results for Non-Renewable Primary Energy (NRPE) usage and monetary costs by the various considered control strategies were summarized in Table 5-4 (with equipment and lighting energy costs included) and Table 5-5 (without consideration of equipment and lighting energy costs). The reason for evaluating costs bare of equipment costs in Table 5-5 was that the latter account for a significant part of the total costs, but cannot be influenced by control. The reason for also excluding the lighting costs was that all control strategies controlled lighting only indirectly, via the positioning of the blinds. Table 5-5 thus summarizes but HVAC costs, i.e. costs related to heating, cooling, water and air transport.

7.2.1.1 RBC

For the novel RBC strategies, compared to the reference control strategy and using energy prices as of 2012, monetary cost savings for the simulated second floor were in the range of 11.4 % to 14.4 % (Table 5-4) or 14.2–22.6 % (Table 5-5). This corresponded to absolute savings of 752–951 CHF/a (Table 5-4), or to 3'760–4'755 CHF/a for all five upper (office) floors. The area specific monetary cost savings were in the range of 1.4 to 1.8 CHF/(m^2a). NRPE cost savings for the simulated second floor were 11.5–14.1 %, corresponding to 14–18 MWh/a, and to area specific savings of 28–35 kWh/(m^2a).

7.2.1.2 MPC

The corresponding figures for MPC were as follows (Table 5.4): Monetary cost savings were 16.9%, which corresponded to 1'118 CHF/a for the second floor, and 5'590 CHF/a for all five upper (office) floors. Area specific monetary cost savings were around 2.1 CHF/(m^2a). NRPE cost savings for the simulated second floor were 16.6 %, corresponding to 22 MWh/a of absolute savings and to 40 kWh/(m^2a) of area specific savings.

7.2.1.3 Further Remarks

Two important points should be noted with regard to the simulated monetary cost savings:

First, the obtained results reflect energy prices but for the year 2012. It can be expected that energy prices will increase in the future, and in this case the monetary cost savings in CHF thanks to the novel control strategies would also increase correspondingly.

Second, due the expected increase in the use of renewable energy sources, future energy prices are likely to show larger time-variations than was assumed for the present study. The newly developed control strategies differed widely in their ability to accommodate time-varying energy prices.

Whereas control strategies RBC-0 and RBC-1 are totally unaware of tariff structures, the control strategies RBC-2, RBC-3 and RBC-4 are able to exploit simple high/low tariff variations. More specifically, when assuming for our target building a purely electricity-driven heat production (based on a ground coupled heat pump instead of a gas burner) and a day/night tariff, simulations with the RBC-2 strategy (Section 6.1.1 and [2]) showed additional potential for monetary cost savings thanks to reductions in both, peak electric power demand costs and reduced costs during high-tariff phases.

MPC goes a big step further, since by design it can accommodate arbitrarily complex, time-varying tariff structures. This was successfully demonstrated in an experiment with the target building (see Section 6.1.2). Note that thanks to its built-in flexibility MPC is suitable not only for minimizing building operation costs under any tariff structure, but that it also opens up entirely new possibilities for fully dynamic demand response applications. Some limitations occur, however, due to uncertainty in the prediction of the energy prices and the disturbances acting upon the system.

7.2.2 Comfort

7.2.2.1 RBC

The simulation results reported in Table 5-6 and Figure 5-17 show that all RBC control strategies were able to achieve a high thermal comfort level. RBC-0 tended however to overheat the office rooms. This was because this strategy is mainly based on an outside air temperature compensation. Also, RBC-0 was found to use cooling in a less differentiated manner than the other RBC strategies, and this also lead to higher room temperatures.

7.2.2.2 MPC

The MPC strategy also achieved a high thermal comfort level. Compared to the RBC simulations, the MPC simulations showed fewer and less severe upper setpoint violations, and more frequent, but less severe lower setpoint violations (Figure 5-17). This result was due to the fact that MPC relies heavily on radiator heating to keep the corner rooms close to the lower temperature setpoint.

7.2.2.3 Further Remarks

Indoor comfort depends next to temperature also on air quality and luminance level.

Here we did not consider air quality in more detail because all controllers used by definition the same prescribed supply airflow rates.

With regard to luminance again all controllers had to obey the same restrictions. The choice of luminance comfort indices and the valuation of any resulting differences is not an easy task. Our simple analysis of under-shading and over-shading hours suggested similar levels of luminance comfort for all novel RBC and MPC strategies (results for strategy RBC-2 were reported in Section 6.2.2.3; results for the other strategies not shown).

Many publications address the effect of varying comfort parameters on productivity and health of building users, see e.g. [2]. Assessing the monetary cost of (differences in) occupant productivity and health is a very challenging task that was beyond the scope of this study. The issue is in our case also of secondary importance, since all investigated control strategies provided comparable and good comfort levels.

7.3 Robustness With Respect To Control Parameter Settings

All newly developed RBC and MPC strategies have certain parameters that need to be set depending on building, building usage and comfort requirements. A control strategy is called robust on a control parameter if the parameter's variation within a wide range shows only small effect on occupant comfort and control costs. Conversely, a control strategy is called non-robust on that parameter if the desired comfort and/or control costs can be achieved only for a narrow value range, i.e. knowledge of the exact parameter value is important.

The most important control parameter settings concern occupant comfort. Examples are the thermal comfort range boundaries, the ventilation schedule, air flow rates, supply air temperature setpoint range boundaries, and blind control restrictions.

The comfort parameters specify operational outcomes that have to be fulfilled by the controllers. All considered control strategies used the same settings for these parameters, and the outcome were differences in controller performance as reported in Sections 7.2.1 and 7.2.2

Here, we elaborate on the robustness with respect to all other parameter settings that are used to tune the internal functioning of the controllers.

7.3.1 RBC-0, RBC-1, RBC-3

For these control strategies the settings for outside air temperature compensation proved particularly delicate. This was found to be the case both in the simulations (see e.g. simulation of case "0-C" in Section 5.3.2, where a reduction of the air flow rate compared to the default case "0" leads to massive comfort violations), as well as according to experience with the target building.

In practice, the default outside air temperature compensation settings can be chosen such that they will prevent major thermal discomfort. Nevertheless, overheating and overcooling (as compared to optimal operation) is likely to occur quite frequently. In particular under varying internal gain levels none of the strategies RBC-0, RBC-1 an RBC-3 can offer adequate control performance, unless the control settings are continuously adjusted. For RBC-0, ventilation supply temperature setpoints have to be adapted manually to account for seasonal variation in outdoor climate, even when building usage does not vary.

7.3.2 RBC-2, RBC-4

These strategies have by design no sensitive control parameters. The key factor ensuring their good performance is the correct installation of the building automation system – in particular the correct installation, placement and functioning of the room temperature sensors. This is because these strategies implement room temperature feedback control that makes it possible to keep comfort even if the initial control parameter settings are far away from the optimal values.

To handle potentially erroneous room temperature measurements that could lead to severe discomfort or damages (e.g., frost damage) the following mechanism was included in strategies RBC-2 and RBC-4: The correction by room temperature feedback was limited to some maximum deviation from the control output of the weather compensation module.

7.3.3 MPC

Next to the control parameters that serve the specification of comfort requirements, the MPC strategy includes three further kinds of control parameters: (i) parameters specifying limitations related to actuator usage (e.g. maximal heating power, or ventilation operation schedules), (ii) cost function parameters, and (iii) key parameters used to define the thermal dynamics model.

Parameters (i) and (ii) can be normally determined quite easily. Wrong settings for actuator limitation can lead to underperformance and discomfort. For instance, the application of too high maximum heating power values can lead to delayed warm-up and discomfort in the morning. However, it is easy to ensure occupant comfort by choosing these parameter values on the safe side, at the cost of a possibly somewhat lower control performance. Wrong settings for cost function parameters may lead to underperformance of the control, but not to discomfort.

The most important control parameter settings of MPC relate to model parameter values, which may be delicate to set. In a pilot parameter sensitivity study not directly related to the demonstrator building (see Section 6.4), the influence of parameter mismatch on the closed-loop performance of MPC was investigated. The most sensitive model parameters were found to be the solar heat gain coefficient of the windows, and the convective heat transfer coefficients within the room. Further sensitivity studies for different buildings and building systems should however be undertaken to better assess the parameter sensitivity of MPC.

7.4 Robustness With Respect To Building System Changes, Disturbances, and User Interactions

The novel strategies' robustness with respect to the choice of building system (how much do the type and details of the system matter?), disturbances (e.g., weather, internal gains), and user interactions (e.g., blind control, opening of windows) was assessed based on careful monitoring of the target building, and with the aid of simulations.

Testing of the robustness with respect to variations of the building system was restricted to simulations only. This was because any field tests would have required costly and time-consuming modifications of hard- and software components in the target building that were beyond the scope of this project.

7.4.1 RBC

The field tests with the target building showed that all novel RBC strategies were robust regarding the disturbances and user interactions that happened during the respective test runs (Section 5.2.2). The strategies did not show any undesired behavior, and comfort for room users was maintained on a high level. This was confirmed both by measurements (Section 5.3.1.2), as well as feedbacks from the facility manager and occupants (Section 5.4).

The robustness with respect to variations of the building system was studied by applying the RBC strategies to different versions of the detailed energy simulation model (Section 3.2) of the target building's second floor. Our conclusion from the analysis of these simulation runs (results not shown) was similar to the one drawn in Sections 7.3.1 and 7.3.2: strategies that are robust on control parameter settings also proved robust on variations of the building system and disturbances.

The control strategies RBC-2 and RBC-4 are by design sensitive to inappropriate room temperature measurements. Erroneous measurements can cause (occasional or lasting) discomfort and/or increased costs. Troubleshooting underperforming control due to misplaced sensors can be rather challenging and time-consuming. At least, if no appropriate action can be taken, a switch-back to weather compensated control is possible at any time.

In the forerunner project OptiControl-I, extensive simulation studies were done to assess robustness with respect to variations of the building system and disturbances using similar RBC strategies as the ones considered here, however for individual room control, [1], [4].

There, we learned that RBC strategies such as RBC-1 and RBC-2 are robust on building systems and disturbances for most typical buildings and disturbances, given that the controller-specific parameter tuning rules are correctly applied.

7.4.2 MPC

Regarding robustness with respect to disturbances and user interactions, our evaluation of the MPC field experiments yielded the same positive result as reported above for RBC. In addition we conducted the following simulation experiments:

i) Sensitivity to heat exchange between the supply air provided by the Air Handling Unit and the concrete slabs of the ceiling (Section 5.3.3). This study showed that inappropriate modeling of key energy flows can lead to significant performance degradation of MPC. In the most extreme – but rather unrealistic – scenario investigated energy usage increased by up to 14%, and annual thermal comfort violations were in the range of a few hundreds Kh. The scenario employing the same model as used on the real building showed an increased cost of 3.8% and increased thermal comfort violations by 100 Kh.

ii) In a parameter sensitivity study (Section 6.4) we investigated, among other things, the influence of internal gains mismatch. Here it was found that a significant (-50%) under-estimation of the internal gains can also lead to comfort violations of a few hundreds Kh.

At least for the second case, we showed that relatively simple adjustments of the MPC formulation make it possible to strongly mitigate these effects.

7.5 Flexibility and Tuning Effort in the Engineering Process

Table 7-2 summarizes the flexibility and complexity of various control solutions depending on the underlying control strategy. The flexibility serves as an indicator of the ease at which the control solution can be adapted to a given building case and building technical system. The complexity is indicative of the effort needed to comprehend and correctly apply the control solution to that particular case.

Table 7-2: Flexibility and complexity of control solutions as a function of underlying control strategy

Control Strategy	Solution Flexibility	Solution Complexity
RBC-0	High: since the control strategy implements isolated control of various subsystems, its parts can be used and modified arbitrarily	Very low: few and simple rules, separate rules for each control discipline
RBC-1	Medium: individual elements can be used and modified more or less arbitrarily, however adaptation of the integration rules must be done with care	Low: few and simple rules, includes minimal set of rules for basic integrated control
RBC-2	Medium: as RBC-1	Medium: as RBC-1, but using a larger number of rules
RBC-3	Medium: as RBC-1, except for TABS control part that cannot be modified easily	High: as RBC-2, but in addition employing of a model based control approach for TABS
RBC-4	Medium: as RBC-3	High: as RBC-2, but in addition use of weather forecasts
MPC	Variable: The strategy is in principle applicable to any building or building system, or parts thereof. Effort for adaptation to a specific case is highly variable, depending on availability of an appropriate model or model generation framework.	Variable: The concept of MPC is easy to grasp and once an MPC system has been set up, only a few, well understandable settings have to be chosen. However, the modeling and implementation of an MPC solution are currently still very demanding.

7.5.1 RBC

As summarized in Table 7-2 all investigated RBC strategies can be flexibly adapted to other buildings and HVAC equipment than the ones considered in this project. In contrast to strategy RBC-0, the strategies RBC-1 to RBC-4 require some adaptation and tuning effort in order to realize integrated control. The RBC-0, RBC-1 and RBC-2 based solutions are quite easy to comprehend. Quite differently, incorporation of the RBC-3 and RBC-4 strategies is only possible for engineers who have some understanding of model based TABS control. The challenges posed by this requirement are similar to those outlined for MPC below.

7.5.2 MPC

Given an appropriate (i.e., sufficiently detailed, yet as simple as possible) model of the controlled process, MPC can be in principle easily applied to any building and HVAC system. The effort needed for the development of an MPC based control solution for a specific building thus depends mainly on two factors: the available model generation framework, and the accessibility of all data needed for model generation and MPC operation.

In Section 3.4.2 we presented a modeling framework that consists of a method for easy generation of reliable thermal models from geometry and materials data, and of a library of easily adjustable/tunable submodels for various typical HVAC systems. The modeling for MPC is expected to be further simplified by combining this approach with online model identification algorithms, as shown in Section 6.4.

A further challenge for MPC-based control solutions consists in obtaining all required data about the target building (construction data, HVAC system data, usage data etc.) as a basis for modeling. Unfortunately, this information is often not readily available in building automation projects. In any case appropriate procedures, software and appropriately trained staff are needed to enable efficient data preparation and to correctly handle ill-defined or missing data.

Use of MPC finally also requires some specialist knowledge for ensuring correct estimation of the building's thermal state and the generation of disturbance predictions (see Section 4.3.3), as well as for specifying the interplay with non-MPC controlled parts of the HVAC system. For instance, if the building is partly controlled by RBC the control rules need to be incorporated such that MPC can account for the behavior of the RBC controlled subsystems over the prediction horizon.

The degree of complexity visible to the people in charge of designing and implementing an MPC-based control solution will depend to a great extent on the quality and power of the tools and methods available at their disposal. These tools will certainly improve in the years to come. However, some specialized training for the engineering and commissioning personnel seems in any case unavoidable.

With regard to the pre-commissioning phase, the tuning of MPC-based solutions is typically limited to few control parameters and the effort is similar to the one in Table 7-3 (for commissioning and service phases).

7.6 User Acceptance for Engineering, Commissioning and Service

7.6.1 Engineering Phase

The acceptance of a control solution by engineering personnel is mainly determined by the personnel's ability to comprehend and adapt the solution to the application at hand (see Table 7-2). Depending on the project, engineering costs can be a significant part (>50%) of the building automation costs, see [5].

7.6.1.1 RBC

Rule based strategies are very common in building automation and therefore well known to engineering personnel. RBC solutions become harder to understand, adapt, commission and service with increasing number of rules and interactions between different control solution parts. However, solutions that do not require adaptation to a given building all imply a comparable low engineering effort, quite independently of their complexity.

7.6.1.2 MPC

Engineering personnel is typically not familiar with MPC. For good acceptance, a MPC framework on product level must be such that engineers can set it up without much background knowledge on MPC. In particular they should be able to easily generate models of specific buildings and HVAC systems (see Section 7.5.2). Effort for the integration of MPC as a high-level controller (see Section 4.1) is similar to the one for RBC solutions.

7.6.2 Commissioning and Service Phases

7.6.2.1 RBC

Table 7-3 gives our assessment of the level of difficulty and the required effort for parameter tuning for the various RBC strategies. The table assumes the skill and knowledge level of typical project and service engineers.

Table 7-3: Difficulty and effort for tuning of Rule Based Control (RBC) parameters

Control parameters	**RBC-0**		**RBC-1**		**RBC-2**		**RBC-3**		**RBC-4**	
	Difficulty	Effort	Difficulty	Effort	Difficulty	Effort	Difficulty	Effort	Difficulty	Effort
Comfort specification	N/a	N/a	Simple	Low	Simple	Low	Simple	Low	Simple	Low
TABS heating	Delicate	(varying)	Delicate	Medium	Moderate	Low	Delicate	High	Delicate	Medium
TABS cooling	Moderate	Medium	Moderate	Low	Moderate	Low	Moderate	Low	Moderate	Low
TABS PWM (optional)	N/a	N/a	Simple	Low	Simple	Low	Simple	Low	Simple	Low
Blinds	Simple	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate	Low
Ventilation	Delicate	High	Delicate	Medium	Simple	Low	Simple	Low	Simple	Low
Night-time vent. (optional)	N/a	N/a	N/a	N/a	Moderate	Medium	Moderate	Medium	Moderate	Medium
Static heating	Simple	Low	Simple	Low	Simple	Low	Simple	Low	Simple	Low
Weather pred. processing	N/a	N/a	N/a	N/a	Moderate	Low	Moderate	Medium	Moderate	Medium

It can be seen that strategy RBC-2 can be tuned with the largest ease and smallest effort as compared to all other strategies. For all other strategies in particular the tuning of the TABS heating parameters is a delicate issue.

The monetary cost associated with the tuning effort is hard to estimate and will differ on a case-by case basis. This is because the cost (in terms of engineering hours and of possible occupant discomfort during the commissioning or servicing) will vary considerably depending on the number of sensors and meters installed.

Tuning effort and tuning difficulty of strategy RBC-0 is particularly sensitive to the instrumentation level (cf. Table 7-3). For example the OptiControl-II target building was originally operated by RBC-0, and initially it also had no room temperature sensors (all other investigated strategies require a certain number of room temperature sensors). Most of the tuning of the TABS heating had thus to be done based on room user feedback and the operator's on-site experience. In case there are some reference room temperature sensors present, the tuning becomes significantly simpler because tuning then can be done using logged data (including room temperatures).

7.6.2.2 MPC

Difficulty and effort for tuning of MPC parameters are summarized in Table 7-4.

Table 7-4: Difficulty and effort for tuning of Model Predictive Control (MPC) parameters

Control parameters	**MPC**	
	Difficulty	Effort
Comfort specification	Simple	Low
Cost function	Delicate	Low
Actuator constraints	Moderate	Low
Internal gains predictions	Moderate	Low
Model	Delicate	High
Weather forecast processing	Moderate	Medium
State estimation	Moderate	Medium

As shown in this table the comfort specifications in the form of lower and upper temperature constraints are straightforward to set. If the goal is to control average (rather than individual) room temperatures, or if the model is not sufficiently accurate, the nominal constraints can be additionally tightened to ensure comfort in all rooms at the price of increased control cost.

The cost function, the actuator constraints, and the internal gains predictions can all be easily changed. However, precise parameter values (e.g., pump/fan energy consumption or maximum power, occupant densities, equipment loads etc.) may be difficult to obtain due to incomplete documentation or lack of measurements.

The model used in MPC also contains a range of parameters (related mainly to geometry and materials properties) that can be tuned such as to compensate for inaccurate modeling (for instance due to ignorance of building details or badly documented features). Automated model generation procedures can help to minimize modeling errors, but potential discrepancies between predicted and measured room temperatures may be difficult to isolate and correct.

The integration of weather forecasts and the estimation of the building's thermal state both require some offline data analysis by a moderately experienced engineer.

7.7 User Acceptance by the End User

The acceptance of different control solutions by end users (in the OptiControl-II project: office room users) can be assessed only to a very limited extent based on measurements or simulations. Therefore we conducted two occupant surveys at the following points in time:
(i) during RBC-0 operation, i.e. before operation of the first novel control solution; and
(ii) after a longer period of RBC-2 application.

As reported in Section 5.4.2 both surveys showed that the room users were mostly satisfied with the building and its control. No significant changes could be detected between surveys.

We had also planned a third survey after a longer phase of MPC operation. Unfortunately, due to organizational constraints, we were not able to carry it out.

The blind control prior to the start of the OptiControl-II project consisted of a simple blind scheduling program that closed the blinds during night-time. Previous to this a shading program had been used that operated the blinds also during the day, but this solution had to be disabled due to negative feedback by the office room users.

All novel RBC and MPC strategies applied automatic blind control as follows: once at lunchtime, and outside of office hours (19:00 to 7:00, and during weekends). Figure 7-1 shows an example of the blind positions commanded by the RBC-2 strategy for the south façade blinds group in a whole-year simulation for the year 2010.

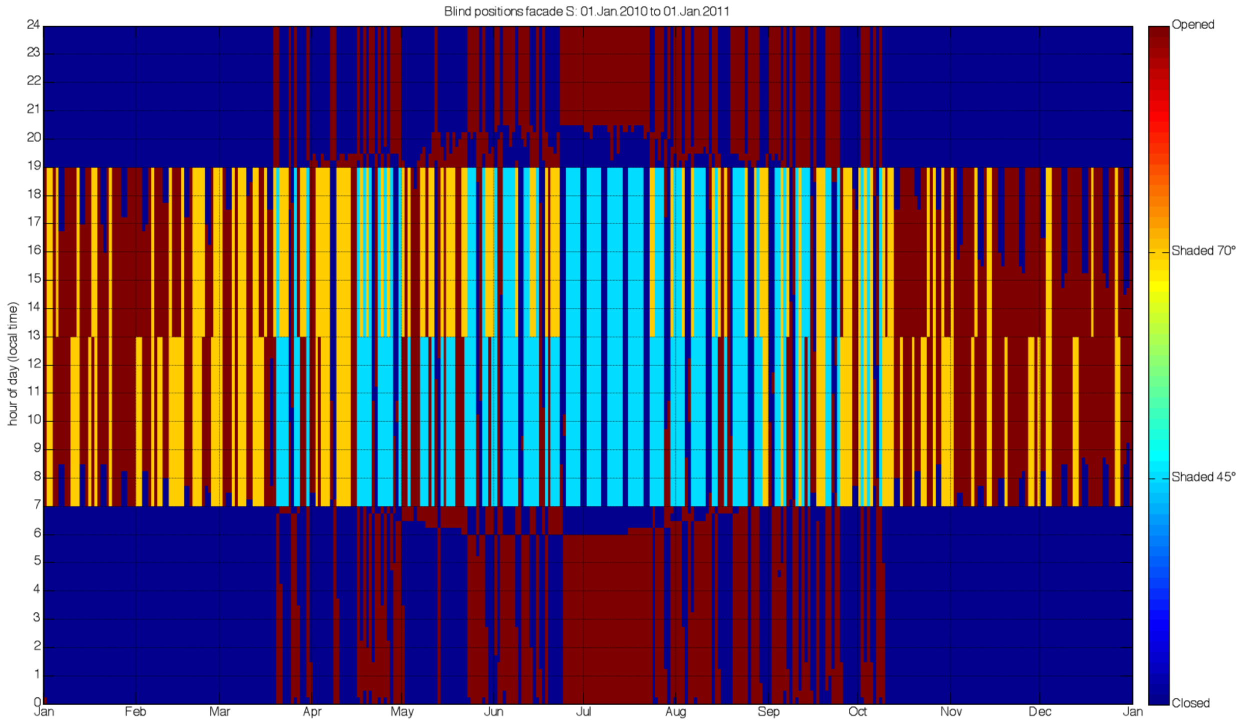

Figure 7-1: Simulated blind positions by the RBC-2 automatic blind control

The second survey confirmed that the employed, very conservative blind operation was accepted well by the room users. The possibility to restrict automated blind operation during certain sensitive periods was also well received by the facility manager.

7.8 Suitable as Extension Option

All newly developed RBC strategies can be specified and implemented as extensions to existing control solutions. In particular for weather forecast integration, there are already existing proven software solutions that were developed outside OptiControl-II (see e.g. [6]).

The MPC strategy was also implemented as supervisory control and thus can be easily used to extend an already existing control solution.

The various extension options require however some additional equipment, as reported in the following Section.

7.9 Investment and Maintenance Costs

Use of the novel control strategies requires some additional investments on the side of the solution provider as well as on the side of the building.

7.9.1 Investment Costs for the Solution Provider

The most important technology-specific investment by the solution provider is the amount of engineering personnel required, and the effort for their training. The training effort depends on the flexibility (related to the tuning effort) and comprehensibility (related to the complexity) of the implemented solution, as discussed previously in Section 7.5.

Training effort is likely to be a minor cost factor for the here investigated RBC strategies. Training effort and cost for MPC based solutions can be expected to be substantially higher since engineering personnel have to first familiarize with this new technology. However, this investment might possibly be offset by higher engineering efficiency, i.e. less required personnel for implementing and servicing of the promised solution.

7.9.2 Investment Costs for Data, Networking and Software

Intelligent data exchange and processing is at the heart of advanced building control. This involves use of specialized data, networks and software. The extra costs for the building owner and the solution provider depend largely on the building's baseline information technological infrastructure, and on the provider's marketing and pricing strategy, respectively. Examination of the benefit-cost balance between the two parties was beyond the scope of the present project. Below we comment only on some cost *differentials* as implied by the different control solutions.

Both, the RBC and MPC strategies must be integrated to provide high-level control in the building's automation system. Thanks to the well-designed high-level/low-level control interface (Section 4.1.3) this can be accomplished for both types of control strategies using standard building automation software. The corresponding programming effort is relatively small, and similar for both types of solutions. The integration of all needed sensors and low-level control devices is described later in Section 7.9.3.

MPC requires additional software to formulate the optimization task (based on an appropriate thermal building model), to estimate the building's thermal state, to prepare all need input data, and to carry out the optimizations (see Section 4.3.3). The cost of the optimization software is probably moderate, since only reasonably sized, linear programs have to be solved. The development cost for the other software is very difficult to estimate. It heavily depends on whether an MPC expert has to implement the needed software from scratch, or whether there exists some software environment that can be used by a regular control engineer to set up and engineer the required MPC solution.

In the first case, the development cost can be roughly estimated by the size of the tailored MPC software that was implemented on the target building and that encompassed ca. 10’000 lines of code. In the second case, one will have to factor in the cost for the development and maintenance of a generic software layer that provides structured access to predefined MPC core algorithms and auxiliary modules. Of course, in this case the costs can be distributed over all projects that are using that software.

The control solutions involving one of the predictive strategies RBC-2, RBC-3, RBC-4 or MPC require regularly updated weather forecasts. These can be obtained from dedicated websites or from a weather service. As compared to the simpler control strategies RBC-0 and RBC-1 this requires some additional hardware and/or software for weather data retrieval, storage and adaptation to site-specific conditions. Also, in case that the forecasts cannot be transmitted to the building site the software should implement a fallback strategy. One option is the generation of a persistence forecast from on-site measured data, i.e. temperature and radiation variables in the days ahead are assumed to show the same daily cycles as measured during the last few days.

Assuming the availability of out-of-the-box software for weather forecast integration into the building’s automation system, costs only arise for forecasts provider fees and for interfacing to the control program of the given building. These engineering costs are negligible compared to the total engineering costs. No costs at all result for the implementation of the fallback strategy if it is already foreseen in the control solution.

7.9.3 Investment Costs for Hardware and its Installation

Table 7-5 summarizes the additional instrumentation needs by the newly developed control strategies as compared to the RBC-0 strategy. Additional needs are shown in terms of sensors and control devices. Any subsequent installations such as electrical wiring, wireless receivers, I/O modules, or electrical panels are not given. The table further assumes completely developed, ready-to-deploy control solutions (see Section 7.10).

Table 7-5: Additional instrumentation needs of the newly developed Rule Based Control (RBC) and Model Predictive Control (MPC) strategies as compared to the baseline strategy RBC-0

Additional Instrumentation	RBC-1	RBC-2	RBC-3	RBC-4	MPC
Dedicated high-level control device (e.g. industry PC)	No	No	(Yes)	(Yes)	(Yes)
Blind control integration	Yes (method depending on communication abilities of blinds control system)				
Solar radiation sensor(s)	1 horizontal, or 1 per façade vertical				
Room temperature sensors	Min. 1-4 sensors per blind group				
		Min. 6 sensors per TABS zone		Min. 6 sensors per TABS zone	Min. 6 sensors per TABS zone
Window contacts	No	Optional	No	Optional	Optional
Presence detectors	No	No	No	No	Optional
Luminance sensors	No	No	No	No	No
Heat/cold meters	No	No	No	No	Optional
Electricity meters	No	No	No	No	Optional
Volumetric flow meters	No	No	No	No	Optional

From Table 7-5 can be seen that the novel control strategies have many common additional installation requirements. The strategies RBC-3, RBC-4 and MPC may also need a dedicated high-level control device, depending on whether they are implemented on standard automation level control devices or not.

Strategies RBC-2, RBC-4 and MPC further depend on the availability of sufficient temperature sensors per TABS zone. These strategies may optionally accommodate window contact information, preferably in the rooms where room temperature sensors are also available. In this case it becomes possible to improve the estimation of relevant room temperatures by truncation of measurements from rooms with open windows.

With regard to MPC, Table 7-5 shows a range of optional additional installations. Presence detectors can be used to improve internal gains predictions, use of heat/cold and electricity meters can be expected to improve the overall control performance, and the availability of volumetric flow meters serves improving the accuracy of the costs calculation and the actuation constraints.

To estimate the monetary cost associated with the additional installations we follow the common assumption that investment and maintenance costs depend on the number of data points to be engineered. Recent estimations of pricing per data point & cost split in typical building automation projects are reported in [5]. The findings of this study can be summarized as follows:

- The average (over many buildings) typical hardware prices per data point are in the range of 60-120 €, depending mainly on the project size. This cost figure includes all hardware for the management and automation level, i.e. the management PC(s), the automation and field bus wiring, the automation station(s), and their I/O modules. Sensor and actuator costs are not included.
- The average (over many buildings) typical labor costs for engineering only are also in the range of 60-120 €. They are expected to correlate with typical hardware prices.

Table 7-6 gives ranges for selected hardware and installation costs. Due to large differences in hardware quality and functionality the prices for sensors, actuators, meters and control devices show huge variation. Installation costs also vary a lot depending on the installation situation (building layout, new building vs. retrofitting etc.).

Table 7-6: Hardware and installation costs for various equipment

Equipment	Hardware Costs [€]	Installation Costs [€]	References
Room temperature sensor/room device	20–100	50–150	[7]
Heat/cold meter	200–1000	500–2000	[8]
Electricity meter	100–300	50–150	[9]
Industry PC	500–2000	–	–
Integration per blind group	–	200–400	[10]

As is nowadays the case also for many other buildings the OptiControl-II target building originally had a low level of instrumentation (see Section 2). Application of the various above cost figures yields the following *minimum* additional investment for implementation of one of the newly developed predictive control strategies (RBC-1, RBC-2, RBC-3, RBC-4 or MPC) in that building:

- Room temperature sensors: 1000 € for all newly developed control strategies
- Industry PC: 0 € for strategies RBC-1 and RBC-2
  500-2000 € for strategies RBC-3, RBC-4 and MPC
- Blind control integration: 2500 € for all newly developed control strategies
- Solar radiation sensor: 300 € for all newly developed control strategies

We note that these figures reflect the estimated lower limit of the investment cost required to implement the various control strategies. In particular, the cost of optional measurements is not taken into account.

7.9.4 Maintenance Costs

Maintenance costs arise due to the need for equipment servicing, troubleshooting, and the procurement of weather forecast data from a meteorological service. Table 7-7 gives a rough estimate of the maintenance costs per control strategy. Exact quantitative estimates are very hard to get at because these costs vary strongly on a case-by-case basis.

Table 7-7: Maintenance costs of the newly developed Rule Based Control (RBC) and Model Predictive Control (MPC) strategies

<table>
<tr><th>Activity</th><th>RBC-0</th><th>RBC-1</th><th>RBC-2</th><th>RBC-3</th><th>RBC-4</th><th>MPC</th></tr>
<tr><td>Weather forecasts procurement</td><td>None</td><td>None</td><td colspan="4">Medium</td></tr>
<tr><td>Equipment Servicing</td><td>Low</td><td>Low-Medium</td><td colspan="4">Low-Medium</td></tr>
<tr><td>Troubleshooting</td><td colspan="2">Medium</td><td>Low-Medium</td><td colspan="2">Medium</td><td>Medium (?)</td></tr>
</table>

The newly developed control strategies require two types of weather data, outside air temperature and global radiation on a horizontal surface. Today, typical fees for state-of-the-art weather forecasts by a meteorological service (e.g. MeteoSwiss [4]) amount to 100-500 € per site, year and meteorological variable. It can be expected that in future, fees will be lower.

7.10 Development Effort

Here, we define development effort as the effort required to develop a product that can be introduced to the market, i.e. a product that can be routinely used by the solution providing units and project engineers of a building automation company. The product development will typically take place at the company's development department and will build upon already existing solutions.

RBC-0: Already existing solution, no development effort necessary.

RBC-1: Only minor development effort is necessary. The development could even be done in the context of a sample customer project.

RBC-2: Requires medium development effort. Some parts of the control solution such as the advanced TABS control implementation and the integration of the weather forecasts need specialist knowledge and resources. Otherwise this control solution is similar to conventional control solutions and therefore fits well in an existing engineering environment.

RBC-3, RBC-4: Control solutions employing these strategies require a high development effort. Specialized engineers need to develop major parts of the solution. The partial use of MPC clearly presents an exception from conventional control solutions and engineering environments.

MPC: Very high development effort is necessary to develop a commercial product. This is for two main reasons:

- *Control Framework*. Experience with MPC in the building industry is currently very limited. A product level MPC framework needs to be coded nearly from scratch, including (or interfacing) a solver for the solution of the mathematical optimization problem embodied in MPC. Even though, given the available experience with MPC from many other control areas the development of such a framework appears quite straightforward.

- *Model Generation Framework*. A flexible model generation framework needs to be developed such that engineering personnel can generate suitable MPC models. The modeling approach developed within the OptiControl-II projects aims in this direction by allowing thermal models to be generated using construction data and building system models to be modularly added (see Section 3.4.2). Nevertheless, significant R&D effort is still required to create a model generation framework that can be broadly used by building automation engineering personnel.

7.11 Innovativeness and Selling Arguments

Today, most decision makers recognize the importance of energy efficiency in buildings. Awareness that control has a significant impact on energy efficiency and occupant comfort is also increasing. Therefore, a growing number of customers of building automation companies are welcoming the innovation offered in improved control applications. Innovative control applications and knowledge/competence on such applications may therefore well be a “door opener” for a building automation provider in certain projects.

Next to energy efficiency there are several other selling arguments in favor of novel control solutions. Table 7-8 gives an overview of the arguments for the control strategies developed in this project. Below, we discuss each argument in turn.

Energy efficiency. In recent years, the energy efficiency selling argument became very important and has been used to advertise a growing number of innovations in building automation. The argument cannot withstand short-term economic thinking because today’s energy prices are still low compared to other costs in typical office buildings. However, it appeals to customers who can afford long-term cost optimization and who are concerned about sustainability and an environmentally friendly image.

Table 7-8: Selling arguments for control solutions based on Rule Based Control (RBC) and Model Predictive Control (MPC) strategies

<table>
<tr><th></th><th>RBC-0</th><th>RBC-1</th><th>RBC-2</th><th>RBC-3</th><th>RBC-4</th><th>MPC</th></tr>
<tr><td>Energy efficiency</td><td>Standard</td><td colspan="4">Improved (due to integrated control)</td><td>Improved (due to energy usage minimi-zation)</td></tr>
<tr><td>Enhanced comfort</td><td>No</td><td>No</td><td>Yes (due to feedback control)</td><td>No</td><td>Yes (due to feedback control)</td><td>Improved (due to room temper. prediction)</td></tr>
<tr><td>Enhanced user acceptance by end users</td><td>No</td><td colspan="5">Yes (due to improved blind control)</td></tr>
<tr><td>Enhanced user acceptance by operator</td><td>No</td><td colspan="5">Yes (due to improved blind control & comfort settings)</td></tr>
<tr><td>Enhanced monitoring capabilities</td><td>No</td><td colspan="5">Yes (due to room temp. sensors)</td></tr>
<tr><td>Integrated control</td><td>No</td><td colspan="5">Yes</td></tr>
<tr><td>Using weather forecast</td><td>No</td><td>No</td><td colspan="4">Yes</td></tr>
<tr><td>Model predictive control</td><td>No</td><td>No</td><td>No</td><td>No</td><td colspan="2">Yes</td></tr>
</table>

Enhanced comfort. Maintaining the occupant comfort in a reliable manner is one of the main reasons for building automation. Enhanced comfort increases the productivity and health of building users and therefore is also of immediate economic importance.

Enhanced acceptance by end (room) user. Building automation can achieve a higher room user acceptance thanks to improved thermal comfort and more careful and intuitive (for room users) automatic blind repositioning during occupancy periods (using weather forecasts).

Enhanced operator acceptance. To gain acceptance of operators, the building automation system's Human-Machine-Interface has to be simple, understandable, robust and efficient.

Enhanced monitoring capabilities. In case that a more advanced control strategy or application requires installation of additional hardware components, several of these may be used not only for control, but also for improved monitoring of the building which may lead to energy savings thanks to improved monitoring.

Integrated control. In the recent past, integrated HVAC, blinds and light control has been used as a selling argument in particular for individual room control. Integrated solutions offer customers not only a common management station for all involved disciplines, but also advanced building automation functionality, such as provided by RBC-1 to RBC-4 and MPC, and energy efficiency awareness functionality, such as Siemens Building Technologies' green leaf display.

Integration of weather forecasts. Experience shows that the use of "predictive control using weather forecasts" is a selling argument due to the demand for such solutions. The reason is that the integration of weather forecasts makes sense for, and their usefulness is evident to, many people.

Model predictive control. Today, most building automation companies do not use model predictive control as a selling argument. In future, MPC could well be branded as an innovative, state-of-the-art technological solution. To this end it needs however to be first successfully applied in a number of projects. A breakthrough selling argument could become available due to the introduction of smart grid applications, where MPC solutions could offer unrivaled performance and flexibility.

7.12 Summary

Figure 7-2 summarizes in a qualitative manner the costs and benefits of all investigated control strategies as identified from the case study of the OptiControl-II target building.

The benefits of the novel integrated RBC strategies (RBC-1 to RBC-4) as compared to the standard, non-integrated reference strategy (RBC-0) lie in their better control performance, user acceptance and comfort during the buildings' regular operation phase.

The additional instrumentation required for the novel strategies also allows for enhanced energy monitoring. The latter will typically also contribute to increasing a building's energy efficiency, e.g. thanks to faster fault detection and better support in recognizing easy-to-implement optimization measures (e.g., adjustment of time schedules for systems operation).

These benefits come, however, at higher cost during the buildings' development, pre-construction and construction phases.

All above trends apply, in a more pronounced manner, also for the investigated MPC strategy. The higher initial investment cost for MPC comes however with two unrivaled additional benefits: easy to implement control of peak power demand, and the ability for cost-optimal control under complex, time-varying energy tariffs.

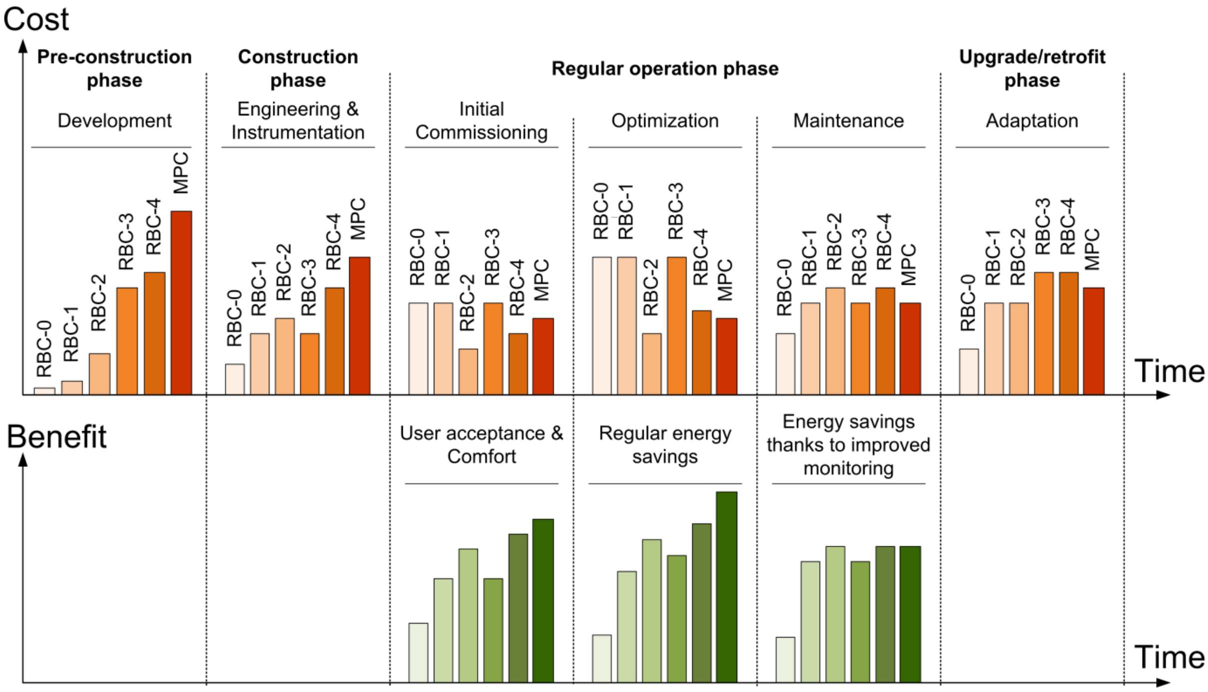

Figure 7-2: Qualitative benefit-cost assessment of the investigated control solutions in different stages of a building's life cycle. RBC: Rule-Based Control; MPC: Model Predictive Control.

7.12.1 Novel RBC

In a building such as the OptiControl-II target building, the *newly developed, integrated Rule-Based Control (RBC) strategies*

- are expected to save 10%–15% Non-Renewable Primary Energy and 10%–15% Monetary Cost for HVAC, lighting and equipment as compared to the reference (*standard, non-integrated*) RBC strategy, while providing a similar level of occupant comfort;
- proved at least as robust with regard to control parameter settings, building system and disturbances as the reference strategy;
- are more demanding regarding engineering, commissioning and service than the reference strategy (with the novel strategies RBC-3 and RBC-4 probably being too complex for broad application);
- reach at least the same level of user acceptance as the reference strategy;
- have somewhat higher investment cost than the reference strategy.

The novel RBC-3 and RBC-4 strategies are still immature. Part of their control functionality still remains to be fully developed into a product. Also, in particular the engineering and service personnel have to gain experience with these strategies. Therefore, further development effort and cost for these two strategies are very difficult to estimate.

The novel RBC strategies RBC-1 and RBC-2 could be developed further mainly with regard to operation and monitoring. Recommended future activities include:

- Development of simpler tuning or auto-tuning methods for control parameter settings in order to lower the effort in the commissioning and service phases.
- Integration of advanced monitoring functionality for the building and its automation systems in order to better support plant error detection and control optimization.

- Adaptation of the novel strategies to further HVAC/blinds/light applications (in real buildings and/or simulations) and assessment regarding their usability in order to increase the novel strategies field of application.

7.12.2 MPC

In a building such as the OptiControl-II target building, the *newly developed Model Predictive Control (MPC) strategy*

- is expected to save ca. 17% Non-Renewable Primary Energy and ca. 17 % Monetary Cost for HVAC, lighting and equipment as compared to the reference (*standard, non-integrated*) RBC strategy, while providing a similar level of occupant comfort in winter and improved comfort in summer;
- can easily be adapted to take into account peak power costs and varying electricity tariffs, thus enabling easy implementation of demand response for buildings;
- is probably more demanding regarding engineering and less demanding regarding commissioning than the reference strategy (the actual effort, however, will largely depend on how MPC would be implemented in a product);
- reaches at least the same level of user acceptance as the reference strategy;
- has somewhat higher investment cost than the reference strategy.

Large development effort is still necessary to bring MPC to product level since to date only very limited experience and products exist in the building industry.

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8 Communication

D. GYALISTRAS

Communication received particular attention from the beginning of the project, in order to account for the presence of many different stakeholders and for the fact that we dealt with a fully occupied building. A professional communication concept was therefore elaborated in Summer 2011 [6]. It was then implemented to ensure that the interests of all involved parties were respected and that the project got good visibility.

8.1 Peer Reviewed Publications

Cigler, J., Gyalistras, D., Siroky, J., Tiet, V.-N., Ferkl, L. (2013). **Beyond theory: the challenge of implementing Model Predictive Control in buildings**. 11th REHVA World Congress Clima 2013, June 16-19, 2013, Prague, Czech Republic. http://www.opticontrol.ethz.ch/Lit/Cigl_13_Proc-Clima2013.pdf

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Morari, M. & The OptiControl Team (2013). **Prädiktive Regelung für Gebäude – Simulation und Praxis**. Presentation at the 8. Schweizer Haustech Planertag, 26. Feb. 2013, Kongresshaus Zurich, Switzerland. http://www.opticontrol.ethz.ch/Lit/Mora_13_Pres-8CH_Haustech_Planertag.pdf

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8.5 On-Site Event

On the afternoon of 20. Sep. 2012 was held the event "**Gesamtheitliche vorausschauende Gebäudeautomation: Forschungsergebnisse im Praxistest**" at the premises of Actelion Pharmaceuticals Ltd., Allschwil, Switzerland. It included presentations by the OptiControl participants, a guided tour of the target building, and an informal part. The event presented a highlight of the OptiContol dissemination activities. It was attended by over 70 persons[7] and was received very positively throughout.

30. May 2012. **Event flyer and program**.
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http://www.opticontrol.ethz.ch/docs/120530_OptiControl_Fachveranstaltung_Hinweis.pdf

20. September 2012. **Media release, ETH Zürich, Siemens Building Technologies, Gruner AG, swiss*electric* research**. Scientific field trial confirms the effectiveness of innovative control strategies / Wissenschaftlicher Praxistest bestätigt die Wirksamkeit innovativer Regelstrategien.
http://www.opticontrol.ethz.ch/docs/120920_OptiControl_MediaCommunication_SpecialEvent.pdf

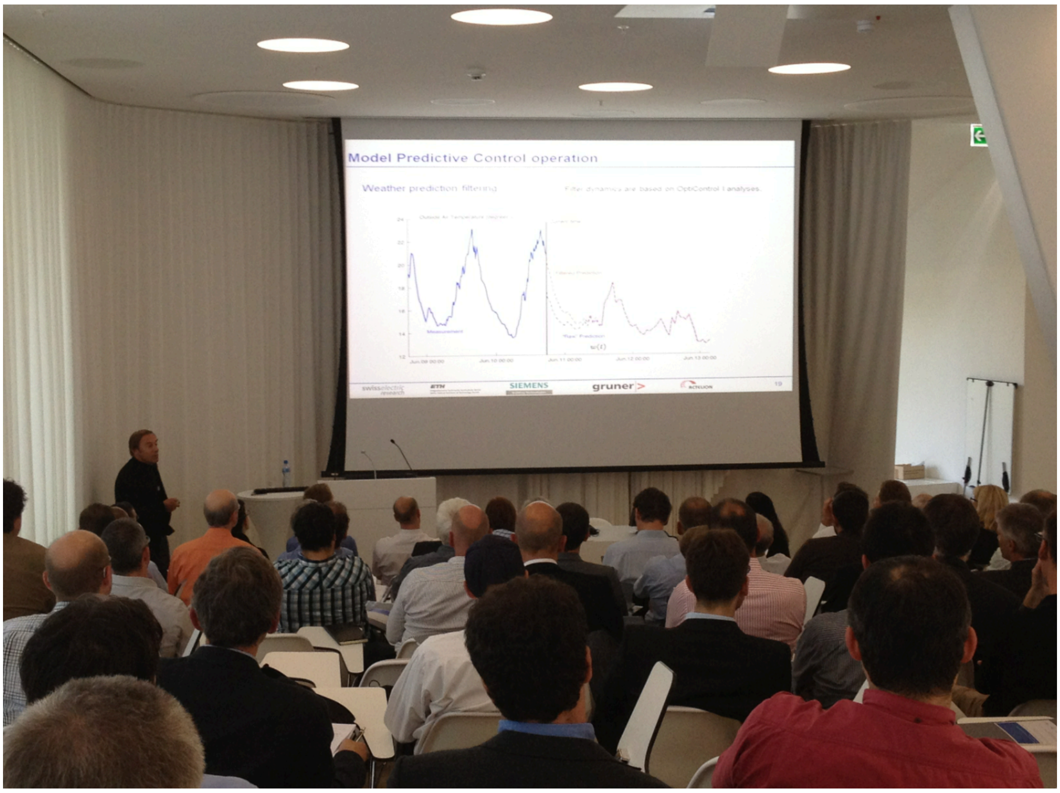

Figure 8.1: Impression from the OptiControl on-site event held on 20. Sep. 2012 at Actelion, Allschwil, Switzerland.

[7] Participants list available from
http://www.opticontrol.ethz.ch/docs/120919_OptiControl_Teilnehmerliste_Fachveranstaltung.pdf

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Sagerschnig, C. (2012). **Erkenntnisse aus Sicht des Planers: Neue Wege in der Gebäudeautomation = Neue Wege in der Gebäudeplanung**.
http://www.opticontrol.ethz.ch/Lit/Sage_12_Pres-FVOptiControl_20Sep2012.pdf

Gwerder, M. (2012). **Erkenntnisse aus Sicht des Anbieters von Gebäudeautomation: Vorfeldentwicklung und Bewährungsprobe für Lösungsideen**.
http://www.opticontrol.ethz.ch/Lit/Gwer_12_Pres-FVOptiControl_20Sep2012.pdf

Smith, R.S. (2012). **Predictive building control: Insights from the research perspective**.
http://www.opticontrol.ethz.ch/Lit/Smit_12_Pres-FVOptiControl_20Sep2012.pdf

Gaiser, A. & Maltese, G. (2012). **Erkenntnisse aus Sicht des Nutzers**.
http://www.opticontrol.ethz.ch/Lit/Gais_12_Pres-FVOptiControl_20Sep2012.pdf

Gyalistras, D. (2012). **Schlusswort**.
http://www.opticontrol.ethz.ch/Lit/Gyal_12_Pres-FVOptiControl_20Sep2012_Schlusswort.pdf

8.6 Varia/Press

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http://www.opticontrol.ethz.ch/Lit/Schl_11_Rep-ETH-Globe_02-11_31.pdf

Media release, Federal Department of Home Affairs FDHA, Federal Office of Meteorology and Climatology MeteoSwiss: Energiesparen mit Wettervorhersagen / Economiser de l'énergie grâce aux prévisions météorologiques / Risparmiare energia grazie alle previsioni del tempo. 12. April 2011.
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http://www.opticontrol.ethz.ch/Lit/Gwer_12_IntelligentBauen_18.pdf

Praxistest bestätigt die Wirksamkeit innovativer Regelstrategien. In: die baustellen, fachkom gmbh, Langnau a. Albis, 29.10.2012

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8.7 Tools/Software

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8.8 Patents

None.

9 Assessment Of The Results

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The project produced a wide range of results that were reported comprehensively in Chapters 2–8. The individual results were assessed in the respective Chapters and various publications (Chapter 8). Here we summarize the most important findings in order to assess the project as a whole, and provide a brief outlook.

9.1 Did the Project Reach Its Goals?

The current project built upon the predecessor project OptiControl-I. Among other things, in this earlier project novel predictive control strategies compatible with state-of-the-art industry practice were elaborated.

In the present project, OptiControl-II, we developed these strategies further for practical application, implemented them and proved their feasibility under real-world conditions in a concrete, challenging case study, tested them during a period of one and a half years using detailed measurements, user feedbacks and simulations, contributed new methods and tools for advanced building contol, communicated the results by means of numerous publications, reports, presentations and a successful on-site event, and provided a comprehensive benefit-cost assessment. According to the results presented in the previous Chapters it can be said that all goals of the OptiControl-II project (Section 1.1) were achieved without exception.

A similar approach as the one reported here has been pursued also in several other projects dealing with research and development in the building controls area. However, to our knowledge, the consideration of integrated control for an entire, fully occupied office building, and the depth and broadness of our assessment are unprecedented. Other projects have typically focused but on smaller buildings or individual rooms, or individual control disciplines (such as heating or ventilation only), or isolated systems (such as chilled water plants), and mostly for much shorter periods of investigation and with a narrower focus. Hence, next to reaching its specific project goals, the OptiControl-II project can be considered to have pioneered research in the area of integrated whole building control.

9.2 How Applicable Are The Results In Practice?

Inquiries and feedbacks from other researchers, as well as citations in international journals and conferences suggest that the project's results have been well received by academia.

The response from practitioners, in particular at the on-site event that took place in September 2012 (Section 8.5), was also very positive. This feedback relates to the fact that thanks to the close cooperation with the industrial partner Siemens Building Technologies all novel control strategies had been designed such as to provide high-level (supervisory) control in a manner fully compatible with state-of-the-art building automation systems and products (Section 4.1). We are therefore confident that at least part of the newly developed Rule Based Control (RBC) strategies will be incorporated in Siemens control products within the next one or two years.

Innovation in the building controls sector is nowerdays driven by a range of factors including the rapid development in information and communication technology, the establishment of open communication protocols in building automation, the demand for higher comfort and safety, increasing architectural and technological diversity and environmental awareness, and the ongoing transformation of energy markets and systems. All these factors imply a trend towards increased functionality, performance and complexity of control solutions.

The novel control strategies developed in the OptiControl project picked up some of these trends, and as a consequence they are also somewhat more demanding in terms of engineering, commissioning and service as compared to current state-of-the-art strategies (Sections 7.5, 7.6 and 7.10).

The applicability of the newly developed control strategies will therefore depend, firstly, on the education of control solution developers (who may have to get acquainted with new control technologies such as Model Predictive Control, MPC), and to some extent also of planners, project and service engineers and facility managers. Secondly, and most importantly, the novel solutions' applicability will depend on whether it becomes possible to hide most of their complexity behind easily understandable concepts, automated procedures, and user-friendly interfaces.

RBC presents the current standard control approach for non-residential buildings. The RBC strategies from the predecessor project OptiControl-I, had initially been formulated for individual room control (so-called Integrated Room Automation). The fact that these strategies could be easily transferred – without any adaptation of the control concept – to the multi-zone control of the demonstrator building presented a strong evidence of their flexibility and suitability for use in everyday building automation practice.

The benefit of the novel RBC strategies lies in their better control performance and user acceptance as compared to state-of-the-art solutions (Sections 5.2 and 7.8). Moreover, the novel strategies have an equal or higher robustness with regard to control parameter settings, building system configuration, and disturbances than current state-of-the-art strategies (Section 5.2.2).

However, the novel RBC strategies imply somewhat higher costs during a building's development, pre-construction and construction phases (Section 7.10). The strategies' adoption by the market can therefore be expected to depend heavily on the control solution provider's marketing and pricing strategy and/or the customer's willingness to pay a higher price for a qualitatively better product.

For the MPC approach the required initial investment in model development is currently too high to justify deployment in everyday building projects on the basis of energy savings alone. The main reasons are that the MPC solution is not yet as close to a product as the novel RBC solutions, and that its engineering and optimization requires in addition to common control engineers also MPC experts. Control solution providers will have to ponder over the extent to which this additional expertise should be provided by in-house project engineers (who already have a wide range of responsibilities) versus being acquired as an external service.

As already shown in the predecessor project OptiControl-I, the added value of MPC depends heavily on the building type, location, and technical systems. For our relatively simple target building the use of MPC was found to give ony a moderate improvement for energy usage and occupant thermal comfort as compared to the best-performing RBC strategies (Sections 5.2 and 5.3).

The good news is (i) that MPC has been shown to run reliably on a modern office building; (ii) that it performed at least as good as for the most advanced available RBC strategies; (iii) and that thanks to its proven flexibility and ease of adaptation it opens up completely new opportunities to integrate buildings as responsive elements in tomorrow's electricity and renewables based energy system.

9.3 Was It Worth The Effort?

The entire OptiControl project (OptiControl-I and II) extended over a period of roughly eight years (2006-2013, including a one-year preparation phase), involved more than 30 persons, and consumed a budget of 4.7 Million Swiss Francs.

The project dealt with improving building operation, which is the most costly and energy-consuming part in a building's life cycle. We believe that the project was worth the effort for several reasons.

Firstly, the project contributed a wide range of novel methods, theoretical works, tools, data sets, insights and control strategies related to advanced building control ([1], Chapters 2-7).

Secondly, it demonstrated that for the case study of a representative office building improved control can save 10–17% of primary energy as compared to state-of-the-art control while maintaining at least a comparable level of occupant comfort. Even larger savings can be expected to occur for buildings with more complex actuation (e.g., several TABS zones), in particular for the MPC method that becomes increasingly powerful when it comes to coordinating a large number of actuators.

Thirdly, the project also clearly demonstrated the feasibility and excellent performance of MPC in the target office building. In particular it showed that MPC can be used to flexibly and efficiently manage the building's dynamic energy demand to an extent far beyond the reach of the best currently available RBC strategies.

On a more basic level, the project also once more clearly showed how important it is to get buildings to function correctly in the first place, to be able to reliably monitor their performance, and to include control considerations already in an early phase of construction or refurbishment projects.

Finally, the project helped to build up advanced building control expertise in academia and industry, it contributed to the training of young researchers, and it offered all participants the opportunity to develop their skills in interdisciplinary teamwork and the handling of complex systems and human-technology interaction.

9.4 Outlook

As already stated, any attempts to improve control make no sense as long as a building is not functioning correctly (cf. Section 2.3). Therefore we assign high priority to the development of advanced monitoring functionality for buildings and their automation systems with the aim to be able to rapidly and reliably detect plant and control errors, and to identify optimization potentials.

With regard to RBC we see the main future work in the following two areas:
(i) Development of simpler tuning methods, or even of auto-tuning methods, for control parameter settings with the goal to lower the required effort in the commissioning and service phases. (ii) Adaptation of the novel RBC strategies to a range of additional HVAC/blinds/light applications based on implementation in real buildings and/or simulation studies.

The present project clearly showed that MPC is a technically feasible and powerful approach for building control, but that significant effort is still necessary to bring it to a product level, i.e. to make it efficiently applicable to a broad range of building automation projects. We think that pushing further the development of general methods and simple-to-use tools for setting up a robust MPC for any given building (cf. Sections 3.4 and 6.4) presents a sound investment. It might one day be urgently needed by building owners and societies to deal with time-varying energy prices and/or the enhanced use of intermittent energy sources, a not unlikely scenario for the future.

A final word relates to the well-known fact that the construction and management of buildings is subject to conflicting interests related to, among other things, money, occupant comfort, environmental concerns, aesthetics, and public image. Our building control study impinged upon all these issues and it was encouraging to see that thanks to a common vision, teamwork, creativity, willingness to compromise, and good communication it becomes possible to improve building operation to the benefit of all involved parties.

9.5 References

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