swiss*electric*
research

Final report

Use of Weather and Occupancy Forecasts for Optimal Building Climate Control (OptiControl)

23-June-2010 (Updated 5-October-2010)

Dimitrios Gyalistras and The OptiControl Team
ETH Zurich
Systems Ecology, Institute of Integrative Biology
Universitätstrasse 16
8092 Zurich, Switzerland
Phone: +41 78 602 54 09
Email: gyalistras@env.ethz.ch

Project Duration: 01. May 2007 – 31. July 2010

1. Management Summary

The objectives of the OptiControl project were (i) the development of novel, predictive control strategies in order to reduce energy usage of buildings, enhance occupant comfort, and reduce peak electricity demand; (ii) the development of software and tools for improved building control; (iii) benefit-cost analyses for predictive control; and (iv) application to a demonstrator building.

The project was co-sponsored by swiss*electric* research, the Competence Center Energy and Mobility, Switzerland (CCEM-CH) and Siemens Switzerland Ltd., Building Technologies Division, Zug.

An interdisciplinary team consisting of the following partners carried out the project: 1. Terrestrial Systems Ecology Group ETH Zurich (D. Gyalistras, A. Fischlin): project management, modelling and simulation tools; 2. Automatic Control Laboratory ETH Zurich (M. Morari, C. Jones, F. Oldewurtel, A. Parisio): development of Model Predictive Control (MPC) algorithms; 3. Building Technologies Laboratory, EMPA Dübendorf (Th. Frank, K. Wirth, B. Lehmann, V. Dorer, S. Carl; project months 1-30): building data base and modeling; 4. Federal Office of Meteorology and Climatology (MeteoSwiss), Zurich (P. Steiner, F. Schubiger, V. Stauch, Ch. Hug): meteorological data base, weather predictions tailored to building control; 5. Siemens Building Technologies, Zug (J. Tödtli, D. Habermacher, B. Illi, M. Gwerder, C. Gähler): modelling, development of industry-standard, rule-based control; 6. Building Climate Control, Building Physics & Simulations, Gruner AG, Basel (A. Seerig, C. Sagerschnig; project months 31-39): building modelling and simulation. The participants contributed jointly to the determination of the research focus, the development of research methods, the construction of software tools, and the preparations for the demonstrator.

Goal (i) was successfully reached for a carefully selected, representative application, the so-called "Integrated Room Automation" (IRA) for office buildings. IRA deals with the automated control of blinds, electric lighting, heating, cooling, and ventilation of a building zone or room and therefore covers many aspects of modern building control. Developed were: (a) improved rule-based, non-predictive, and novel rule-based predictive IRA control algorithms, plus associated tuning rules; (b) a family of entirely new, Model Predictive Control (MPC) algorithms that allow for integration of weather forecasts and for the management of peak electricity demand; (c) new algorithms for delivering hourly temperature and radiation forecasts at a building's location at the high quality required by predictive controllers.

Goal (ii) was also fully reached. Developed was a novel, general and flexible modelling and simulation environment for the study of building control. The environment includes databases for buildings, building technical systems, weather, weather forecasts, and occupancy data. Next to being a unique research and development tool the software provided also the basis for a prototype, web-based tool that supports the online assessment of predictive control strategies also for non-expert users.

Goal (iii) was reached partially, namely regarding the assessment of the benefits of predictive control. Based on extensive simulation studies it was shown, firstly, that

improved non-predictive control allows for readily achievable annual energy savings by on average 1%–15%. Secondly, the average theoretical savings potential of predictive control was found to be 16%–41%[1]. Generally, savings potentials were found to vary widely with location, building case, and technical system characteristics. The potentials were mainly due to the predictive management of building thermal mass thanks to optimized control of blinds/solar heat gains and of free cooling. Detailed analyses for a range of representative building cases demonstrated substantial benefits of the novel MPC algorithms as compared to conventional, non-predictive rule-based control. Advantages were found in terms of energy usage, robustness, tunability, flexibility (e.g., optional limitation of peak power demand, either directly, or in response to time-varying electricity prices), and comfort.

The second part of Goal (iii), the cost assessment, was not reached because it was tightly linked to the demonstration objective (iv) that could not be pursued as initially planned. This was because both controller development as well as the identification of an appropriate demonstrator building turned out to be much more time consuming than initially planned.

Therefore after the first two project years the project was refocused, and it was decided to pursue the demonstration Goal (iv) in a separate follow-up project. Preparations for the new project included the identification of a suitable demonstrator building (a representative Swiss office building in Allschwil close to Basle, Switzerland), negotiations with the building owner, the setting up of a project team, the planning of the needed modifications to the building, and careful initial modelling and simulation work. Based on simulations the theoretical savings potential of predictive control for the chosen demonstrator building was estimated to be > 20%. A project proposal has been submitted for funding by swiss*electric* research. Planned project start is in September 2010.

Substantial effort was done to disseminate the project's results and to transfer them into practice. Next to the prototype web-based tool mentioned above dissemination efforts included the maintenance of a project website, poster and oral contributions at conferences and seminars, and numerous journal papers, technical reports, and publications in the specialized press.

In summary, the OptiControl project has successfully answered many important questions related to the potential and feasibility of predictive building control, and it has paved the way towards the development of a new generation of controllers offering an unprecedented performance, robustness and flexibility. The planned follow-up project aims at the practical demonstration of the proposed control solutions and the development of industry-compatible prototypes.

---

[1] Note, only part of this theoretical potential may be realized in practice, and smaller potentials may apply depending on the allowed freedom for blind movement in the reference control. This explains the somewhat smaller numbers stated in the project's intermediate report from 30. June 2009.

2. Final report

2.1 Introduction

This report gives an overview of the work done in the OptiControl project (http://www.opticontrol.ethz/), an interdisciplinary project dedicated to the development of predictive control technologies for buildings that was carried out in the period May 2007–July 2010. The project's main objective was the development of predictive control strategies that minimize energy usage while allowing to maintain or even improve occupant comfort and to reduce peak electricity demand.

The project focused on the application Integrated Room Automation (IRA) for office buildings. IRA is a very general application that deals with the automated control of blinds, electric lighting, heating, cooling, and ventilation of an individual building zone or room. The control task consists in maintaining occupant comfort in terms of temperature, illumination level and air quality at minimum energetic or monetary cost while at the same time rejecting disturbances related to weather, internal gains and occupant behavior.

The project's progress during the first 27 months up to July 2009 was documented in the progress report to swiss*electric* research from 30. June 2009 and in particular in the "Two-years Technical Report" [1] referenced therein. Below we first summarize the main findings from the entire project, and then we briefly comment on the achievements of the last 12 project months (August 2009 – July 2010). More detailed information can be found in the various cited references and all other references given in Section 2.4.1.

2.2 Studies done and achieved results

2.2.1 Methodology

The OptiControl project dealt entirely with so-called "non-standardized" control solutions, i.e. solutions where the control has to be tailored to the given building, technical system and user requirements by means of corresponding programs that govern the behavior and interplay of the individual subsystems.

Ten criteria for the assessment of non-standardized control solutions were identified at begin of the project. The criteria ranged from control performance, robustness, and requirements of different users to marketing potential [2]. While all criteria were kept in mind throughout the project, the focus was placed on the achievable control performance. The latter was defined as the maximum performance that can be attained for a correctly functioning and well-tuned system. It can be quantified at reasonable precision by simulation studies in the form of energy usage, monetary costs, comfort indices etc.

The conceptual framework used to assess the performance of control strategies is shown in Figure 1. The key element is a model based, mathematical optimization procedure that computes the so-called Performance Bound (PB). The PB is a theoretical value that is determined by assuming perfect knowledge of the building's dynamics plus of all future weather and internal gains disturbances. It gives the lowest possible control cost (in terms of energy or money) for a given building, particular set of disturbances, cost function, and set of comfort requirements.

The difference to the PB presents the theoretical savings potential (maximum achievable savings) for any given control algorithm. Clearly, no real controller will ever reach the PB. Given a large improvement potential further control strategy development appears particularly promising, although nothing can be said a priori to what extent the potential can be exploited by a feasible control.
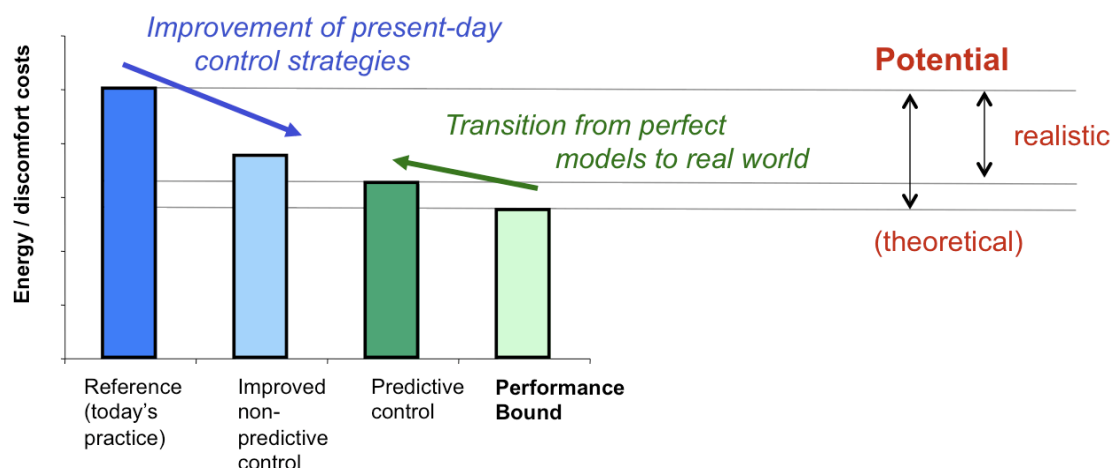

Figure 1: Conceptual framework for assessing controller performance. From [2].

From the large variety of approaches that have been proposed for building control two specific approaches were selected for more detailed study: Rule Based Control (RBC) and Model Predictive Control (MPC).

The main reason for selecting RBC was that it is the common solution for non-standardized Building Automation applications.

MPC was chosen because of the experience available in the project team and because MPC is tailored to predictive control. A major advantage of MPC as compared to all other control approaches is that it employs a mathematical, physically based model of the controlled process, and can thus account for non-linear and complex interactions in multiple-input-multiple-output systems.

An important synergy of the RBC and MPC approaches should be stated: MPC is mathematically equivalent to a method for finding the globally optimal set of rules and associated parameters in a very large decision space. Hence, careful study of MPC results can be used to derive approximate, reduced sets of relevant rules and parameters for use in RBC controllers.

2.2.2 Modelling

Figure 2 gives an overview of the automated subsystems that were considered for IRA. The project addressed six typical variants of building systems that employed different combinations of subsystems [3,4].
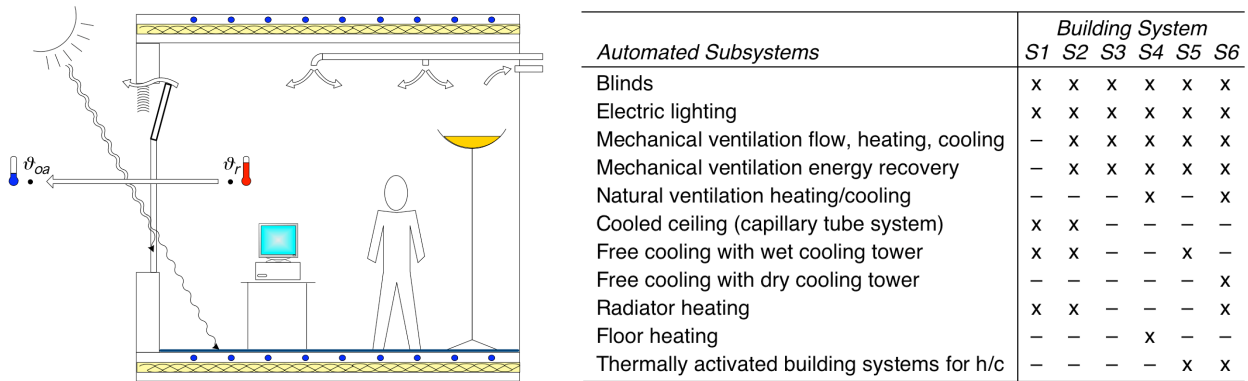

Automated Subsystems	Building System					
	S1	S2	S3	S4	S5	S6
Blinds	x	x	x	x	x	x
Electric lighting	x	x	x	x	x	x
Mechanical ventilation flow, heating, cooling	–	x	x	x	x	x
Mechanical ventilation energy recovery	–	x	x	x	x	x
Natural ventilation heating/cooling	–	–	–	x	–	x
Cooled ceiling (capillary tube system)	x	x	–	–	–	–
Free cooling with wet cooling tower	x	x	–	–	x	–
Free cooling with dry cooling tower	–	–	–	–	–	x
Radiator heating	x	x	–	–	–	x
Floor heating	–	–	–	x	–	–
Thermally activated building systems for h/c	–	–	–	–	x	x

Figure 2: Overview of building zone and of automated subsystems considered for modelling. Modified from [3,5].
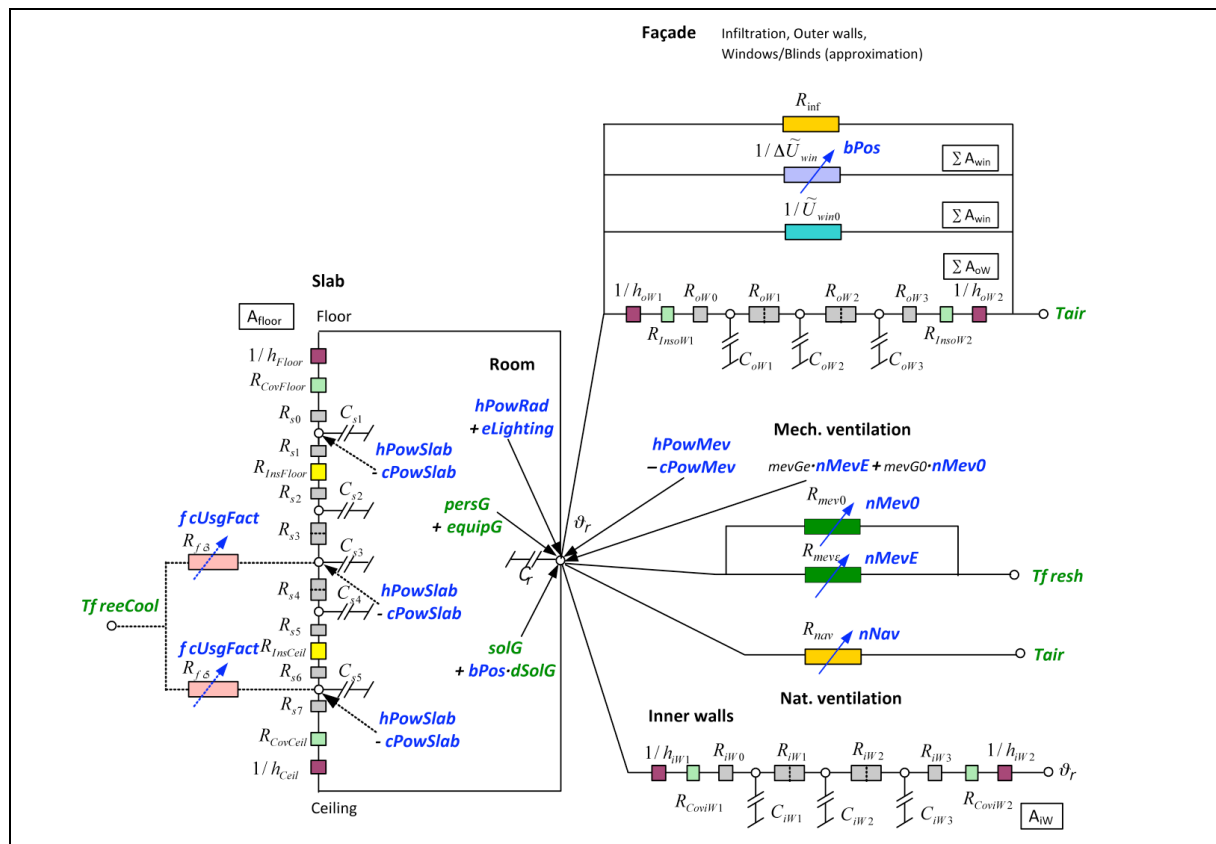

Figure 3: Thermal Resistance-Capacitance (RC) network model. For illustration all supported subsystems are shown simultaneously. From [5].

In order to be able to assess different control strategies by simulation and for the development of Model Predictive Controllers (MPC) the building zone's coupled thermal, light and air quality dynamics and their interaction with the technical installations were first described mathematically [6]. In a second step the mathematical description was reformulated such as to be suitable for MPC, and in a last step the resulting equation systems were coded into a computer program.

In the selection of the computer modelling approach we had to balance the conflicting requirements arising from the needs for sufficient process detail, good modelling accuracy, and a high temporal resolution (≤ 1 hour) on the one hand, and for minimizing the input data needs, and maximizing the simplicity, robustness, and computational efficiency of the model on the other hand [5].

The chosen solution was a 12th order bilinear thermal Resistance-Capacitance (RC) network modelling approach that lumps the radiative and convective heat transfer processes. The resulting model is shown in Figure 3. Note that for illustration purposes this Figure shows all supported automated subsystems simultaneously.

The RC model and the various approximations it contains were validated against detailed building physical simulations. The model was found to deliver accurate and reliable results [7].

2.2.3 Databases

For the simulation-based assessment of the IRA control algorithms corresponding input data sets had to be made available. Different kinds of data were needed that were compiled into two different data bases.

The first developed database was the Building Systems Database (BuSyDB). It contains all needed parameters to simulate typical building zones with typical heating, cooling, ventilation, blind and lighting subsystems that span many of the most important IRA configurations. The BuSyDB also provided information on typical control costs (in terms of energy usage or money), comfort definitions, and constraints for control strategies (e.g. heating/cooling power limits) that were defined, among other things, from appropriate dimensioning procedures.

The second developed database was the OptiControl Weather and occupancy Data Base (OCWDB). It contained all disturbances (weather, plus standard internal heat gain profiles for offices) that were required for performing whole-year, hourly time step building simulations. In this context algorithms for the disaggregation of hourly global radiation into the direct and diffuse part, and the derivation of global radiation components on vertical oriented surfaces were implemented (i) as MATLAB functions for general use within the project, and (ii) within the MeteoSwiss operational processing and dissemination software [8].

Figure 4 shows the sites considered in the OCWDB. The database offered annual data sets for different years from the period 2001-2009, depending on site. Various Design Reference Year data sets were partially newly derived and were also included in the OCWDB [8,9].
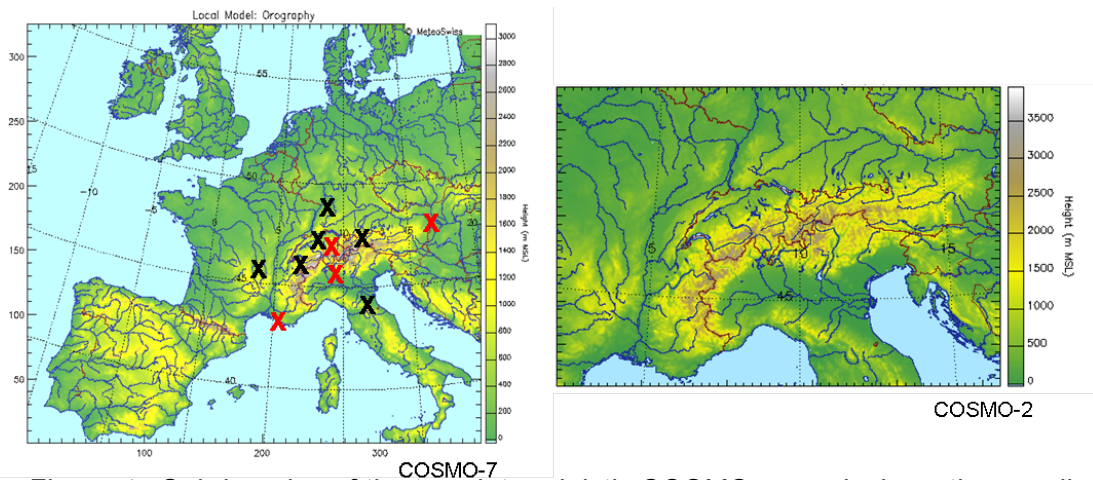
Figure 4: Subdomains of the two deterministic COSMO numerical weather prediction models (COSMO-7 on the left, COSMO-2 on the right) run operationally by MeteoSwiss. The boundary conditions for the COSMO-7 forecasts are provided by the global NWP model Integrated Forecasting System (IFS) of the European Centre for Medium Range Weather Forecasting (ECMWF) in Reading, UK. The crosses on the left indicate the location of the selected case study sites for the OptiControl project. Red crosses indicate the four main sites investigated (Zurich, Lugano, Marseille, Vienna). From [9].

The OCWDB sites were chosen according to the following criteria: representativeness for the European climate; availability of high quality, long-term hourly observations of the most important weather variables for building control applications; location within the domains of the MeteoSwiss COSMO-7 and COSMO-2 operational weather forecast models, and recommendations of the National Weather Services in charge. The OCWDB also contained the best available weather predictions (see next section) from the COSMO-7 model for the chosen sites.

2.2.4 Weather Forecasts

The accuracy of local weather predictions from numerical weather forecast models is affected, among others, by the model's limited horizontal resolution that is in the order of a few kilometres, at best. Meteorological measurements at the building's location can however be used to improve the local forecasts based on statistical post-processing. Two such post-processing methods were developed and applied to improve the local predictions of the weather variables needed by the IRA application.

The first method was designed to affect the entire forecast range (three days for the COSMO-7 model). It implicitly takes into account the daily cycle of temperature and radiation by using hourly observations of an entire day for each correction step. The method uses a linear error model that is updated recursively as soon as new observations become available based on a linear Kalman filter [9]. It had been successfully implemented at MeteoSwiss several years ago and was extended and improved in the course of the OptiControl project. Figure 5 illustrates the obtained improvement for three-days ahead predictions of air temperature and global radiation in Zurich for 2007.
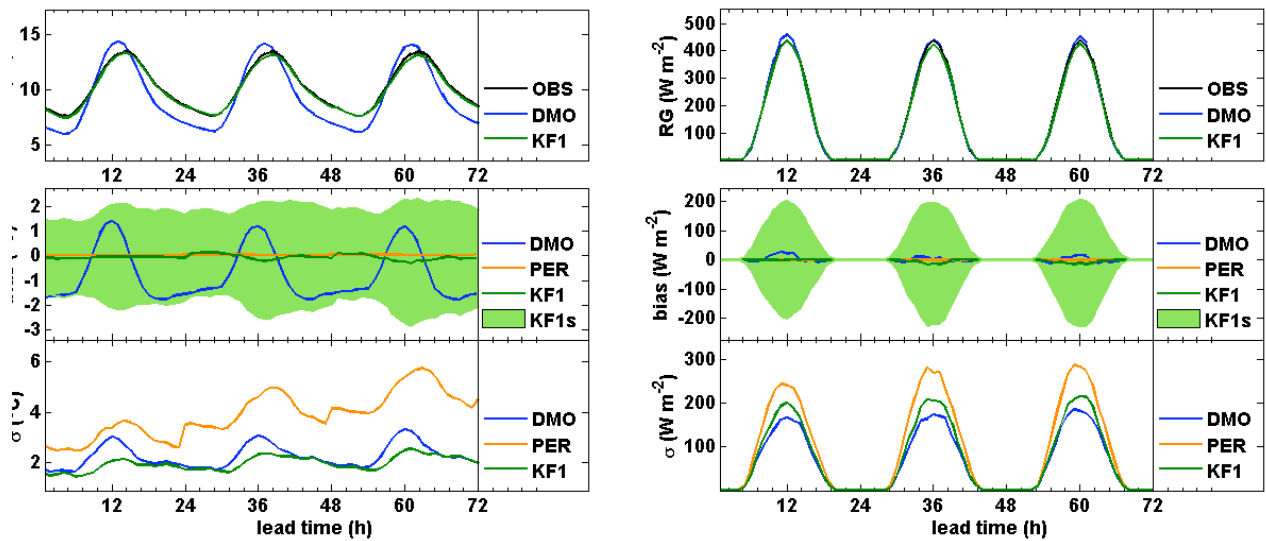
Figure 5: Summary verification results for the air temperature, TA (left), and global radiation, RG (right), for the entire year 2007 at Zurich. OBS are the mean observations, DMO is the direct COSMO-7 model output, PER shows the persistence forecast taking the latest measurements available and project them into the future, KF1 is the Kalman filter correction and KF1s is the standard deviation of the forecast error of KF1. σ in the bottom panels denotes the standard deviation of the forecast error. From [9].

In general, it was found that forecast biases could be successfully removed on a seasonal basis. The root mean square error of local temperature predictions for the first 24 hours ahead was reduced by 20–30%. For wet-bulb temperature the reduction was 35–45%. For the radiation components no reductions or slight increases were obtained for winter and summer, but reductions of 10–60% were achieved for spring and autumn.

The second post-processing method accounted for the fact that the first few time steps (here one hour) of the weather forecasts proved to be most crucial for the performance of the IRA controllers. Developed was therefore a short-term correction algorithm that used the latest (hourly) observation only and explicitly modelled an autoregressive process for the forecast error [8; an alternative algorithm for the same task was also developed, 10].

Figure 6 (upper two panels) illustrates the performance of COSMO-7 forecasts when used to predict solar heat gains in a building as a function of start time of the forecast and lead time. It can be seen that the largest differences between the COSMO-7 predictions and the observations were found during mid-day.

The lower two panels in Figure 6 demonstrate the benefit of the local correction in terms of the difference between the systematic errors (bias) and standard deviations of the COSMO-7 direct model output (DMO) and the corrected forecasts. When averaged over the entire year, the bias correction was found to hold for up to four forecast hours, whereas the positive effect on the forecast error variance was found to fade out a little earlier.
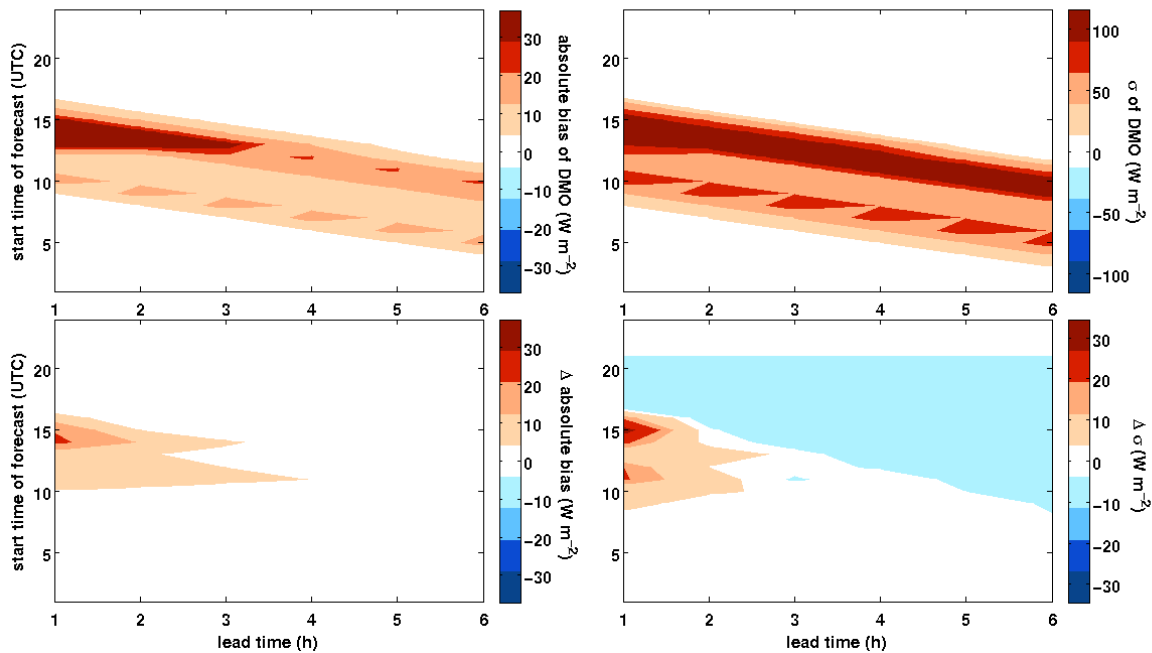
Figure 6: Mean effect of the correction for solar heat gain predictions for the entire year 2007 at Zurich. Considered is a building zone with "Swiss average" thermal insulation level, a south orientated façade, and a window area fraction of 80%. The upper two panels show the absolute bias (on the left) and the standard deviation, σ (right) for the uncorrected COSMO-7 predictions (DMO) over the day (start time of the forecast, y-axis) and as a function of (short) lead time (x-axis). The lower panels show the difference between the DMO and the corrected COSMO-7 predictions for the same two scores. Red colors in the bottom panels indicate an improvement of the scores. From [8].

2.2.5 Control Strategies

All considered control strategies conformed to the hierarchical architecture of modern Building Automation and Control systems [see 3]. This structure involves so-called high-level and low-level controllers that are typically realized in both, the hard- and the software. The task of the high-level controller is to determine a set of so-called operating modes that are sent to the low-level controller. In the opposite direction, the low-level controller delivers measurements (e.g. room temperatures), heat/cold demand, setpoints etc. to the high-level controller.

2.2.5.1 Rule-based control

Rule-based control (RBC) presents the state-of-the-art for IRA and was therefore studied in more detail and it was also used as the benchmark for MPC.

RBC determines all control inputs based on a series of rules of the kind "if condition then action". The conditions and actions typically involve numerical parameters (e.g., threshold values), the so-called control parameters. Determining both, a good set of rules, as well as the associated parameters is decisive for good RBC performance.

Strategy	Description	Input Data	Blind Transmission Values	Blind Repositioning
RBC-1	Typical, broadly applied strategy	Current measurements of external gains	Three transmission values: fully open, fully closed and shading transmission	Event driven (threshold corssings). In simulations: once per hour.
RBC-2	As RBC-1, but more freedom in blind movement.	– ¨ –	Continuous blind transmission values	Continuous
RBC-3	Novel strategy (newly elaborated within the OptiControl project)	Historical heat and cold demand signals, historical room temperature data	– ¨ –	Continuous
RBC-4	As RBC-3, but with restricted blind repositioning	– ¨ –	– ¨ –	Once per hour

Table 1: Investigated rule-based control strategies. From [11].

Four basic, non-predictive RBC strategies and associated procedures for the automated tuning of their control parameters were identified or newly designed and implemented for use in simulations (Table 1).

The strategies RBC-2 and RBC-3 assumed continuous blind control that normally would not be accepted by building occupants. The reason why we considered these strategies was because we wanted to investigate how far one can push non-predictive control. Indeed, RBC-3 is in terms of energy usage the best performing non-predictive control strategy currently known to us. In the future RBC-2 and RBC-3 could gain practical importance for electrochromic windows control.

Figure 7 shows the rules used by RBC-3 for determining the blind operating mode. Instead of working with threshold values (the standard solution in present-day RBC) RBC-3 for uses historical heat and cold demand signals and historical room temperature data. Primarily, heating and cooling demands of the last 24 hours are evaluated; if there was no heating and cooling demand during the last 24 hours, the strategy attempts to shift the room temperature towards the middle of the room temperature comfort range.

The ideas underlying the RBC-3 strategy lead to a patent application by J. Tödtli & M. Gwerder (see Section 2.4.3).

The strategies RBC-1 and RBC-2 provided the basis for two newly developed *predictive* RBC strategies, PRBC-1 and PRBC-2. These employ rules that account for the mean predicted external heat gains over the next hour, or the next 24 hours, and the mean predicted outside air temperature over the next 24 hours. Further information can be found in [12].
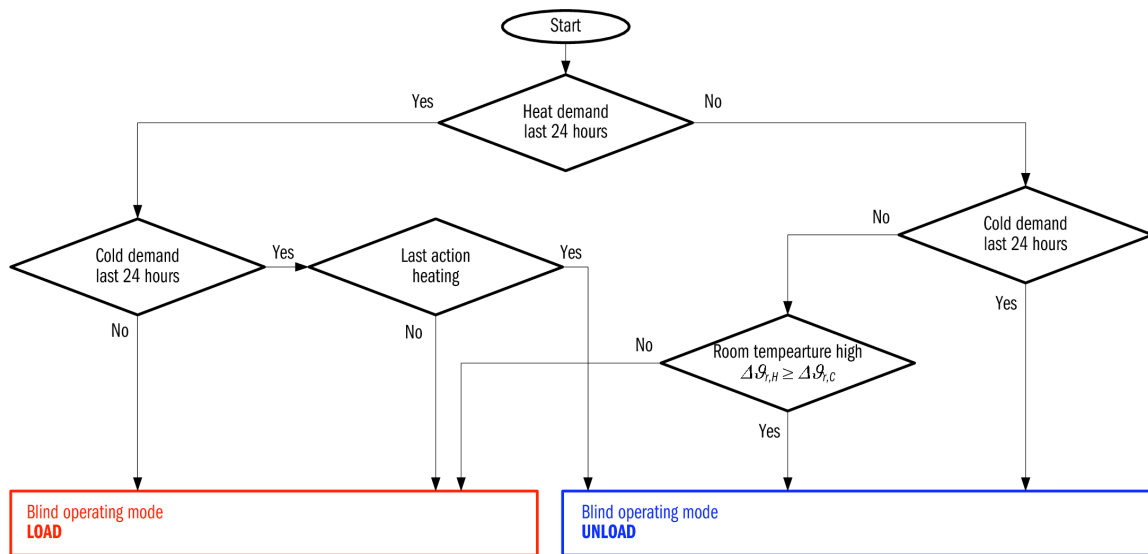
Figure 7: Determination of blind operating mode for control strategy RBC-3. From [11].

2.2.5.2 Model Predictive Control

Figure 8 gives an overview of the developed Model Predictive Control (MPC) procedure for buildings. The procedure requires that measurements of the building state and the local weather conditions are available. These measurements are sent to the MPC controller alongside weather predictions that are corrected with local measurements (Section 2.2.4), as well as information about energy costs and comfort criteria.

Figure 8: Application of Model Predictive Control to building control. From [13].

Based on a model describing the building's dynamics MPC solves an optimization problem to determine the optimal control inputs. The first step of the control plan is applied to the building, setting all heating, cooling, ventilation, lighting and blind subsystems (and/or appropriate high-level control modes), before moving one step forward and repeating the process at the next sampling time (e.g., after on hour). This receding horizon approach is what introduces feedback into the system, since the

new optimal control problem solved at the next time interval will be a function of the new state at that point in time and thus also of any disturbances that have meanwhile acted on the building.

The MPC modelling and design effort consists of specifying the dynamic building model (Section 2.2.2), as well as constraints of the control problem and a cost function that encapsulates the desired behavior (Section 2.2.3). A generic framework is given by the following finite-horizon optimization problem:

$$\min_{u_0,\dots,u_{N-1}} V_N(x_N) + \sum_{i=0}^{N-1} l(x_i, u_i, r_i) \qquad (1) \text{ Cost function}$$

$$\text{subject to} \qquad x_0 = x \qquad (2) \text{ Current state}$$

$$x_{i+1} = f(x_i, u_i) \qquad (3) \text{ Dynamics}$$

$$(x_i, u_i) \in \mathbb{X}_i \times \mathbb{U}_i \qquad (4) \text{ Constraints}$$

where u denotes the control inputs (e.g., heating power, cooling power etc.), V and l are cost functions (that can be used to penalize undesired system states and to account for total energy usage), N is the prediction horizon (e.g., 48 hours), x is the system state (e.g., room temperature, wall temperatures etc.), and r are cost function parameters (e.g. heating or cooling cost). f is the model describing the system's dynamics (cf. Section 2.2.2). For further explanations see [14].

The above MPC framework implicitly assumes that the provided dynamic model is able to perfectly predict the future behavior of the building over the desired control window, or prediction horizon. This assumption is clearly not reasonable because there will be both modeling errors and disturbances (weather, occupants, etc.) acting on the system over this period.

We therefore developed robust or stochastic MPC schemes that work with a model of these disturbances and that attempt to compensate for these future unknown inputs in the formulated control plan. Specifically, we accounted for uncertainty in the weather predictions in two ways:

Firstly, motivated by Swiss building standards we did not require the constraints (e.g., the allowed range for the room temperature) to be satisfied at all times, but only with a predefined probability, which is formulated with so-called chance constraints $P(x \in \mathcal{X}) \geq 1 - \alpha$ where $\mathcal{X}$ denotes the set of constraints and α denotes the predefined probability level of constraint violation (e.g., the probability that room temperature lies outside the prescribed comfort range). As is shown later α can be used for tuning purposes in a very intuitive and simple way.

Secondly, we explicitly accounted for the uncertainty in the controller by formulating the future control inputs as functions of future past disturbances, i.e. each predicted control input was considered a function of the disturbances that will have happened up to that point in time.

With this formulation we were able to take the stochastic nature of the problem into account without being overly conservative. The detailed mathematical formulation and background can be found in [15,21].

2.2.6 Controller Assessment

2.2.6.1 Theoretical Potential of Predictive Control

The maximum achievable energy savings thanks to predictive control were assessed by comparing the performance of the various RBC strategies with the PB.

To this end were performed various large-scale factorial simulation experiments that comprised several ten thousands whole-year, hourly time step dynamic simulations [16, 12]. Considered were up to 64 building zone types (differing in façade orientation, construction type, building standard/thermal insulation level etc.), 5 building systems (employing different heating, cooling, ventilation etc. subsystems), 2 "cost" functions (Non-Renewable Primary Energy [NRPE] usage, and monetary costs), 4 different building sites, 4 thermal comfort definitions, and 2 ventilation strategies. Annual total costs and annual comfort indices were analyzed by building system, building standard (PA–"Passive House", or SA–"Swiss average"), and building class (I–"very frequent", II – "less frequent", III–"exotic" building case).
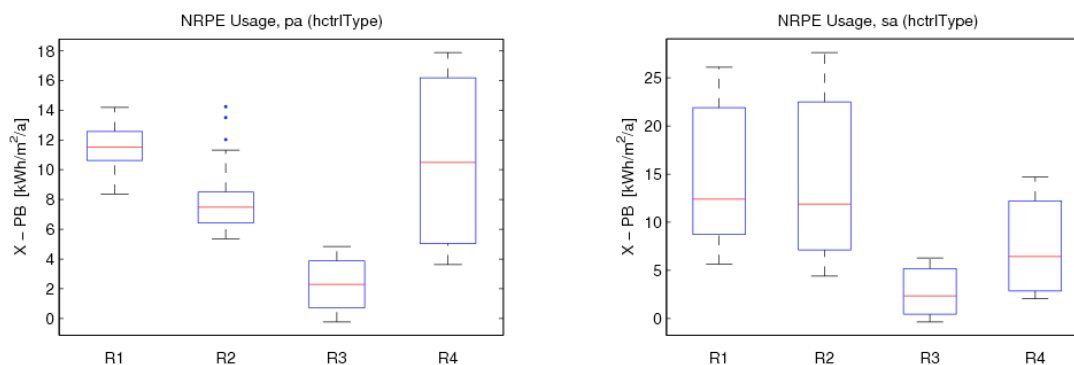

Figure 9: Overview of Non-Renewable Primary Energy (NRPE) theoretical savings potentials for the rule-based control strategies RBC-1 to RBC-4 (abbreviated as R1–R4). Results are shown separately for the "Passive House" (left) and the "Swiss average" (right) thermal insulation levels, and for building system variant S2 and Buildings Class I (n=32). X: NRPE usage by RBC algorithm; PB: Performance Bound. Note the different y-axis scaling. From [16].

Figure 9 shows a typical result for the found theoretical NRPE savings potentials of strategies RBC-1 to RBC-4. It can be seen that the smallest absolute savings potentials were always obtained for RBC-3, followed by RBC-2 for the "Passive House" (left) and RBC-4 for the "Swiss average" (right) thermal insulation standard. The absolute potentials (given in kWh/m^2/a) were always higher for the "Swiss average" as compared to the "Passive House" building standard.

The found savings potentials were put into context by comparing them with possible NRPE savings due to the following low-cost measures related to control: *a)* a reduction of the thermal comfort when the building is not used, by allowing for room temperature set-backs during nights and weekends (base case: no set-backs allowed); *b)* a general reduction of thermal comfort due to a widening of the room temperature comfort range by ~1.5 ºC (base case: narrow comfort range); *c)* the use of Indoor Air

Quality controlled ventilation (base case: application of a constant minimum fresh air supply rate according to a fixed occupancy schedule); *d)* the adjustment of the control such that it optimized control actions for energetic rather than monetary cost (base case: optimization of control for money).
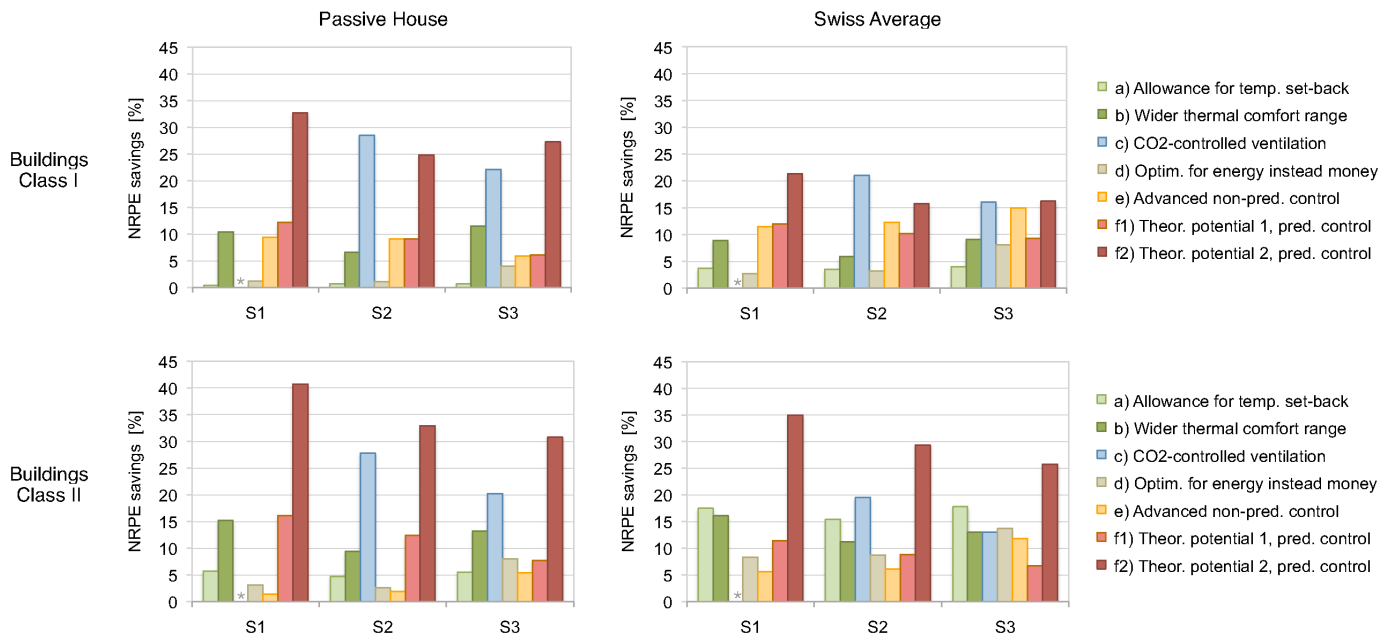

Figure 10: Comparison of average relative savings potentials for annual total Non-Renewable Primary Energy (NRPE) usage. Savings potentials a)–e) *can be realized in practice, whereas* f1) *and* f2) *are theoretical values representing the maximum achievable savings given perfect predictive control. S1–S3: building system variant; *: value not available. From [17].*

Figure 10 compares the average achievable energy savings thanks to the aforementioned low-cost measures *a)–d)* with: *e)* the average energy savings when using a newly defined strategy, RBC-5 (= "best of RBC-1 and RBC-4", see [17]), instead of RBC-1; *f1)*: the average theoretical savings potentials for RBC-3; and *f2)*: the average theoretical savings potentials for RBC-5.

It can be seen that *c)*, the use of CO2-controlled ventilation, bears the largest immediately accessible energy savings potential; average energy savings for this measure were 13%–28%. Further significant energy savings can be achieved by *b)*, the widening of the thermal comfort range by ~1.5 °C (average savings of 6%–16%), and *a)* the allowance for night/weekend room temperature set-back (0%–18%). Average readily achievable savings from improved non-predictive control *e)* were 1%–15%. Average theoretical savings potentials for predictive control *f2)* were 16%–41%. Smaller theoretical potentials *f1)* may apply depending on the allowed freedom for blind movement in the reference control (see RBC-3 in Table 1).

Figure 11 juxtaposes the annual total NRPE usage of various IRA RBC algorithms on a case-by-case basis. It can be seen that there are large performance variations both between each other and across individual cases regarding buildings, building operation and different climates. There is considerable potential for reducing NRPE

usage, most of all for the "standard" algorithm RBC-1, but in many cases also for the advanced predictive algorithms PRBC-1 and PRBC-2. Note, for the PRBC algorithms throughout perfect weather predictions were assumed.
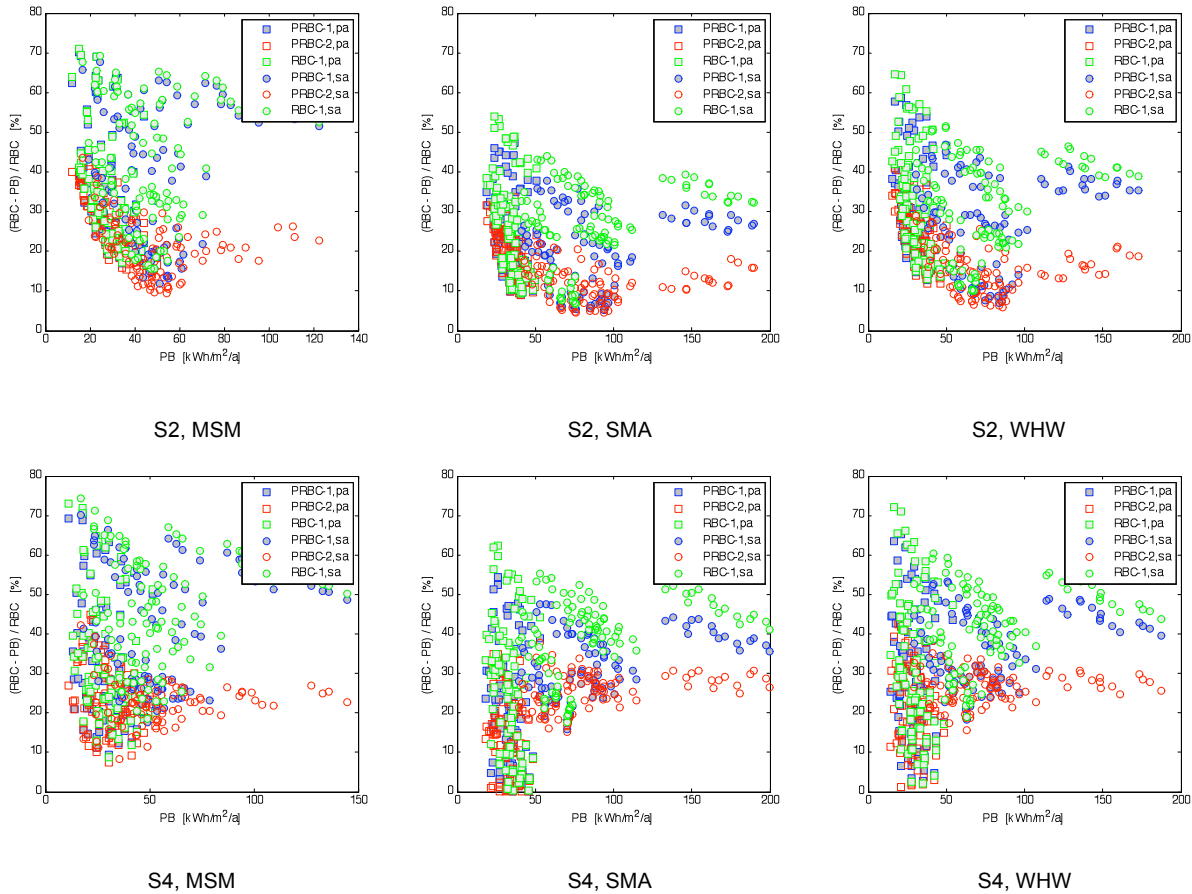

Figure 11: Relative additional annual total Non-Renewable Primary Energy (NRPE) usage for control algorithms RBC-1, PRBC-1 and PRBC-2 compared to the Performance bound (PB). S2, S4: building system variant; MSM: Marseille; SMA: Zurich; WHW: Vienna; pa, sa: "Passive House" and "Swiss average" thermal insulation level, respectively. From [12].

A closer analysis of the RBC theoretical savings potentials [17,18] showed that they generally occur throughout the year, and that they tend to increase with higher solar and internal gains. Façade orientation was found to be the most important single factor explaining the savings potentials' variability, followed by window area fraction and building site. The effect of thermal mass (heavyweight vs. lightweight construction) was found to vary strongly with reference control.

The savings potentials were traced back to the optimized use of the blinds, free cooling and energy recovery. Predictive control of these low-cost devices allows to efficiently pre-heat or pre-cool the building structure. This makes it possible to avoid frequent switching between heating and cooling, and to keep room temperatures as much as possible floating freely within the thermal comfort range [18].

2.2.6.2 Assessment of Model Predictive Control

In a second step a comparative analysis of various RBC and MPC strategies in terms of energy usage, thermal comfort, and peak electricity demand was undertaken for a number of carefully selected [18], representative building zone cases.

Figure 12 (left panel) compares for six such cases the performance of the RBC-5 and stochastic MPC controllers in terms of annual amount of thermal comfort violations (x axis) and additional annual total NRPE usage above the PB (y axis). The MPC procedure employed weather predictions from the MeteoSwiss COSMO-7 operational weather forecast model; all other needed information, i.e. the building model, its state, and the internal heat gains were all assumed to be perfectly known.

It can be seen that MPC always used clearly less NRPE than RBC-5, and in four of six cases it showed in addition also smaller amounts of violations. In two cases MPC showed somewhat higher violations, but they were clearly below the acceptable violation limit of 70 Kh/a. In summary, MPC was found to systematically outperform the best available reference control [19,10,13].
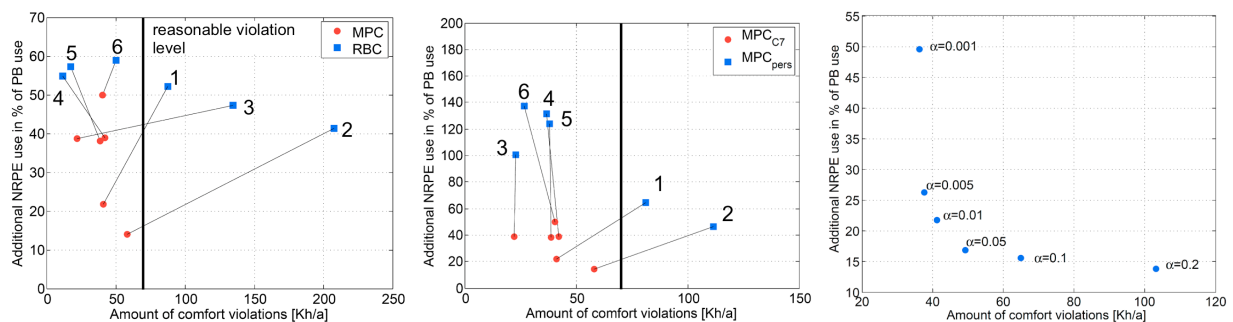

Figure 12: Assessment of MPC. Left: Comparison of MPC and RBC-5 ("best of RBC-1 and RBC-4") performance, numbers denote building zone case. Middle: Comparison of MPC performance when using persistence weather predictions versus weather predictions from the MeteoSwiss COSMO-7 operational weather forecast model. Right: Tradeoff curve: Performance of MPC for different probability levels of constraint violation α. From [13].

Figure 12 (middle panel) illustrates for the same six cases as for the left panel the sensitivity of the MPC procedure to the qualtiy of the weather forecast. Compared were the use of COSMO-7 predictions vs. predictions obtained by a simple persistence forecast (continuous recycling of the weather data from the last 24h). It can be seen that with the persistence forecast the control performance tended to deteriorate in terms of both, energy usage and violations. This result underlines the importance of sufficiently accurate weather forecasts as an input to MPC.

Figure 12 (right panel) shows for one selected building zone case the tradeoff curve between NRPE usage and thermal comfort violations as obtained by changing the probability level of comfort violations α (see Section 2.2.5.2). The possibility to tune the behavior of a complex IRA controller in such a simple and straight-forward manner tuning presents a unique property of the developed MPC solution.
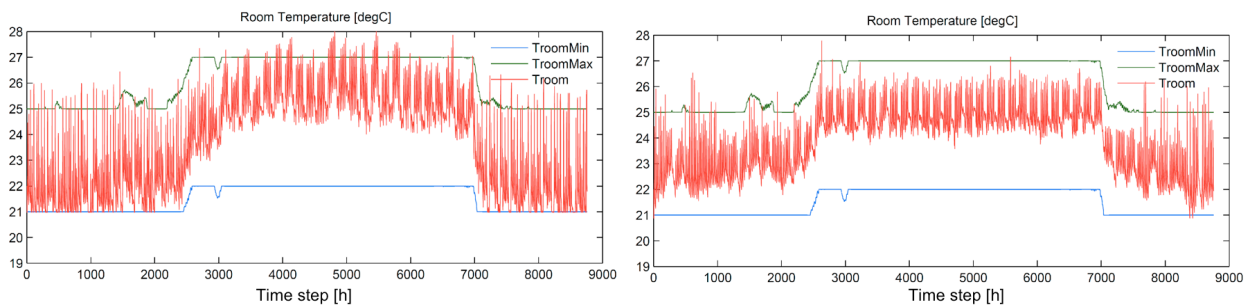
Figure 13: Simulated yearly room temperature profiles for the year 2007 in Marseille. Results refer to a building zone of heavy construction type with "Swiss average" thermal insulation level, a south orientated façade, and a window area fraction of 30%. Building system variant S2. Left: RBC-4; Right: MPC. The thermal comfort range is a function of the 24h running mean of the outside air temperature. From [13].

Figure 13 gives an example of the simulated room temperatures under RBC-4 and MPC. It can be seen that MPC showed smaller and less frequent thermal comfort violations than RBC-4. Furthermore, the diurnal temperature variations were much smaller with MPC, suggesting an increase in occupant comfort. At the same time the annual total NRPE usage by MPC was 6% below that of RBC-4.

Further investiogations (not shown) suggested that the MPC procedure is robust to imperfect knowledge of the model parameters [19,13].

2.2.6.3 Peak Electricity Demand

Peak electricity demand is normally considered for an entire building but such values were not readily available from our simulations. We therefore investigated but the electricity demand of individual building zones.

As a basis for the peak demand analyses hourly mean electric power demand (EPD) values were estimated from the hourly total delivered energy to the building system. The power demand by the office equipment was also included in the calculation.

Figure 14 compares the EPD distributions obtained from the PB and RBC-3 simulations of three selected building zone cases. It can be seen that the PB yielded significantly smaller (left), similar (middle), or significantly higher (right, "Case 13") peak EPD values, respectively, than RBC-3. The highest EPD values in "Case 13" in the PB simulations were found to occur during wintertime.

Figure 15 provides selected simulation results from "Case 13" for a typical winter episode: during the January 9th–11th period cool outdoor air temperatures coincided with almost no solar gains (top panel) and during these days the daytime room temperatures simulated by PB and RBC-3 showed strong differences (second panel). At the same time the PB simulation yielde consistently higher daytime and lower nighttime EPD than the RBC-3 simulation (third panel) . The reason related to the very different operation of heating by means of mechanical ventilation in the two simulations (bottom panel).
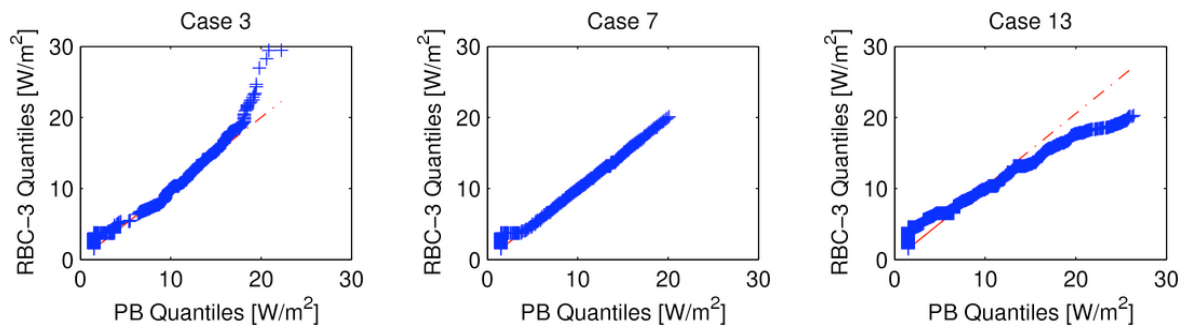
Figure 14: Quantile-quantile plots of hourly mean total electric power demand for three selected building zone cases. PB: electric power demand values from the whole-year Performance Bound simulation; RBC-3: electric power demand values from corresponding simulation using the RBC-3 control strategy. Sample size n = 8759. After [18].

Apparently, the energy-optimal solution by the PB consisted in pre-heating the room during daytime (with the aid of internal gains) whereas the RBC-3 controller minimized daytime heating at the cost of having to use more heating power during night-time and in the early morning hours of the next day. Note that the average power consumption over the entire week was lower in the PB (8.9 W/m^2) as compared to the RBC-3 simulation (9.6 W/m^2).
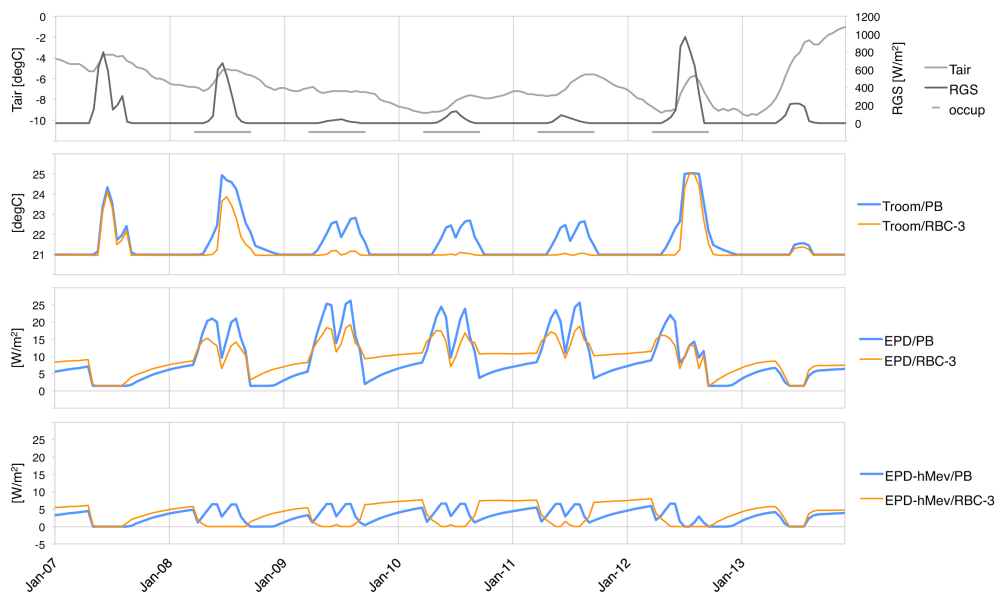

Figure 15: Comparison of hourly simulation results for the second week of January 2003 in Zurich. Results refer to a building zone of heavy construction type with "Swiss average" thermal insulation level, a south orientated façade, and a window area fraction of 30%. Building system variant S3. PB: Performance Bound simulation; RBC-3: simulation using rule-based control RBC-3. Tair: outdoor air temperature; RGS: global radiation component on a south-facing vertical surface; occup: occupancy status (gray = office working hours); Troom: room temperature; EPD: hourly mean total electric power demand; EPD-hMev: electric power demand for heating by mechanical ventilation. From [18].
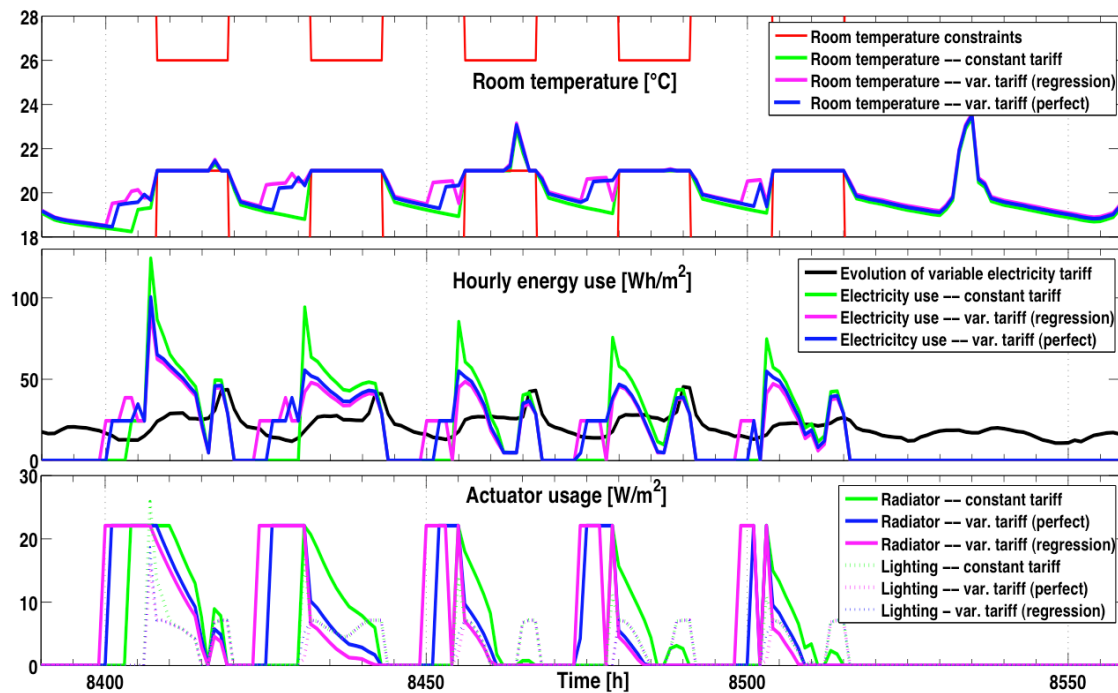
Figure 16: Reduction of peak electricity demand by shifting radiator usage during wintertime (Performance Bound calculations). Radiator heat is assumed to be delivered by an earth coupled heat pump. Results are shown for the third week of December 2007 in Zurich and refer to a building zone of heavy construction type with "Swiss average" thermal insulation level, a south orientated façade, and a window area fraction of 30%. Building system variant S1. From [20].

These findings showed that minimization of both, energy usage and peak electricity demand can present conflicting objectives. With MPC the degree to which one objective is pursued at the expense of the other can however be managed in a quite straight-forward manner by appropriately extending the formulation of the MPC task. Two possible solutions were considered, as described below.

The first solution consisted in prescribing a time-varying, hourly electricity tariff for end-consumers that is incorporated into the MPC cost function. The tariff can be constructed such that it truly reflects marginal costs of electricity provision based on spot market prices, and electricity transmission and distribution grid loading, based on actual grid measurements [20].

Figure 16 illustrates for a winter episode how the use of a variable tariff (black line in the middle panel) induces a shift in radiator usage (bottom panel) that in turn leads to a significant reduction in peak demand (green vs. other colored lines in middle panel). This is because the PB controller pre-heats the office room during the early morning hours (top and bottom panels), when electricity prices are typically lowest.

Using a constant tariff as the baseline the comparison for the entire year 2007 yielded a reduction of the highest load event during the year by 15%–20%, a decrease of average daily peak demand by ca 2%, practically no change in total electricity consumption, and an increase in total electricity costs by ca 15%. The reason for the latter result was that part of the office room's consumption (such as lighting)

can not be shifted and that the variable tariff was much higher than the constant tariff during daytime. This calls for careful tuning of variable tariffs such that an economic incentive to use load shifting is maintained, yet consumers do not have to pay excessive prices when shifting is not possible [20].

The second investigated solution for limiting the peak electricity demand was to introduce EPD as a new variable and to impose in the MPC task a constraint on its maximum value.
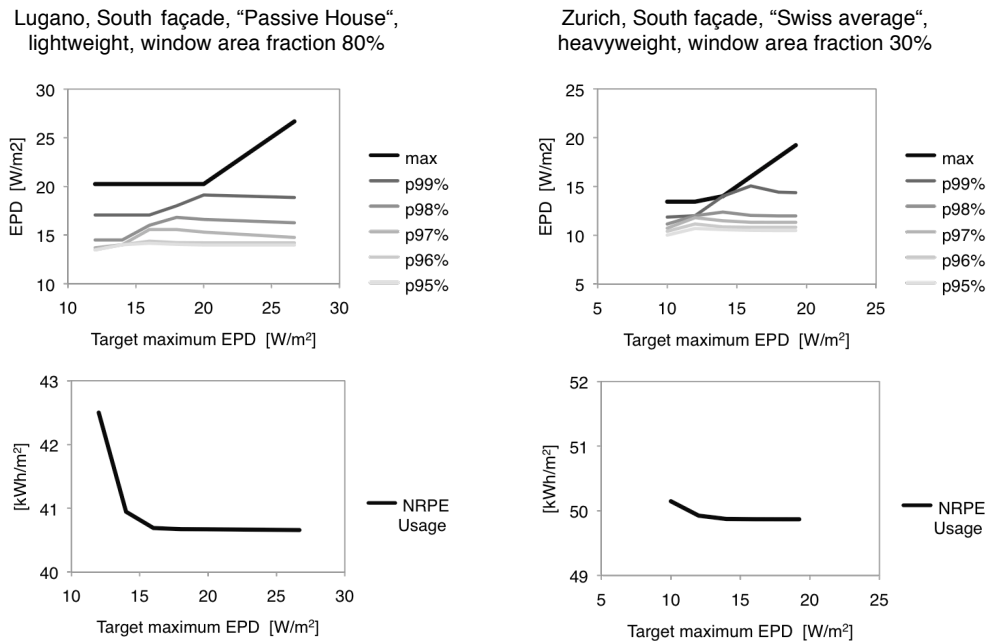

Figure 17: Constraining peak values of hourly mean total electric power demand (EPD) with the aid of MPC (Performance Bound calculations). Top: EPD statistics as a function of specified target maximum EPD for MPC. Shown are the simulated maximum (max) value and the 99th...95th percentiles of all hourly values within a year. Bottom: annual total Non-Renewable Primary Energy (NRPE) usage as a function of specified target maximum EPD. Building system variant S5.

Figure 17 illustrates the obtained results for two selected building zone cases. Shown are selected annual EPD statistics (top panels) and annual total NRPE usage (bottom panels) as a function of the target maximum EPD value that was specified for MPC. From the top panels can be seen that lowering of the target value consistently reduced the annual maximum EPD down to a certain point from where on the curve leveled off. The level was given by the maximum demand for lighting and equipment that by design was always met in the simulations. The NRPE usage (bottom panels) was only marginally affected by the tightening of the EPD constraint.

Note that in contrast to variable electricity pricing EPD constraints can be specified directly by the building owner, thus giving him additional degrees of freedom for negotiating customized contracts with electricity providers. In particular, MPC can be easily adjusted to allow for time-dependent constraints. For instance, the target maximum EPD can be prescribed to vary with time of the day.

2.2.7 Software Tools

The various models, data sets and control algorithms that were developed during the project were integrated into a new, specialized modeling and simulation environment, the Building Automation and Control Laboratory (BACLab) software.

BACLab was specified, designed, implemented, documented and tested based on approved software engineering principles in order to ensure its correctness, portability, reusability, extendibility and maintainability. It provides the following functionalities: OptiControl Weather and occupancy DataBase (OCWDB); Buildings and building Systems DataBase (BuSyDB, accessed through the so-called BuSy server); structured definition of simulation experiments; management of model and simulation parameters; simulation engine; graphical and statistical post-processing.
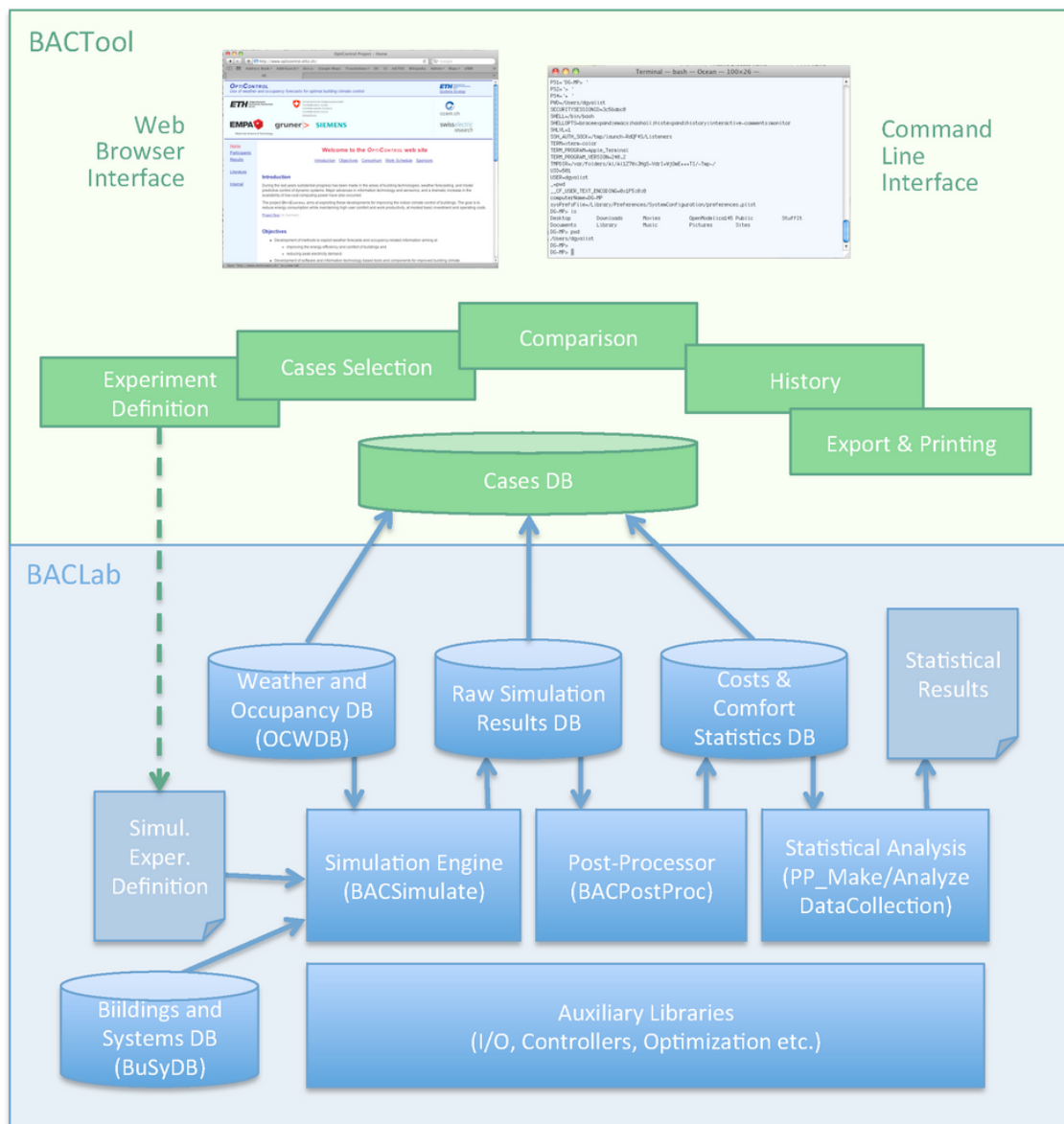

Figure 18: BACTool/BACLab software architecture.

Extensive simulation work with BACLab resulted into a unique database containing results from several 10'000 whole-year, hourly time-step simulation simulations (see Section 2.2.6). Additional cases are being continuously added as a result of ongoing research and development work.

The BACLab software provides a powerful modelling and simulation environment that can be easily adapted to perform a variety of analyses and investigate new building set-ups. However, its usage requires computer and programming skills that exceed the capabilities of most users.

In order to make the the BACLab results and functionality accessible to non-specialists an extra software layer was designed. The new software was named Building Automation and Control Tool (BACTool). It features two user interfaces, a graphical web-browser based interface for normal users, and a command-line user interface for expert users who may use the BACTool functionality for research and development work.

Figure 18 summarizes the overall BACTool/BACLab software architecture, and Figure 19 shows two selected pages from the BACTool web interface.

The official release of BACTool version 1.0 is planned for September 2010. This version will support the performance comparison of control strategies for the already existing, pre-computed cases by BACLab. The software was designed such that in further versions users could be granted the possibility to trigger customized simulations and comparisons for arbitrary building cases.

Numerous software tools for assessing the energy performance of buildings exist already. However, to our knowledge Building Automation and Control issues have received only limited attention so far. In particular we are not aware of any general tools that support Performance Bound calculations and predictive control. The BACTool/BACLab software presents a contribution to filling this gap.
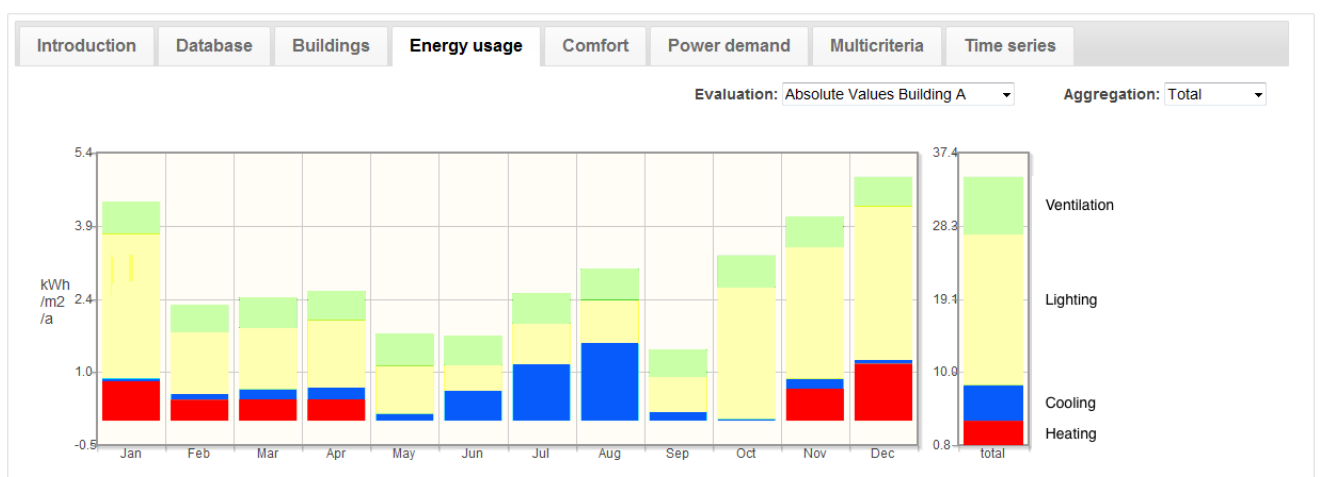
Figure 19: Sample screen dumps from the BACTool web interface. Top: Selection of building cases for comparison. Bottom: Display of results on energy usage.

2.2.8 Demonstrator

After the second year of the OptiControl project the decision was taken to transfer the demonstration part of the project to a separate follow-up project. The reason was that both, controller development, as well as the identification of an appropriate demonstrator building turned out to be much more time consuming than initially planned.

In the search for an appropriate object various meetings and partially lengthy discussions took place with facility managers or building owners from the ETH Zurich, the city of Zurich, the Technopark Linz in Austria, and the companies Axpo, Novartis and Actelion.

Two candidate office buildings were selected and analyzed in more detail: The SANAA building (Novartis, Novartis campus, Basle) and the building Actelion C1 (Actelion, Allschwil, Basle). Visits to both buildings were done, their suitability as demonstrator objects was discussed with the Siemens BT regional company Switzerland, and their current building automation programs were examined.

Figure 20: The OptiControl demonstrator building: Office building "C1" of Actelion Pharmaceuticals Ltd., located in Allschwil close to Basle, Switzerland.

After a thorough evaluation the Actelion C1 building (Figure 20) was selected as a demonstrator. This was due to the following reasons: the building is representative for many modern office buildings in Switzerland; it is functioning well, i.e. there is a valid base line for the assessment of energy savings and comfort improvements; its technical systems match well the systems studied so far in the OptiControl project; a building automation system is available; the owner and operator fully support the implementation and testing of novel control strategies; and last but not least, preliminary simulation studies (see below) showed a substantial potential for energy savings thanks to predictive control.

Various preparatory works were undertaken for the follow-up project: the setting up of the project team, the planning of the needed modifications in the building and its

automation system, the planning of the study approach and experiments, and the submission of a follow-up project to swiss*electric* research.

Preparations also included careful initial modelling and simulation studies. In this context the currently used control strategy was analyzed and its relevant parts were implemented within the BACLab software (rule-based control strategy "RBC-A").

Figure 21 reports some results from the potential assessment for the Actelion building. It can be seen that the heating with the Thermally Activated Building Systems (TABS) offers the highest energy saving potential. The total savings potentials for the RBC-1 and RBC-A strategies amounted to 24% and 22% , respectively. Even larger numbers were obtained when the corner zones were included in the assessment [see 4].
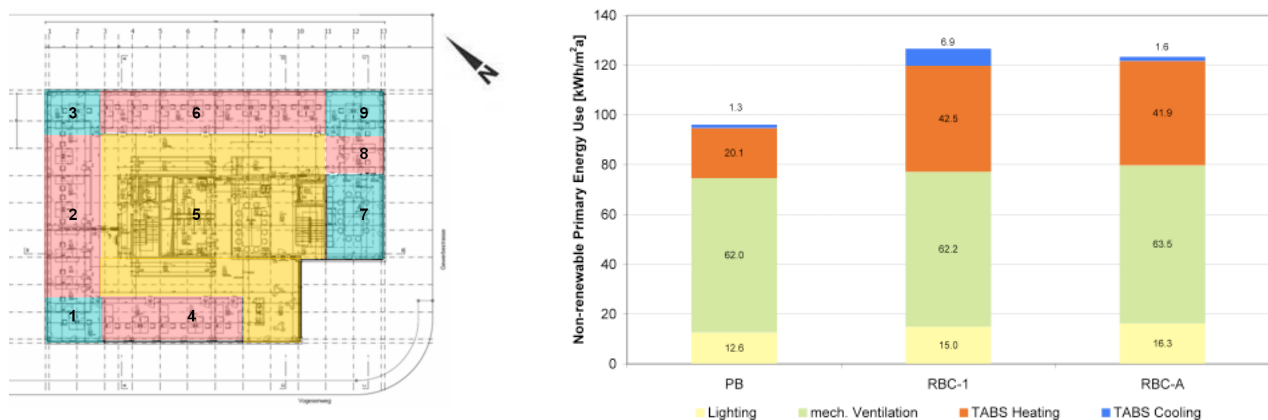

Figure 21: Potential assessment for the OptiControl demonstrator building.
Left: Layout of a representative upper floor with the used zone definitions.
Right: Simulated annual Non-Renewable Primary Energy (NRPE) usage by technical subsystem, building system variant S5. PB: Performance Bound; RBC-1: reference control; RBC-A: actually implemented control. Shown are the arithmetic mean values for zones no. 2, 4, 6, and 8. From [4].

2.2.9 Third Project Year

The project goals for the last project year were: (1) the finalization of rule-based predictive control algorithms for Integrated Room Automation (IRA); (2) further development of Model Predictive Control (MPC) algorithms for IRA towards their finalization at prototype level; (3) further simulation-based assessments on the potential and benefit/cost of predictive control; (4) preparation of the demonstration follow-up project; (5) potential assessment for a second predictive control application next to IRA.

During the last project year it became obvious that preparation of the follow-up project required much more effort than expected. Therefore goal no. 5 was not pursued further, i.e. all work during the 3rd project year focused on the IRA application.

Further the research plan for the 3rd project year was modified as follows:

Firstly, development of a method for coping with occupancy/internal heat gains in the MPC controllers (milestone M4, see below) was postponed to the follow-up project. Instead, a detailed investigation was undertaken to identify building cases and situations where the availability of occupancy predictions is beneficial. We preferred this work because of its practical importance and because the topic has hardly been researched so far.

Secondly, the analyses on the benefit/cost of different weather forecasting methods and the relative importance of different weather parameters (milestone M6) received by all research groups somewhat less attention than initially planned. The freed workforce was instead invested in the preparation of radiation algorithms and additional weather data [8] that turned out to be essential for the follow-up project.

Milestone / Deliverable	Description	Target month	Status
M 1 + D 5	Technical Report on first two project years finalized.	**5** (Dec 09)	(achieved) *
M 2	Candidate demonstrator building No. 1 analysed.	**5** (Dec 09)	achieved
M 3	Improved correction scheme for weather predictions at building site developed.	**6** (Jan 10)	achieved
M 4	Method for coping with occupancy/internal heat gains in IRA developed.	**6** (Jan 10)	not achieved
M 5 + D 9	First simulation models for candidate demonstrator building No. 1 implemented, available measurements analyzed, first comparisons available.	**8** (Mar 10)	achieved
M 6	Analyses on benefit/cost of different weather forecasting methods and the relative importance of different weather parameters completed.	**10** (May 10)	(achieved) *
M 7	IRA control approaches assessed according to multiple criteria (including peak electricity demand).	**10** (May 10)	achieved
M 8 + D 10	Demonstrator object(s) selected, agreement(s) signed, communication concept(s) established.	**10** (May 10)	(achieved) *
M 9 + D 11	Proposal for follow-up project submitted.	**10** (May 10)	achieved
M 10	Analyses on theoretical and realistic savings potentials of predictive control completed.	**12** (Jul 10)	achieved
M 11 + D 6	Predictive rule-based control algorithms for IRA finalized for use in DESIGO system.	**12** (Jul 10)	(achieved) *
M 12 + D 7	Model Predictive Control algorithms for IRA finalized for use in prototype system.	**12** (Jul 10)	(achieved) *
M 13 + D 8	Synthesis accomplished, final report published.	**12** (Jul 10)	(achieved) *

*Table 1: Overview of project Milestones and Deliverables for the 3rd project year. Reproduced from «Zweite Änderung der "Vereinbarung vom 22. Aug. 2007" … betreffend das Forschungsprojekt "Use of Weather and Occupancy Forecasts for Optimal Building Climate Control (OptiControl)"» from 27. November 2009 (Article 3.4). * : work in progress at the time of writing of this report (begin of June 2010).*

Table 1 summarizes the project's milestones and deliverables for the 3rd year. It can be seen that all milestones (except for milestone M4, see explanation above) were achieved or are about to be achieved at the time of writing of this report (June 2010).

2.3 Assessment of the Results

The OptiControl project has successfully answered many important questions related to the potential and feasibility of predictive building control. From a methodical point of view the project has pioneered research at the interface of buildings, applied meteorology, modeling/simulation, and control. The obtained results have only been possible thanks to the excellent collaboration between all project participants and the unique combination of expertise in the project team.

The project combined elements of basic engineering research, development, and technology deployment. Research always involves elements of surprise, and the scientific investigation of the predictive control of modern, automated building systems revealed to be much more challenging than initially expected. The main reasons related to the very high complexity of the systems considered and the large number of variants and choices involved.

It has been a major success of the project of having found ways to deal with this complexity. The methods, data bases and software developed during the project enabled important insights into the relevant mechanisms and problem areas and successfully assisted the development of new control solutions.

The main outcomes of the project have been improvements in rule-based control, the development of novel Model Predictive Control solutions tailored to buildings, and new methods for delivering optimal weather forecasts at the building site. All these works are paving the way towards the development of a new generation of controllers offering an unprecedented performance, robustness and flexibility.

Three goals of the project were not reached as initially planned: firstly, the practical demonstration of the developed control solutions did not prove feasible within the time frame of the project; secondly, as a consequence, the cost aspect of the new technologies could not be assessed; and thirdly, the issue of occupancy/internal heat gains predictions was treated only to a limited extent.

Failure to reach these goals was however not due to any basic, unsolvable problems, but rather it resulted from a somewhat slower progress than initially expected. We are therefore confident that all open issues can be successfully tackled in the planned follow-up project.

2.4 Communication

2.4.1 Peer Reviewed Publications

Gwerder, M., Lehmann, B., Tödtli, J., Dorer, V. & Renggli, F. (2008). **Control of thermally-activated building systems (TABS)**. Applied Energy, 85(7): 565-581.
doi: 10.1016/j.apenergy.2007.08.001

Gwerder, M., Tödtli, J., Lehmann, B., Dorer, V., Güntensperger, W. & Renggli, F. (2009). **Control of thermally activated building systems (TABS) in intermittent operation with pulse width modulation**. Applied Energy, 86(9): 1606-1616.

[15] Oldewurtel, F., Jones, C.N. & Morari, M. (2008). **A tractable approximation of chance constrained stochastic MPC based on affine disturbance feedback**. In: Proc. 47th IEEE Conference on Decision and Control, December 9-11, 2008, Cancun, Mexico (CDC08).

[10] Oldewurtel, F., Parisio, A., Jones, C.N., Morari, M., Gyalistras, D., Gwerder, M., Stauch, V., Lehmann, B. & Wirth, K. (2010). **Energy efficient building climate control using stochastic Model Predictive Control and weather predictions**. Paper presented at the 2010 American Control Conference (ACC2010), 30 June - 2 July 2010, Baltimore, Maryland, USA.

2.4.2 In Proceedings

Gähler, C., Gwerder, M., Lamon, R. & Tödtli, J. (2007). **Optimal control of cogeneration building energy systems**. In: Seppänen, O. & Säteri, J. (eds): Proceedings of REHVA World Congress Clima 2007 - WellBeing Indoors, FINVAC ry, Helsinki, Finland, Session B05, paper no. 1148.

Gwerder, M., Tödtli, J., Lehmann, B., Renggli, F. & Dorer, V. (2007). **Control of Thermally Activated Building Systems**. In: Seppänen, O. & Säteri, J. (eds): Proceedings of REHVA World Congress Clima 2007 - WellBeing Indoors, FINVAC ry, Helsinki, Finland, Session D04, paper no. 1092.

[12] Gwerder, M., Gyalistras, D., Oldewurtel, F., Lehmann, B., Wirth, K., Stauch, V. & Tödtli, J. (2010). **Potential assessment of rule-based control for Integrated Room Automation**. Paper presented at the 10th REHVA World Congress Clima 2010, 9-12 May 2010, Antalya, Turkey, 8pp.

Gwerder, M., Gyalistras, D., Oldewurtel, F., Lehmann, B., Wirth, K., Stauch, V. & Sagerschnig, C. (2010). **Prädiktive Gebäuderegelung mithilfe von Wetter- und Anwesenheitsvorhersagen: Resultate des Projekts OptiControl**. In: Proc. 16. brenet Status-Seminar Energie- und Umweltforschung im Bauwesen, "Forschen und Bauen im Kontext von Energie und Umwelt", 2-3 September 2010, ETH Zurich, Switzerland.

Gyalistras, D., & Fischlin, A., Morari, M., Jones, C.N., Oldewurtel, F., Parisio. A., Frank, T., Carl, S., Dorer, V., Lehmann, B., Wirth, K., Steiner, P., Schubiger, F., Stauch, V., Tödtli, J., Gähler, C. & Gwerder, M. (2009). **Saving energy by improved building control**. In: Abstracts Book of the Annual Meeting of The Alliance for Global Sustainability: Urban Futures: the Challenge of Sustainability, 26-29 January 2009, ETH Zurich, Switzerland, p36.

[17] Gyalistras, D., Gwerder, M., Oldewurtel, F., Jones, C.N., Morari, M., Lehmann, B., Wirth, K., & Stauch, V. (2010). **Analysis of energy savings potentials for Integrated Room Automation**. Paper presented at the 10th REHVA World Congress Clima 2010, 9-12 May 2010, Antalya, Turkey, 8pp.

[13] Oldewurtel, F., Gyalistras, D., Gwerder, M., Jones, C.N., Parisio, A., Stauch, V., Lehmann, B. & Morari, M. (2010). **Increasing energy efficiency in building climate control using weather forecasts and Model Predictive Control**. Paper presented at the 10th REHVA World Congress Clima 2010, 9-12 May 2010, Antalya, Turkey, 8pp.

[20] Oldewurtel, F., Ulbig, A., Parisio, A., Andersson, G. & Morari, M. (2010). **Reducing peak electricity demand in building climate control using real-time pricing and Model Predictive Control**. Proc. 49th IEEE Conference on Decision and Control (CDC), December 15-17, 2010, Atlanta, USA.

Renggli, F., Gwerder, M., Tödtli, J., Lehmann, B., & Dorer,V. (2007). **Effect of the hydraulic piping topology on energy demand and comfort in buildings with TABS**. In: Seppänen, O. & Säteri, J7. (eds): Proceedings of REHVA World Congress Clima 2007 – WellBeing Indoors, FINVAC ry, Helsinki, Finland, Session D05, paper no. 1140.

Stauch, V., Gwerder, M., Gyalistras, D. & Schubiger, F. (2008). **Statistical adaptation of mesoscale numerical weather forecasts for designing predictive control of indoor building climates**. In: Proc. 8th Annual Meeting of the EMS and 7th European Conference on Applied Climatology, 29 September – 3 October 2008, Amsterdam, The Netherlands, Vol. 5, EMS2008-A-00545.

Stauch, V., Gwerder, M., Gyalistras, D., Oldewurtel, F., Schubiger, F., & Steiner, P. (2010). **Tailored high-resolution numerical weather forecasts for energy efficient predictive building control**. In: Proc. 10th Annual Meeting of the EMS and 8th European Conference on Applied Climatology, 13-17 September 2010, Zurich, Switzerland. EMS Annual Meeting Abstracts Vol. 7, EMS2010-228.

Tödtli, J., Gwerder, M., Lehmann, B., Renggli, F. & Dorer,V. (2007). **Integrated design of Thermally Activated Building Systems and of their control**. In: Seppänen, O. & Säteri, J. (eds): Proceedings of REHVA World Congress Clima 2007 – WellBeing Indoors, FINVAC ry, Helsinki, Finland, Session D04, paper no. 1093.

2.4.3 Theses

Baltensperger, T. (2009). **Embedding predictive control in hierarchical Integrated Room Automation systems (Part ½)**. Semester Thesis, Siemens Building Technologies, Zug and Automatic Control Laboratory (IFA), ETH Zurich, Switzerland, 48pp.

[21] Parisio, A. (2009). **Handling uncertainty with application to indoor climate control and resource allocation planning**. PhD Thesis, University of Sannio, Benevento, Italy, 2009, 135 pp.

Ullmann, F. (2009). **Embedding predictive control in hierarchical Integrated Room Automation systems (Part 2/2)**. Semester Thesis, Siemens Building Technologies, Zug and Automatic Control Laboratory (IFA), ETH Zurich, Switzerland, 36pp.

2.4.4 Reports

Dorer, V. & Wirth (2010). **Appendix C – Performance assessment: methodology and factors**. In: [1].

Gwerder, M. (2007). **Summary of WS 09: Enhanced Use of Weather Data and Forecasts to Improve the Energy Efficiency and Indoor Environment in Buildings (13th June 2007).** Workshop summary, REHVA World Congress Clima 2007 – WellBeing Indoors, 10-14 June 2007, Helsinki, Finland.

[11] Gwerder, M., Tödtli, J. & Gyalistras, D. (2010). **Rule-based control strategies**. In: [1], pp 29-42.

Gwerder, M., Ullmann, F. & Illi, B. (2010). **Contributions by Siemens for the 3rd year of the project OptiControl**. Technical Report, Siemens Switzerland Ltd., Building Technologies Division, Zug, Switzerland.

Gyalistras, D. & Gwerder, M. (2010). **Project status**. In: [1], pp 153-158.

[1] Gyalistras, D. & Gwerder, M. (eds.) (2010). **Use of weather and occupancy forecasts for optimal building climate control (OptiControl): Two Years Progress Report**. Terrestrial Systems Ecology ETH Zurich, Switzerland and Building Technologies Division, Siemens Switzerland Ltd., Zug, Switzerland, 158 pp, Appendices. ISBN 978-3-909386-37-6.

[2] Gyalistras, D., Gwerder, M. & Tödtli, J. (2010). **Introduction.** In: [1], pp 5-14.

[16] Gyalistras, D., Lehmann, B., Wirth, K., Gwerder, M., Oldewurtel, F. & Stauch, V. (2010). **Performance bounds and potential assessment**. In: [1], pp 79–106.

[18] Gyalistras, D., Wirth, K. & Lehmann, B. (2010). **Analysis of savings potentials and peak electricity demand**. In: [1], pp 107–134.

[3] Lehmann, B., Wirth, K., Dorer, V., Frank, Th. & Gwerder, M. (2010). **Control problem and experimental set-up**. In: [1], pp 15–28.

[5] Lehmann, B., Wirth, K., Carl, S., Dorer, V., Frank, Th. & Gwerder, M. (2010). **Modeling of buildings and building systems**. In: [1], pp 59–66.

[14] Oldewurtel, F., Jones, C.N., Parisio, A. & Morari, M. 2010. **Model predictive control strategies**. In: [1], pp 43–58.

[19] Oldewurtel, F., Gyalistras, D., Jones, C.N., Parisio, A. & Morari, M. (2010). **Analysis of Model Predictive Control strategies**. In: [1], pp 135–151.

[4] Sagerschnig, C., Gyalistras, D., Gwerder, M. & Seerig, A. (2010). **The OptiControl demonstrator building: Description, modeling and energy savings potential of predictive control**. Technical Report, Building Climate Control, Gruner AG, Basel, Switzerland.

Stauch, V. (2009). **Intelligente Gebäuderegelung mit Wetterprognosen**. In: Annual Report 2009, Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland, p29.

[8] Stauch, V., Hug, C., Schubiger, F. & Steiner, P. (2010). **Weather forecasts, observations and algorithms for building simulation and predictive control – Contributions by MeteoSwiss for the 3rd year of OptiControl**. Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland, 15 pp.

[9] Stauch, V., Schubiger, F. & Steiner, P. (2010). **Local weather forecasts and observations**. In: [1], pp 67–78.

[6] Wirth, K., Lehmann, B., Carl, S., Frank, Th. & Gwerder, M. (2010). **Appendix A – Building model description**. In [1].

[7] Wirth, K., Lehmann, B. & Carl, S. (2010). **Appendix B – Building model validation**. In [1].

2.4.5 Presentations

2007 and earlier

Gyalistras, D., Gwerder, M., Dorer, V., Frank, T., Gähler, C., Jones, C., Lehmann, B., Morari, M., Oldewurtel, F., Schubiger, F., Stauch, V., Steiner, P. & Tödtli, J. (2007). **OptiControl – Verwendung von Wetter- und Anwesenheits-Vorhersagen für die optimale Gebäudeklimaregelung**. Poster presentation, «swiss*electric* research award 2007», 4 September 2007, Technopark Zurich, Switzerland.

Rostalski, Ph. & Oldewurtel, F. (2006). **Wireless sensor-networks and HVAC Systems**. MICS Scientific Conference, 17-19 October 2006, Zurich, Switzerland.

Tödtli, J. (2007). **Aus der Forschung: Verwendung von Wettervorhersagen in der Ge-**
bäudeautomation. Referat am Fachpresseforum 2007 der Siemens Building Tech-
nologies, 16 October 2007, Lissabon.

Tödtli, J. & Gwerder, M. (2007). **The use of weather forecasts in building automation**
and control systems: How to use them? What is the benefit? REHVA World
Congress Clima 2007 – WellBeing Indoors, 10-14 June 2007, Helsinki, Finland,
Workshop No. 9, Enhanced use of weather data and forecasts to improve the energy
efficiency and indoor environment in buildings (13. Juni 2007).

2008

Gwerder, M. (2008). **Verwendung von Wettervorhersagen in der Gebäudeautomation.**
MeteoSchweiz COSMO-2 Kundenanlass, 12 June 2008, Zurich, Switzerland.

Morari, M. & Tödtli, J. (2008). **Weather forecasts enhance comfort and save energy**.
Smart Energy Strategies 2008 Conference, 8-10 September 2008, ETH Zurich, Swit-
zerland.

Oldewurtel, F., Jones, C.N. & Morari, M. (2008). **A tractable approximation of chance**
constrained stochastic MPC based on affine disturbance feedback. 47th IEEE
Conference on Decision and Control, 9-11 December 2008, Cancun, Mexico.

Stauch, V., Gwerder, M., Gyalistras, D., Lehmann, B., Morari, M. & Schubiger, F.
(2008). **Statistical adaptation of COSMO-7 predictions and their impact on pre-**
dictive control of indoor building climate. Poster presentation, 8th Annual Meet-
ing of the EMS and 7th European Conference on Applied Climatology, 29 September
– 3 October 2008, Amsterdam, The Netherlands.

Steiner, P., Stauch, V., Gwerder, M., Gyalistras, D., Lehmann, B., Morari, M. & Schubiger,
F. (2008). **Numerical weather prediction at MeteoSwiss – Statistical postproc-**
essing for building climate control. Poster presentation, 30th meeting of the Euro-
pean Working Group on Limited Area Modelling (EWGLAM) and 15th meeting of the
Short Range Numerical Weather Prediction network (SRNWP), 6-9 October 2008,
Madrid, Spain.

2009

Gähler, C. (2009). **Combined heat & power production: Micro-CHP with Stirling En-**
gine – Activities at Siemens Building Technologies. Smart and Efficient Energy
Council (SEEC'2009), 8-9 October 2009, Trento, Italy.

Gyalistras, D. (2009). **Use of MPC for Building Control**. Short Course on Model Predic-
tive Control, 24 February 2009, ETH Zurich, Switzerland.

Gyalistras, D. (2009). **Prädiktive Regelung von Gebäuden: Methoden, Werkzeuge und**
Fallstudie Integrierte Raumautomation. 26 October 2009, Hochschule Lu-
zern/Teilschule Technik und Architektur, Horw, Switzerland.

Gyalistras, D., & Fischlin, A., Morari, M., Jones, C.N., Oldewurtel, F., Parisio. A., Frank, T.,
Carl, S., Dorer, V., Lehmann, B., Wirth, K., Steiner, P., Schubiger, F., Stauch, V.,
Tödtli, J., Gähler, C. & Gwerder, M. (2009). **Saving energy by improved building**
control. Poster presentation, Annual Meeting of The Alliance for Global Sustainabil-
ity: Urban Futures: the Challenge of Sustainability, 26-29 January 2009, ETH Zurich,
Switzerland.

Gyalistras, D., & Fischlin, A., Morari, M., Jones, C.N., Oldewurtel, F., Parisio. A., Frank, T.,
Carl, S., Dorer, V., Lehmann, B., Wirth, K., Steiner, P., Schubiger, F., Stauch, V.,
Tödtli, J., Gähler, C. & Gwerder, M. (2009). **Use of Weather and Occupancy Fore-**
casts for Optimal Building Climate Control (OptiControl). Project Presentation,
version 15-Jan-2009.

Schubiger, F. (2009). **Das numerische Wettervorhersagemodell COSMO von Me-**
teoSchweiz und seine Anwendung für die Gebäudeklimaregelung. 5. Plan-
erseminar Hochschule Luzern, 24 March 2009, Luzern, Switzerland.

2010

Gwerder, M., Gyalistras, D., Oldewurtel, F., Lehmann, B., Wirth, K., Stauch, V. & Tödtli, J. (2010). **Potential assessment of rule-based control for Integrated Room Automation**. 10th REHVA World Congress Clima 2010, 9-12 May 2010, Antalya, Turkey.

Gwerder, M., Gyalistras, D., Oldewurtel, F., Lehmann, B., Wirth, K., Stauch, V. & Sagerschnig, C. (2010). **Prädiktive Gebäuderegelung mithilfe von Wetter- und Anwesenheitsvorhersagen: Resultate des Projekts OptiControl**. 16. brenet Status-Seminar Energie- und Umweltforschung im Bauwesen, "Forschen und Bauen im Kontext von Energie und Umwelt", 2-3 September 2010, ETH Zurich, Switzerland.

Gyalistras, D. (2010). **Der energetische "Performance Bound" – eine rechnerische Messlatte für die Gebäuderegelung**. 6. Planerseminar Hochschule Luzern - Technik & Architektur, 23 March 2010, Horw, Switzerland.

Gyalistras, D. (2010). **Use of MPC for building control**. Short Course on Model Predictive Control, 4 March 2010, ETH Zurich, Switzerland.

Gyalistras, D., Gwerder, M., Oldewurtel, F., Jones, C.N., Morari, M., Lehmann, B., Wirth, K., & Stauch, V. (2010). **Analysis of energy savings potentials for Integrated Room Automation**. 10th REHVA World Congress Clima 2010, 9-12 May 2010, Antalya, Turke.

Morari, M., Chung, K., Gyalistras, D., Jones, C.N., Oldewurtel, F., Parisio, A., Rostalski, P. & Ullmann, F. (2009). **Energy efficient building climate control**. Smart and Efficient Energy Council (SEEC'2009), 8-9 October 2009, Trento, Italy.

Oldewurtel, F., Parisio, A., Jones, C.N., Morari, M., Gyalistras, D., Gwerder, M., Stauch, V., Lehmann, B. & Wirth, K. (2010). **Energy efficient building climate control using stochastic Model Predictive Control and weather predictions**. American Control Conference (ACC2010), 30 June - 2 July 2010, Baltimore, Maryland, USA.

Oldewurtel, F., Gyalistras, D., Gwerder, M., Jones, C.N., Parisio, A., Stauch, V., Lehmann, B. & Morari, M. (2010). **Increasing energy efficiency in building climate control using weather forecasts and Model Predictive Control**. 10th REHVA World Congress Clima 2010, 9-12 May 2010, Antalya, Turkey.

Stauch, V. (2010). **Tailored high-resolution numerical weather forecasts for energy efficient predictive building control**. 10th Annual Meeting of the EMS and 8th European Conference on Applied Climatology, 13-17 September 2010, Zurich, Switzerland.

2.4.6 Press

Boller, U. (2007). **Wettervorhersagen bringen mehr Komfort und sparen Energie.** Pressemitteilung Siemens Building Technologies Deutschland, Fachpresseforum 2007, Lissabon, 16. Oktober 2007.

Gyalistras, D., Morari, M. & Fischlin, A. (2009). **OptiControl – Integrierte Raumautomation für Bürogebäude**. ESC Newsletter, April 2009, p.3.

Heinzelmann, E. (2010). **Weather forecast auch für Gebäudeleitsysteme**. Schweizer Energiefachbuch 2010, 164-166.

Niedermann, C. (2008). **Wetterfee steuert Gebäudeautomation.** cash Innovation, 12. Dec. 2008, Ringier AG, Zofingen, p24.

Würsten, F. (2009). **OptiControl – Integrated Room Automation for Office Buildings**. ESC-NEWS, Newsletter of the Energy Science Center at ETH Zurich, No. 4, April 2009, p. 3..

2.4.7 Patents

- Nutzung von Bedarfssignalen, Messdaten und Wetterprognosen in der Gebäude-automation zur Regelung und Steuerung von Gewerken welche mit "freien" Energien assoziiert sind. Patentanmeldung vom 15.12.2009. Erfinder: Jürg Tödtli, Markus Gwerder, Siemens Switzerland Ltd., Building Technologies Division, Zug, Switzerland.

2.5 Appendix

None.

2.6 Financial report

See separate document.