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.