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Abstract

In the Swiss research project OptiControl (www.opticontrol.ethz.ch), new predictive building control strategies are developed and applied to a fully occupied, well instrumented demonstrator building. The demonstrator building is a typical Swiss office building located in Allschwil close to Basel. The building has 5 levels and a conditioned floor area of ca. 6'000 m^2. Heating and cooling are mainly done with the aid of thermally activated building systems (TABS). Hygienic air change is ensured by an air handling unit including energy recovery.

This work presents our experience with the application of integrated predictive Rule-Based Control (RBC) to the demonstrator building. In a companion paper (Model Predictive Control of a Swiss Office Building), the results of the implementation of novel model predictive control on the demonstrator building are presented.

The newly developed control strategies integrate heating, cooling, ventilation and blind control. This integrated approach differs strongly from most conventional control solutions, where different control parts of the plants are but only loosely coordinated, if at all. Comparison of measurements and simulations for our demonstrator building showed that the newly developed control strategies are superior to the reference (original) control strategy in terms of control performance and operation. The benefit of using weather forecasts was found to be due to improved blind operation as well as due to anticipating future weather with slow heating and cooling systems. Moreover, it was found that the newly developed RBC strategies can in particular reduce tuning effort significantly.

Keywords – building automation; predictive control; integrated control; demonstration

1. Introduction

The research project OptiControl (www.opticontrol.ethz.ch) deals with the use of weather and occupancy forecast for optimal building control. During the first project phase (2007-2010), computer simulations were used to develop new control strategies and to identify their potential mainly for the control application Integrated Room Automation (see e.g. [1-4]). In the second phase (2011-2013), some of the newly developed control strategies were applied to a fully occupied, well instrumented demonstrator building.

This work presents our experience with the application of integrated predictive Rule-Based Control (RBC) to the demonstrator building. In a companion paper (Model Predictive Control of a Swiss Office Building [5]), results of the implementation of novel model predictive control on the demonstrator building are presented. (Non-predictive) RBC strategies still are the standard approach in today's building automation. The newly developed RBC strategies integrate heating, cooling, ventilation and blind control. This differs strongly from most conventional control solutions, where different parts of the plants are but only loosely coordinated, if at all.

In [6,7], the benefit of integrated control for heating, cooling, ventilation, blinds and lights mainly regarding energy consumption has been investigated. There, energy savings potentials were either determined for example buildings or estimated for typical buildings, locations as well as HVAC, blinds and lighting systems. These publications state that there is a significant potential for integrated control regarding energy efficiency – at least for selected cases. The European standard [8] as well as [9] give directives/guidelines regarding the impact of building automation on energy efficiency in buildings. Most publications on predictive building automation examine model predictive control strategies. Only few publications can be found on (predictive) rule-based control for integrated room automation, see e.g. [10], [11] (focusing on blind control) or [12] (focusing on light control).

2. The demonstrator Building

The demonstrator building is a typical Swiss office building located in Allschwil close to Basel, see Fig. 1. The building was built in 2007; it has 5 levels and a conditioned floor area of ca. 6'000 m^2. Heating and cooling are mainly done with the aid of concrete core conditioning, here called thermally activated building systems (TABS). Hygienic air change is ensured by an air handling unit including energy recovery. While heating is provided by gas boiler, cold generation for the offices is exclusively done using free cooling by a hybrid cooling tower and by an adiabatic air washer. Measured average heat consumption is 46 kWh/(m^2a); measured average electrical energy consumption is 83 kWh/(m^2a). These numbers include the whole building (including a restaurant on the ground floor), while the demonstration project's controller only controlled the 5 upper office floors.

Fig. 1 The demonstrator building (view from South).

Since the building's original control instrumentation was not sufficient for the project's purposes, substantial additional equipment – in particular sensors and meters (see Fig. 2) – had to be installed (i) to support the implementation of different high-level control strategies; (ii) to allow for a conclusive evaluation of the control experiments; (iii) to support the validation of detailed building models. Over 130 wireless sensors using EnOcean technology were installed in various parts of the building; additional control hardware, e.g. for blinds control; an external database for monitoring of the building's operation; and an industry PC connected to the building's automation system that served as an experimental control development environment. After installation, a thorough monitoring led to correction of several errors of different nature (building automation software, installation, HVAC design).

Fig. 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 for illuminance (bottom right, within the media channel).

3. Methods

We compare the new RBC variants with the non-integrated reference RBC control operating in the demonstrator building before the project. The comparison is done in terms of energy costs and comfort. Here, we use both non-renewable primary energy (NRPE) or power (NRPP) and monetary costs (MC) as energy cost criteria (see Table 1 for cost factors used). Further evaluation criteria ensued from the fact that the RBC strategies investigated were designed for application in engineered building automation projects. These typically involve large buildings that are controlled by means of customized programs. To reduce engineering effort and cost these programs' adaptation, commissioning, tuning, monitoring and optimization should be kept as simple as possible. Further criteria considered were robustness regarding user interaction, ability to include standard measurements only and adaptability to originally unintended building usages.

In the demonstrator building, new control strategies were implemented on the industry PC as high-level control applications written in Matlab. These high-level control strategies calculate operating modes and setpoints, which are sent to the existing building automation system acting as low-level control. Whereas the high-level control includes coordination and optimization of the different control parts, low-level control typically includes simple setpoint control or schedules.

An exact comparison of control performances based on measurements is very difficult since in the building, control experiments can only be done sequentially and therefore different (in parts unknown) disturbances are acting on the system in every experiment. Hence, whole-year simulation results based on a building model validated by measurements are used to compare different control strategies. For that purpose, we used a co-simulation environment where the control implemented in Matlab and a model of the complete 2^{nd} upper floor of the building implemented in EnergyPlus are coupled by BCVTB, see [13]. For control, the same (high-level control) code was used both in the real building and in simulations.

Table 1. Cost calculation numbers (high tariff applies Monday to Friday except major holidays from 6 a.m. to 9 p.m. and Saturday 6 a.m. to 12 noon, else low tariff applies); monetary cost numbers originate from billing costs for the year 2012 (no fixed costs considered).

	Value	**Unit**
NRPE conversion factor natural gas	1.2	-
NRPE conversion factor electricity	3.32	-
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

4. Control Strategies

The control strategy that was in operation before the project was emulated. It serves as a reference and is called RBC-0. This strategy is not predictive and does not follow an integrated approach, i.e. there is separate control for heating by TABS, cooling by TABS, heating by radiators, ventilation, blinds and electrical lighting.

RBC-1 is the first considered newly developed control strategy. It features 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 [1]; it uses similar rules to determine operation of blind positioning and heat recovery of the mechanical ventilation. By introducing the integrated control, it is assured that energy recovery unit and blinds support the active heating and cooling of the building. Control of TABS is done as described in [14] using no room temperature control but intermittent operation also called pulse width modulation (PWM) as an option.

The second, medium complexity predictive algorithm, RBC-2, was derived partly based on the strategy Ref-3 described in [1] and partly based on the predictive rule-based control described in [2]. RBC-2 uses outside air temperature and global radiation forecasts from MeteoSwiss [15] for the control of both TABS and blinds. Unlike RBC-1, the strategy uses room temperature measurements in the offices not only for blind control but also for TABS control thereby reducing tuning and optimization effort. Based on discussions with the facility managers of the demonstrator building prior to starting with the controller developments, it was decided to strongly limit automatic blind control in order to keep disturbance for the occupants at a minimum level. So far, for all experiments only one automatic blind control action at 12:30 was allowed during daytime at work days. However, from 7 p.m. to 7 a.m. and at weekends, no restrictions were applied.

Table 2 summarizes the strategies' characteristics. The instrumentation effort of RBC-2 is increased due to the need of room temperature measurements (standard in newer buildings in Switzerland). The reason for increased engineering effort of RBC-1 and RBC-2 is that integrated control has to be engineered project specifically. Lower tuning and optimization effort results if room temperatures are measured (RBC-1, RBC-2) and if measured room temperatures are automatically controlled (RBC-2).

Table 2. Characteristics of the investigated RBC strategies

	RBC-0	**RBC-1**	**RBC-2**
Integrated control	-	✓	✓
Predictive control	-	-	✓
Instrumentation effort	Low	Low	Medium
Engineering effort	Low	Medium	Medium
Initial tuning and optimization effort	High	Medium	Low

5. Results

A. Measurement results

Starting in November 2011, various RBC and MPC strategies were sequentially applied to the demonstrator building. In Fig. 3, measurement results for the strategy RBC-2 can be found: Both energy costs (calculated from measurements using Table 1) and thermal comfort evaluations are shown for February 2012 and August 2012. The results given are for the 2nd upper floor of the building only to simplify comparison to simulation results.

It can be seen that for cold winter days, energy costs (NRPE and MC) caused by heating are dominating. During summer, costs caused by electrical equipment are dominating. These costs (grey parts of bars) are not dependent on the season and cannot be influenced by control strategies.

In February, there were violations of the lower comfort setpoint (22°C). These violations resulted mainly from window openings by occupants. In August, there were violations of the upper comfort setpoint (27°C) when the outside air temperature was high. These violations resulted because there was only free cooling available and even maximal cooling was not able to keep the comfort. The comfort range was exploited because of using passive solar gains (winter) and pre-cooling (summer), respectively. All in all, the strategy RBC-2 was able to maintain a desired comfort well.

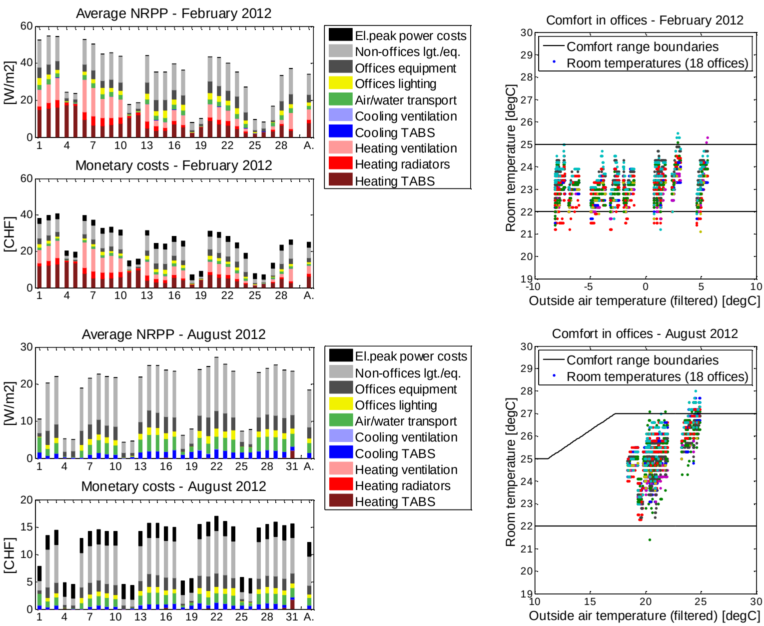

Fig. 3 RBC-2 measurement results: Daily and monthly average NRPP and MC (left); thermal comfort during building use (right); February 2012 (above) and August 2012 (below).

B. Simulation results: comparison of RBC strategies

Fig. 4 shows a comparison between control strategies RBC-0, RBC-1 and RBC-2 based on whole-year simulations of the year 2010 using MeteoSwiss [15] weather data measured at Basel Binningen close to the building's location. Again, as in Fig. 3, the data shown is for the 2nd upper floor of the building only. The whole-year numbers are also given in Table 3 (cf. columns below "Gas boiler"). In terms of energy costs, the integrated control strategy RBC-1 performs considerably better than the reference RBC-0 – in particular costs for heating and lighting are reduced. Total costs are reduced by 9% (NRPE) and 8% (MC). The integrated and predictive strategy RBC-2 further reduces energy costs. Compared to RBC-0, total costs are reduced by 14% (NRPE) and 15% (MC), costs for HVAC only are lowered by 20% (NRPE) and 25% (MC).

In terms of comfort, the performances of the different strategies are more or less equal – comfort requirements are kept well. In Fig. 4, maximal comfort violations, meaning violations for the coldest and warmest zone, are given. For the warmest zone, we additionally split hours with room temperatures above the comfort range into hours when outside air temperature was low enough to cool by window openings and other hours.

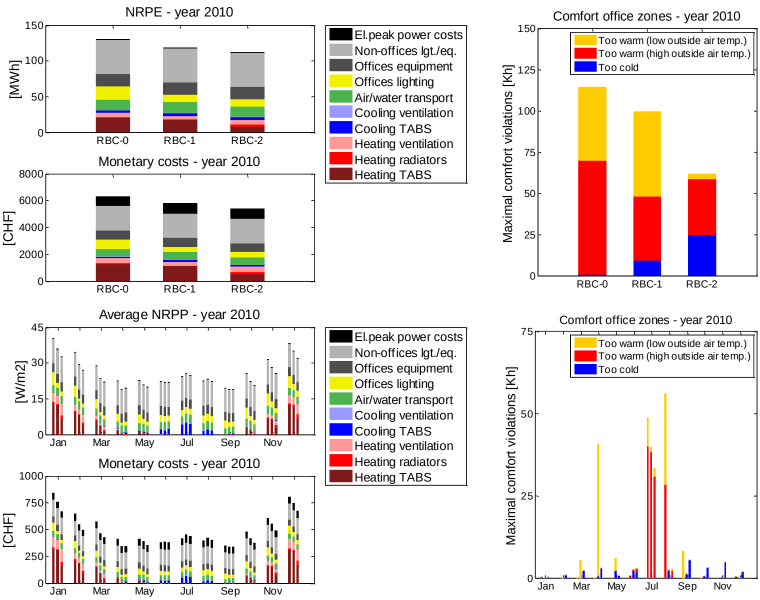

Fig. 4 Simulation results: Yearly NRPE, monthly average NRPP and MC (left); thermal comfort during occupancy (right) for RBC-0, RBC-1 and RBC-2; year 2010.

Table 3. Simulation results: non-renewable primary energy (NRPE), monetary costs (MC) and comfort; year 2010.

		Gas boiler			Heat pump	
		RBC-0	**RBC-1**	**RBC-2**	**RBC-2**	**RBC-2P**
NRPE heating TABS	[MWh]	20.8	18.3	8.4	5.5	5.2
NRPE heating radiators	[MWh]	1.2	0.5	3.0	1.9	2.1
NRPE heating ventilation	[MWh]	5.6	4.6	6.1	4.0	4.0
NRPE cooling TABS	[MWh]	3.5	4.0	4.5	4.5	4.6
NRPE cooling ventilation	[MWh]	0.4	0.5	0.1	0.1	0.1
NRPE transport air/water	[MWh]	14.4	14.8	14.3	14.3	14.0
NRPE HVAC total	**[MWh]**	**45.7**	**42.6**	**36.4**	**30.4**	**30.0**
NRPE offices lighting	[MWh]	18.7	10.1	10.0	10.0	9.9
NRPE offices equipment	[MWh]	17.6	17.6	17.6	17.6	17.6
NRPE non-office lgt./eq.	[MWh]	48.0	48.0	48.0	48.0	48.0
NRPE total	**[MWh]**	**130.0**	**118.3**	**112.0**	**106.0**	**105.5**
MC heating TABS	[CHF]	1298	1142	524	200	153
MC heating radiators	[CHF]	74	31	185	68	75
MC heating ventilation	[CHF]	350	286	383	158	158
MC cooling TABS	[CHF]	109	136	141	141	143
MC cooling ventilation	[CHF]	13	18	4	4	4
MC transport air/water	[CHF]	557	572	554	554	540
MC HVAC total	**[CHF]**	**2401**	**2184**	**1790**	**1125**	**1074**
MC offices lighting	[CHF]	731	393	389	389	387
MC offices equipment	[CHF]	661	661	661	661	661
MC non-office lgt./eq.	[CHF]	1829	1829	1829	1829	1829
MC el. peak power	[CHF]	699	739	712	759	732
MC total	**[CHF]**	**6322**	**5807**	**5382**	**4764**	**4684**
Comfort too cold (coldest zone)	[Kh]	0.8	9.4	24.7	24.7	25.0
Comfort too warm (warmest zone)	[Kh]	113.6	90.2	36.9	36.9	34.0

C. Simulation results: monetary costs and electrical peak load reduction

Results shown so far are valid for heat generation by a gas boiler as there is in the demonstrator building. In this section, we make the assumption that heat is generated by a heat pump with a constant COP of 4. For that system, we compare two whole-year simulations for the year 2010; (i) using RBC-2 as in the previous section, and (ii) using a modified RBC-2 version called RBC-2P with TABS heating shifted completely within the low tariff phase from 9 p.m. till 6 a.m. (implemented similar to free cooling PWM during night-time). By doing that, monetary costs as well as electrical peak load are reduced.

As can be seen in Table 3 (cf. columns RBC-2 and RBC-2P below “Heat pump”), the energy costs in terms of NRPE are almost equal; thermal comforts resulting also are similar. I.e. the thermal storage of TABS effectively allows for shifting heat generation completely within low cost phases, without having to compensate for storage losses. Looking at energy costs in terms of MC, RBC-2P performs better than RBC-2: total MC are reduced by 2%, MC for TABS heating only are lowered by 24% and MC for electrical peak power are lowered by 4%. Since for the actual pricing in the demonstrator building, the high tariff rate is only 50% higher than the low tariff rate (see Table 1), MC savings remain relatively small.

6. Conclusions

Based on our experience in the demonstrator building as well as in other buildings, an appropriate monitoring of a building is mandatory in order to detect errors and optimization potential in the building. Here, different types of errors such as e.g. incorrect installation, erroneous design or building automation software errors are meant. Often, an appropriate monitoring also means to add additional instrumentation to the building. The correction of the errors detected by monitoring should always be done before changing, extending or replacing the control strategy.

Today, in most buildings (also in the demonstrator building before the project) there are completely separated control systems for different control disciplines (e.g. HVAC, lighting, blinds). Such separated control systems complicate the monitoring process and make integrated control strategies troublesome or even impossible.

In addition to improvements achieved by a conventional plant optimization, the building's performance can be further enhanced (reduced energy costs and/or enhanced comfort, as shown for the demonstrator building) by introduction of simple, integrated rule-based control strategies such as the here presented newly developed control strategies. These control strategies are fully automated which makes them simple to operate e.g. for facility managers. The newly developed control strategies also are simple to tune. A procedure for initial control parameter settings as well as correction during operation is defined.

TABS as installed in the demonstrator building (typical concrete core conditioning) allow decoupling of heat/cold demand and heat/cold production. This can be used to exploit natural energy sources (e.g. low night-time outside air temperatures for free cooling), but also to exploit electrical tariff structures and reduce electrical peak load. We showed that for the demonstrator building, TABS heating (as well as cooling) actions can be shifted completely to night-time (low electrical tariff phase) without increasing delivered energy demand but with reduced monetary costs compared to continuous operation. We expect that such management of effective and low-cost thermal storages also become more and more important in future smart grid applications.

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