Potential Assessment of Rule-Based Control for Integrated Room Automation

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SUMMARY

In the Swiss research project OptiControl, the use of weather and occupancy forecast for optimal building control is investigated. The paper presents one result of the project: A potential assessment of both non-predictive and predictive rule-based control for integrated room automation. Different rule-based control algorithms – still the standard approach in today's building automation – are examined and compared in a large-scale simulation study. To our knowledge, no such systematic potential assessment has been carried out so far. Control performance is measured by non-renewable primary energy (NRPE) usage while thermal, luminance and air quality comfort is maintained within desired ranges.
The control algorithms show large performance variations, both between each other and depending on individual cases. Blind operation restrictions are found to heavily impact the control performance. Comparisons of the control performances with the so-called performance bound (theoretical minimum NRPE usage) suggest substantial potential for further NRPE savings by advanced control.

INTRODUCTION

The research project OptiControl (www.opticontrol.ethz.ch) on the use of weather and occupancy forecast for optimal building control has been started in 2007. One selected result is presented: The potential assessment of rule-based control (RBC) for Integrated Room Automation (IRA). Other results from OptiControl can be found in [1] and [2].
IRA deals with the simultaneous control of blinds, electric lighting, heating, cooling and ventilation in a single building zone (e.g. an office room) such that the room temperature as well as CO_2 and luminance levels stay within given comfort ranges. RBC employs rules of the kind "if *condition* then *action*". This is the standard approach used nowadays in commercial building automation systems for most building control problems, including IRA. In this paper, established as well as new advanced RBC strategies are investigated.
In recent publications [3-6], the benefit of advanced control for IRA mainly regarding energy consumption has been investigated. There, energy savings potentials were either determined for example buildings or estimated for typical buildings, locations and blinds, electric lighting, heating, cooling and ventilation systems. Publications such as [3-6] state that there is a

significant potential for advanced control regarding energy efficiency – at least for selected cases. Also, the European standard EN 15232 [7] as well as VDI 3813 [8] give directives / guidelines regarding the impact of building automation (not just IRA) on energy efficiency in buildings. However, to our knowledge, no systematic potential assessment of IRA RBC algorithms has been carried out so far outside of the OptiControl project. As a result of this project, such an assessment is now publicly available in [9]. Among other things, it shows that the absolute and comparative performance of different control algorithms is highly case-dependent, such that meaningful assessments in particular regarding savings potentials require consideration of a sufficiently large number of representative cases. The goal of this paper is to show if there is significant potential for advanced RBC strategies in terms of energy savings in IRA applications. Besides an established control strategy that is used as a reference, newly developed RBC strategies are evaluated.

METHODS

The methods used in this paper are described in detail in [9]. All results were produced with the aid of the Building Automation and Control Laboratory (BACLab) modeling and simulation software developed within OptiControl.
We conducted large-scale simulation studies consisting of several thousands, whole-year, hourly time step dynamic simulations of a single building zone. Table 1 lists the considered variants regarding different technical building systems (see Figure 1 for schematic diagrams), building configurations, locations, weather and building usage. Control performance was assessed quantitatively in terms of annual total Non-Renewable Primary Energy (NRPE) usage only. Comfort violations were not included in the cost function since comfort requirements were always maintained by assuming the availability of unlimited power of the energy system. The simulation model including parameters and their values as well as details regarding the different considered variations can be found in [10].

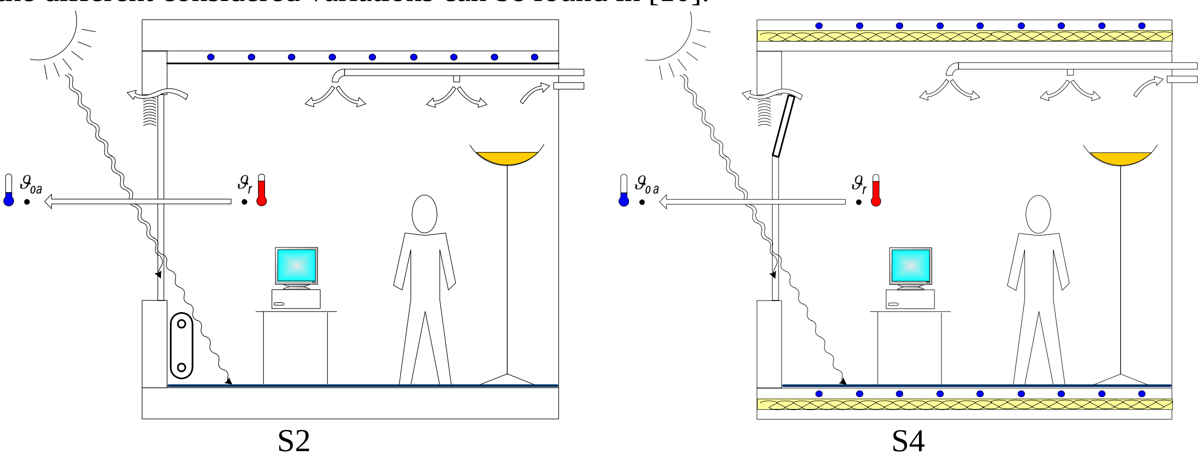


Figure 1. Building systems S2 and S4 [10]. S2: blinds, electrical lighting, radiators, chilled ceiling (with cold from chiller or from free cooling), mechanical ventilation. S4: blinds, electrical lighting, floor heating, (controlled) natural night-time ventilation, mechanical ventilation. ϑ_{oa}: outside air temperature, ϑ_r: room temperature

Control strategies considered here are separated in a high-level and a low-level control part (see Figure 2). This is motivated by the hierarchical control structure in present-day building automation systems (e.g. [11]). The high-level control determines a number of operating modes and associated setpoints that are interpreted by the low-level control. Here, only high-level RBC strategies are varied, the presence of an ideal low-level controller is assumed (see [12]).

Table 1. Simulation study set-up: overview of components varied per control algorithm.

No	Component	Variations considered	# Variants
1	Building system	- S2: blinds, electrical lighting, radiators, chilled ceiling (with cold from chiller or from free cooling by wet cooling tower), mechanical ventilation - S4: blinds, electrical lighting, floor heating, mechanical ventilation, (controlled) natural night-time ventilation	2
2	Energy system	- Heat: earth coupled heat pump Cold: mechanical (compression) chiller	1
3	Dimensioning Strategy	- Unlimited power (i.e. no dimensioning)	1
4	Cost Function	- NRPE – Non-Renewable Primary Energy Usage	1
5	Thermal Comfort	- No set-back, narrow comfort range, outside air temperature dependent - No set-back, wide comfort range, outside air temperature dependent	2
6	Ventilation Strategy	- Scheduled ventilation control - Demand-controlled ventilation (CO_2)	2
7	Illuminance Comfort	- Occupancy dependent (setpoint 500 lux)	1
8	Site	- SMA: Zurich (Fluntern) - WHW: Vienna (Hohe Warte) - MSM: Marseilles (Marignane)	3
9	Weather Data Set	- Design reference year medium	1
10	Façade Orientation	- North - South - South and west (corner room)	3
11	Construction Type	- Heavy weight - Light weight	2
12	Building Standard (thermal insulation)	- sa: Swiss average - pa: Passive house	2
13	Window Area Fraction	- Low (window area fraction 30 %) - High (window area fraction 80 %)	2
14	Internal Gains Level	- Low (maximal internal heat gains 12 W/m^2) - High (maximal internal heat gains 24 W/m^2)	2
		Total number of cases per control algorithm investigated:	**1152**

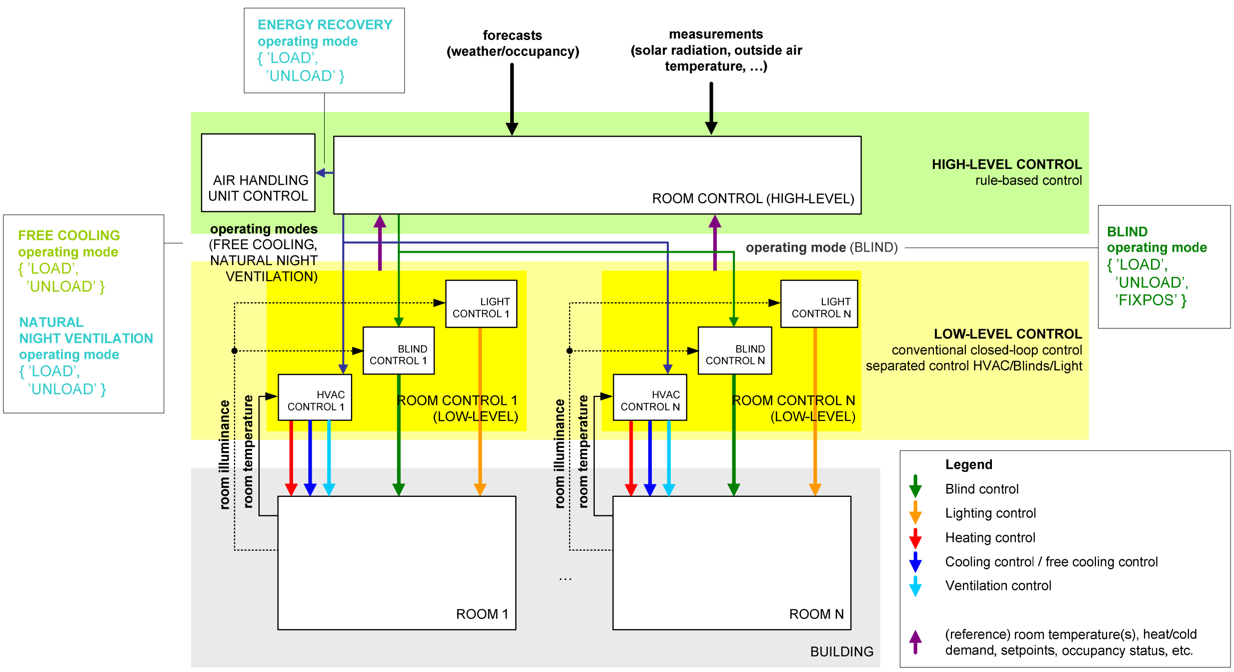


Figure 2. Schematic representation of present-day IRA control solutions [13]. Note, only a subset of the signals involved is displayed.

CONTROL STRATEGIES

Four different RBC high-level control strategies were investigated (Table 2 and Figure 2). They were compared to the so-called Performance Bound (PB) that represents the lower boundary of control costs for a given case and thus served as a reference. More detailed information about the PB and the various RBC strategies can be found in [14] and [12]. It is important to note that the considered control strategies differ in operation of the blinds: In particular, RBC-3 features unrestricted (i.e. position- and time-continuous) blind operation for direct luminance control via blinds which is typically not applicable in practice (eventually feasible by new technologies such as electrochromic windows). Therefore, its performance cannot be directly compared to the performance of other RBC strategies since these strategies are subject to various blind operation restrictions (Table 2).

Table 2. The investigated RBC strategies and the PB.

Control	Description	Blind operation restrictions
RBC-1	Typical, broadly applied non-predictive RBC strategy	Only three blind transmission values possible (fully open, fully closed and shading transmiss.)
PRBC-1	Newly developed predictive RBC strategy	Only three blind transmission values possible (fully open, fully closed and shading transmiss.)
PRBC-2	Newly developed predictive RBC strategy	Continuous blind transmission values, blind reposition only once per hour
RBC-3	Newly developed non-predictive RBC strategy	**No restriction** (continuous blind positions, continuous operation)
PB	Performance bound: Represents the lower boundary of control costs for a given case	**No restriction** (continuous blind positions, continuous operation)

Below, high-level control rules for the strategies RBC-1, PRBC-1 and PRBC-2 are stated. Results are operating modes for blinds, free cooling, energy recovery and natural night-time ventilation as well as the blind transmission value. Except for blind control with fixed blind transmission values, operating modes 'LOAD' and 'UNLOAD' are used. 'LOAD' means that the associated device should be used to heat the thermal storage of the room (if possible), 'UNLOAD' means that the associated device should be used to cool the thermal storage of the room (if possible). Control parameters and variables are printed bold; Table 3 shows their different determination depending on the control strategy.

Blind control rules

```
Blind operating mode = FIXPOS;
If (external gains > external gains threshold)
    if (room is occupied)
        blinds set to shading transmission;
    else
        blinds fully closed;
    end
else
    blinds fully open;
end
```

Free cooling control rules (free cooling by wet cooling tower)

```
If (outside air temperature > free cooling limit) & (room is unoccupied)
    if (room temperature > free cooling target room temp. setpoint)
        free cooling operating mode = UNLOAD;
    else
        free cooling operating mode = LOAD;
    end
else
    free cooling operating mode = LOAD;
end
```

Energy Recovery (ERC) control rules

```
If (room temp. below center of room temp. comfort range)
    energy recovery operating mode = LOAD;
else
    energy recovery operating mode = UNLOAD;
end
```

Natural night-time ventilation control rules

```
If (outside air temperature > natural night-time ventilation limit) &
(unoccupied night-time)
    if (room temp. > natural night-time vent. target room temp. setpoint)
        natural night-time ventilation operating mode = UNLOAD;
    else
        natural night-time ventilation operating mode = LOAD;
    end
else
    natural night-time ventilation operating mode = LOAD;
end
```

Table 3. Control parameters and their calculation rules for RBC-1, PRBC-1 and PRBC-2.

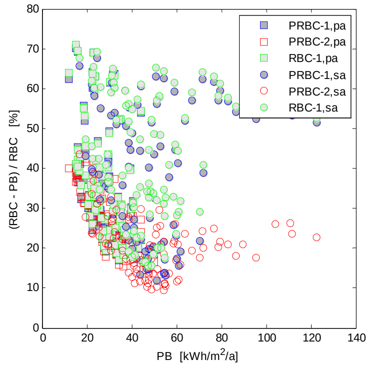
	Control parameter / variable	RBC-1	PRBC-1	PRBC-2
Blinds	External gains	Measured	Predicted; one-hour prediction	Predicted; one-hour prediction
Blinds	External gains threshold	Constant; 15 W/m^2 for all cases	Variable; Dependent on mean predicted outside air temperature of next 24 hours; Nominal value = 15 W/m^2 (nominal: predicted temp. = lower room temp. comfort setpoint)	Variable; Dependent on mean predicted outside air temperature and internal gains of next 24 hours; Nominal value = 10 W/m^2 (nominal: predicted temp. = lower room temp. comfort setpoint and predicted gains = 0); If room is occupied, the threshold value is limited to be above the nominal value
Blinds	Shading transmission	Constant; Calculated for each case, see [12]	Constant; Calculated for each case, as for RBC-1	Variable; Shading transmission is set so that maximal external gains are equal to "External gains threshold"
Free cooling	Outside air temperature	Measured; Average of last 24 hours	Predicted; Average of predicted next 24 hours	Predicted; Average of predicted next 24 hours
Free cooling	Free cooling limit	Constant; Calculated for each case, see [12]	Variable; Dependent on mean predicted external gains of next 24 hours; Nominal value = constant value of RBC-1 (nominal: predicted gains = 0)	Variable; Dependent on mean predicted internal and external gains of next 24 hours; Nominal value = lower room temp. comfort setpoint (nominal: predicted gains = 0)
Free cooling	Free cooling target room temperature setpoint	1K above lower room temperature comfort setpoint	1K above lower room temperature comfort setpoint	1K above lower room temperature comfort setpoint
Nat. night-time ventilation	Outside air temperature	Measured; average of last 24 hours	Predicted; average of predicted next 24 hours	Predicted; average of predicted next 24 hours
Nat. night-time ventilation	Natural night-time ventilation limit	Constant; Calculated for each case, see [12]	Variable; Dependent on mean predicted external gains of next 24 hours; Nominal value = constant value of RBC-1 (nominal: predicted gains = 0)	Variable; Dependent on mean predicted internal and external gains of next 24 hours; Nominal value = lower room temp. comfort setpoint (nominal: predicted gains = 0)
Nat. night-time ventilation	Natural night-time vent. target room temp. setpoint	1K above lower room temperature comfort setpoint	1K above lower room temperature comfort setpoint	1K above lower room temperature comfort setpoint

RESULTS

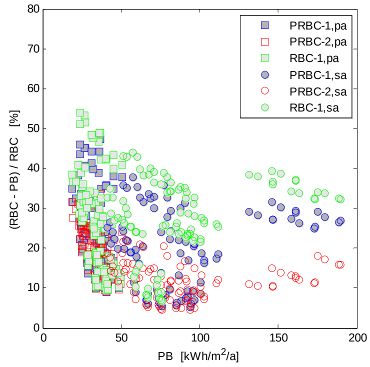
Control strategies with restricted blind operation

In Figure 3, control performance in terms of relative additional annual total NRPE usage (for all technical subsystems) compared to PB is shown for the three control strategies with restricted blind operation. The figure shows results of 3456 whole-year simulations in total: 1152 cases for each of the three control strategies. The results are stratified by building system variant (S2, S4) and site (MSM, SMA, WHW), see Table 1. Different data point symbols

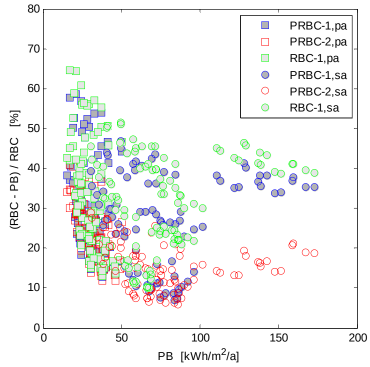
are used to discriminate between the building standards Swiss average (sa) and passive house (pa). For both building systems S2 and S4, control performances are widely spread, in particular for buildings with relatively low NRPE usage. For building system S2, there are no cases where an RBC strategy performs close to the PB (minimal 4% above PB), whereas for S4, there are a number of cases where RBC performance is almost equal to the PB. Largest relative additional NRPE usages (for RBC-1) are in the range of 70% above PB.
Generally, control performance for RBC-1 is worst, PRBC-1 performs somewhat better, and PRBC-2 shows the best performance of these strategies. However, even for PRBC-2, the potential for improvement is still significant, as can be seen by comparison with the PB.



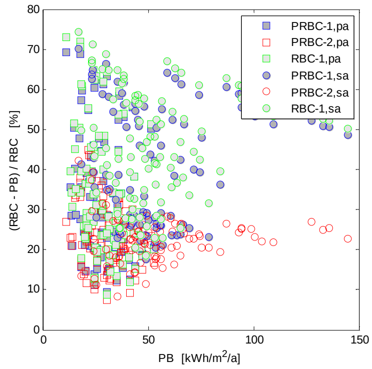
S2, MSM



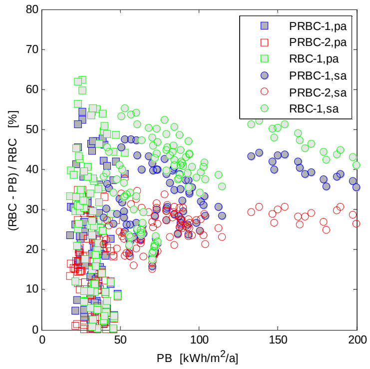
S2, SMA



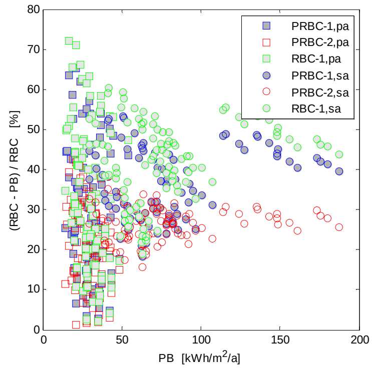
S2, WHW



S4, MSM



S4, SMA



S4, WHW

Figure 3. Relative additional annual total NRPE usage for control algorithms RBC-1, PRBC-1 and PRBC-2 compared to the PB.

Control strategy with unrestricted blind operation

Figure 4 shows the same results as Figure 3, but for the RBC-3 algorithm, a control strategy with no blind operation restrictions that features direct luminance control via blinds. It can be seen that its NRPE usage is significantly closer to the PB than that of the other control strategies with restricted blind operation. In particular for building system S2, RBC-3 shows very low relative (and also absolute, not shown) savings potentials.

Distribution of NRPE usage across technical subsystems

Figure 5 gives average annual total NRPE usages by all considered RBC strategies as well as the PB as a function of building system (S2, S4), site (MSM, SMA, WHW) and building standard (pa, sa). Different colors are used to denote the contribution by heating, cooling, free cooling (only for S2), ventilation and lighting. As expected, it can be seen that the individual subsystems' contributions vary strongly depending on the building standard and the site. Besides, it is notable that the fraction of total NRPE usage for lighting for the Swiss average building standard is generally much smaller than for the passive house building standard.

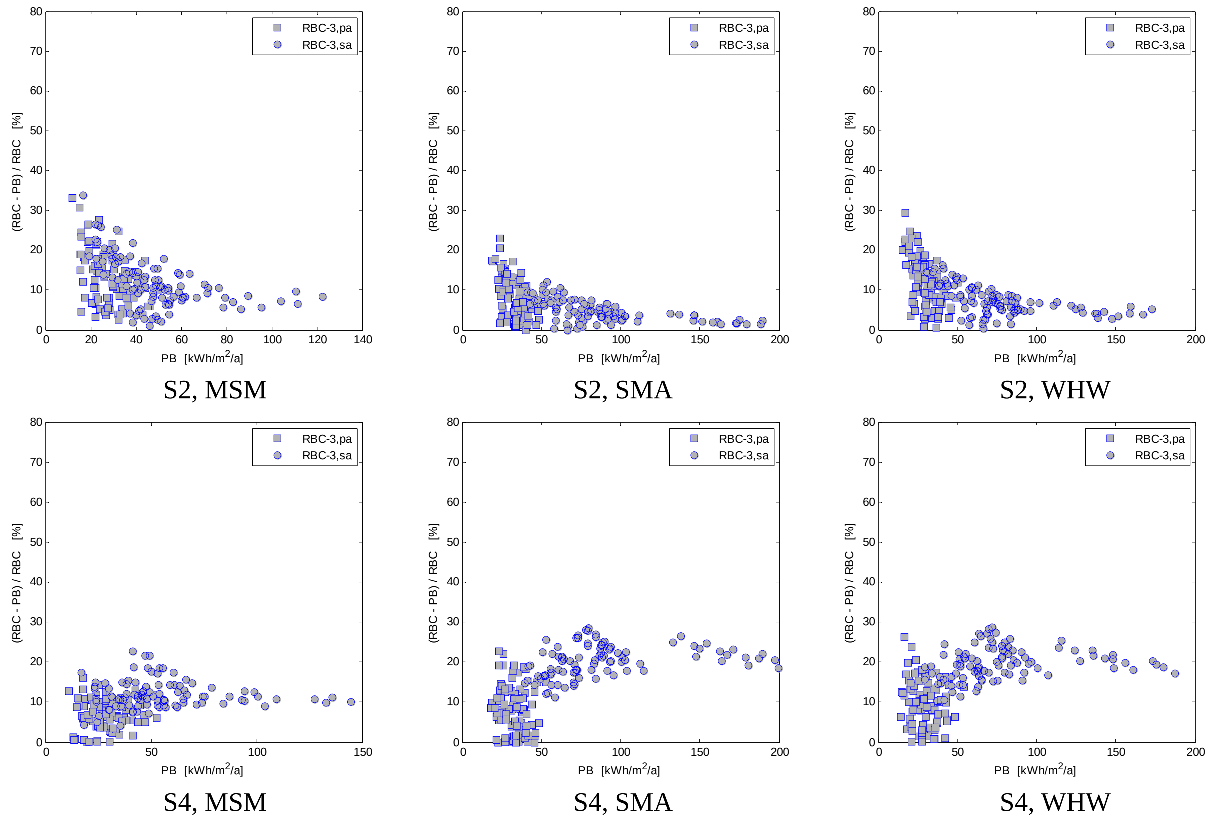


Figure 4. Relative additional annual total NRPE usage for control algorithm RBC-3 compared to the PB.

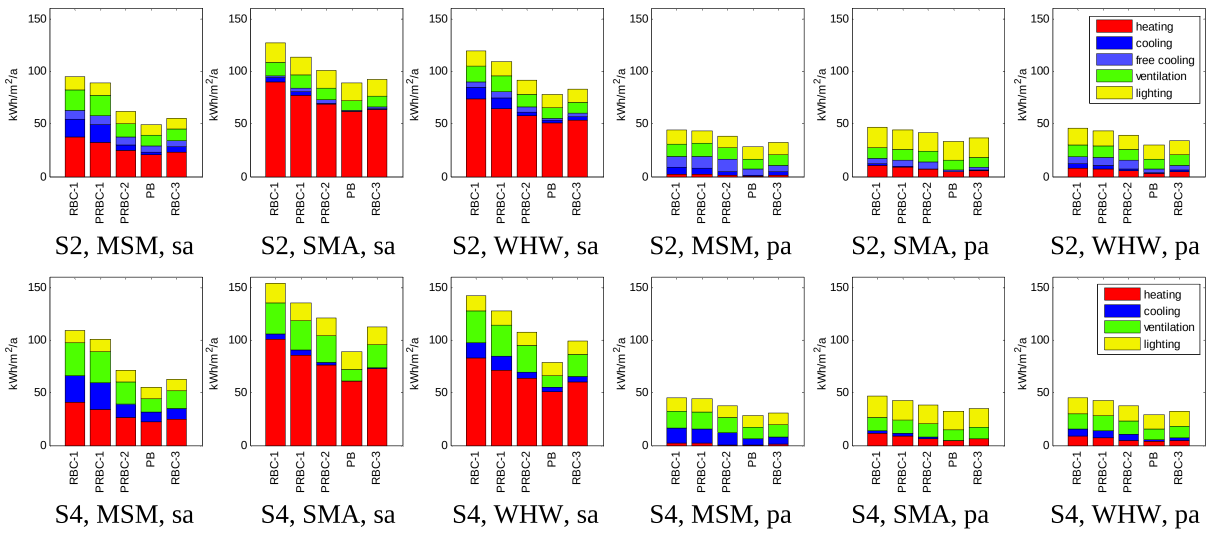


Figure 5. Average annual total NRPE usage for heating (by radiators, floor heating, mechanical ventilation), cooling (by chilled ceiling, mechanical ventilation), free cooling, ventilation (by fans) and lighting depending on control strategy.

DISCUSSION & CONCLUSIONS

IRA RBC algorithms show large performance variations both between each other and across individual cases regarding buildings, building operation and different climates. There is considerable potential for reducing annual total non-renewable energy (NRPE) usage, most of all for the “standard” algorithm RBC-1, but in many cases also for the advanced algorithms PRBC-2 and RBC-3 (Figures 3-5).

Possible NRPE savings depend heavily on the available degrees of freedom for blind operation. In practice, blind operation is typically restricted, and there are numerous kinds of blind operation restrictions. If continuous adjustment of blind transmission is allowed for, the savings potential can largely be exploited by advanced RBC strategies such as RBC-3 that feature direct luminance control via blind operation that might become applicable in the future thanks to the use of electrochromic windows. Strategies with blind operation restrictions normally perform worse than strategies without restrictions, as has been confirmed by the RBC strategies considered here. Our results also demonstrate the utility of weather and occupancy predictions, although the decrease in control performance due to the use of real predictions as opposed to the perfect ones employed here remains to be investigated: The predictive strategy PRBC-1 clearly outperforms its non-predictive counterpart RBC-1, while PRBC-2 performs considerably better than PRBC-1. The best considered (non-predictive) algorithm RBC-3 in many cases still shows substantial theoretical savings potentials (Figures 4 and 5) that can be attributed to the fact that the PB calculations use and fully exploit perfect knowledge of the controlled system and predictions. We therefore conclude that more advanced control approaches such as Model Predictive Control are also promising for IRA [1,2,14].
The very high variability in our results underlines the importance of our overall approach to controller development that is based on (i) the Performance Bound concept that enables the detection of savings potentials; (ii) the use of physically based models that make possible the study of relevant mechanisms and controller behaviors; and (iii) the appropriate modeling and simulation tools that support iterative controller development and large-scale simulation experimental studies.

ACKNOWLEDGEMENT

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