Analysis of Energy Savings Potentials for Integrated Room Automation

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SUMMARY

The energy savings potential of selected low-cost measures related to the simultaneous control of blinds, electric lighting, heating, cooling and ventilation in a single building zone (Integrated Room Automation) was investigated. The analysis was based on a factorial study comprising several thousands, whole-year hourly time step simulations. The largest energy savings potential was found for the use of CO_2-controlled ventilation as opposed to non-air quality controlled ventilation (average savings of 13%–28%, depending on the building zone characteristics and the choice of technical building system), followed by a widening of the thermal comfort range by ~1.5 ºC (6%–16%), and the allowance for night/weekend room temperature set-back (0%–18%). Substantial energy savings potentials were also detected for advanced control: readily realizable energy savings thanks to improved non-predictive control amounted to 1%–15%, and theoretical savings potentials for predictive control to 16%–41%. The found, large case-to-case variability surrounding these average numbers underlines the importance of simulation-based assessments on a per case basis.

INTRODUCTION

Building control is increasingly recognized as an important factor that can contribute to improving the energy efficiency of buildings [1,2]. Here we study by means of simulation how energy can be saved in office buildings using low-cost measures related to control that do not require major construction work, or any major retrofitting or changes in the installed energy systems.

We consider the following factors: *a)* a reduction of the thermal comfort when the building is not used, by allowing for room temperature set-backs during nights and weekends; *b)* a general reduction of thermal comfort due to a widening of the room temperature comfort range; *c)* the use of Indoor Air Quality controlled ventilation; *d)* the adjustment of the control such that it is optimized for energetic rather than monetary cost; *e)* the use of advanced, non-predictive control; *f)* the use of predictive control (theoretical potential only, i.e. maximum achievable savings under a range of idealized assumptions).

Two further measures with substantial energy savings potential that are currently implemented only in a small fraction of office buildings are the use of constant lighting control and automated blind control [2,3,4]. These were always assumed to be present in our simulations, and this allowed us to avoid the modeling of corresponding occupant actions. In doing so we assumed that the users are satisfied with the room comfort achieved by the automation.

METHODS

All results were derived from whole-year, hourly time step simulations with a physically based, single zone, twelfth order, time discrete bilinear building model of coupled thermal, air quality and light dynamics [5,6]. The simulations were driven by (i) standard, diurnally and weekly varying occupancy and internal gains profiles for cellular offices, and (ii) hourly outside air temperature, wet-bulb temperature and radiation data for four representative European locations (Zurich, Lugano, Marseille and Vienna; see [7]). Evaluated was the annual total (all automated subsystems) Non-Renewable Primary Energy (NRPE) usage and the annual amount of thermal comfort violations. The comfort statistics are not reported here because violations were generally small (< 50 Kh/a) or did not affect much our conclusions [8].

The NRPE savings potentials of the factors *a)–f)* were determined by pairwise comparison of simulations results from two sets of simulations covering various study sites, building types, technical building systems etc. (see below). The first set of simulations (A) always provided the reference, whereas the second set (B) incorporated the assumed change in the particular energy-saving factor considered. Absolute and relative energy savings potentials for the i-th pair of simulations from the two sets were computed as B_i-A_i and (B_i-A_i)/B_i, respectively.

The modeled building zones differed in façade orientation (N or S for normal offices, and S+E or S+W for corner offices), construction type (heavy/light), Buiding Standard (Passive House/Swiss Average), window area fraction (low 30%, both Building Standards; high 80%, Passive House only), and internal gains and associated CO_2-production (high/low) (see [9]).

Studied were three different technical building systems with the following automated subsystems: S1 – blinds, electric lighting, cooled ceiling by capillary tube system (with cold from a chiller or from free cooling by a wet cooling tower), radiator heating; S2 – in addition: variable air volume mechanical ventilation (VAV, used for heating/cooling), plus mechanical ventilation energy recovery; S3 – blinds, electric lighting, VAV, and energy recovery.

All delivered energy was in the form of electricity. Consumers were the electric lighting, an earth coupled heat pump for heat generation, a mechanical chiller or auxiliary drives for (free) cooling, and fans for mechanical ventilation. Maximum heating and cooling power was determined by a standard, scant dimensioning procedure [9]. Control costs were assessed in terms of NRPE usage or of Monetary Cost (MC) for electricity assuming a diurnally varying (high/low tariff) profile [9]).

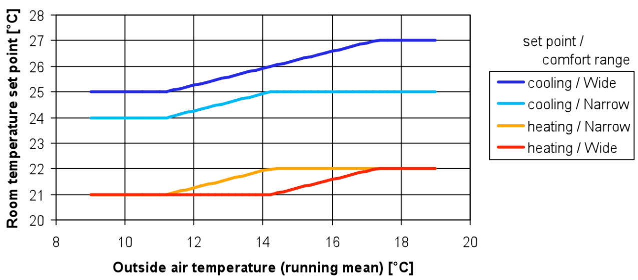

Figure 1. Room temperature set points for heating and cooling, and for the temperature comfort ranges “Narrow” and “Wide”. Reproduced from [9].

The used thermal comfort ranges are shown in Figure 1. The actual comfort range at a given point in time was determined as a function of the exponentially weighted running mean of the past measured outside air temperature values (for details see [9]).

For the illuminance comfort we applied a standard lower illuminance setpoint value for occupied offices of 500 lux. No upper limit was defined assuming that in case of excess incoming solar radiation the user would be able to obtain glare protection by manual adjustment of an internal blind.

For the study of factors *a)–d)* all control actions (heating and cooling power etc.) were delivered from a model based 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 [10]. 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. All PB calculations minimized the NRPE usage, except for the simulations set A in the study of factor *d)* (see below).

For the investigation of factors *e)* and *f)* were employed in addition to the PB two rule-based control (RBC) algorithms, as explained later.

Factor *a)*: A: no set-back – the comfort settings from Figure 1 were applied 24 hours a day and 7 days a week. B: with set-back – above comfort settings were applied only during working hours, as determined from a fixed occupancy schedule. During non-working hours the room temperature setpoint range was relaxed to 12°C–35°C.

Factor *b)*: A: "narrow" comfort range. B: "wide" comfort range. See Figure 1.

Factor *c)*: A: non-air quality controlled ventilation – application of a constant minimum fresh air supply rate according to a fixed occupancy schedule. B: CO_2-controlled ventilation.

Factor *d)*: A: monetary-cost optimal control – the PB calculations were set-up such as to minimize the MC, and then the associated NRPE usage of the resulting control actions was computed. B: energy-optimal control – the PB calculations minimized the NRPE usage.

Factor *e)*: A: Typical, broadly applied non-predictive rule-based control – used was the RBC-1 algorithm reported in [11, 12]. B: Advanced non-predictive control – we developed a new algorithm, RBC-5, that combined RBC-1 and a further algorithm, RBC-4 (see [11]) as follows: "If one of the following conditions i)-iv) applies use RBC-4, otherwise use RBC-1: i) façade orientation is N; ii) Building Standard is Passive House, system variant is S3, and façade orientation is SW; iii) Building Standard is Swiss Average and construction type is heavy; iv) Building Standard is Swiss Average and system variant is S3."

Factor *f)*: Two definitions for the theoretical potential of predictive control were used. Definition 1: A: Non-predictive RBC allowing for time-continuous adjustment of blinds – RBC-3 algorithm reported in [11, 12]. B: PB. Definition 2: A: Non-predictive RBC allowing for adjustment of blinds once per hour – RBC-5. B: PB.

For the statistical analysis of the results all simulated cases with façade orientations N or S and of heavy construction type were subsumed under Buildings Class I (most common cases in practice), and all remaining cases under buildings Class II (less frequent cases).

RESULTS

Figure 2 shows the found average relative savings potentials, stratified by Building Standard, Buildings Class and building system variant. It can be seen that among factors *a)–e)* the use of CO_2-controlled ventilation instead of non-air quality controlled ventilation (factor *c)*, light blue bars) yielded generally the strongest effect. The second most important effect was obtained either for the increase in comfort range width (factor *b)*, dark green bars), or – top right panel in Figure 2 – for the advanced non-predictive control (factor *e)*, orange bars). The latter was found to yield generally smaller savings for Buildings Class II as compared to Class I (top vs. bottom panels). Allowance for room temperature set-back (factor *a)*, light green bars) showed a small effect, except for the Swiss Average buildings standard and Buildings Class II (bottom right panel). The obtained average NRPE savings when control was optimized for NRPE instead of monetary cost (factor *d)*, light brown bars) was generally small.

The average theoretical savings potentials for predictive control were found to depend strongly on the reference control algorithm. The obtained savings potentials for the RBC-3 algorithm (factor *f1)*, light red bars) were comparable to those from factors *a)*, *b)*, *d)* and *e)*, and they were generally much smaller than those for the RBC-5 algorithm (factor *f2)*, dark red bars). The latter were comparable to the found savings for factor *c)*.

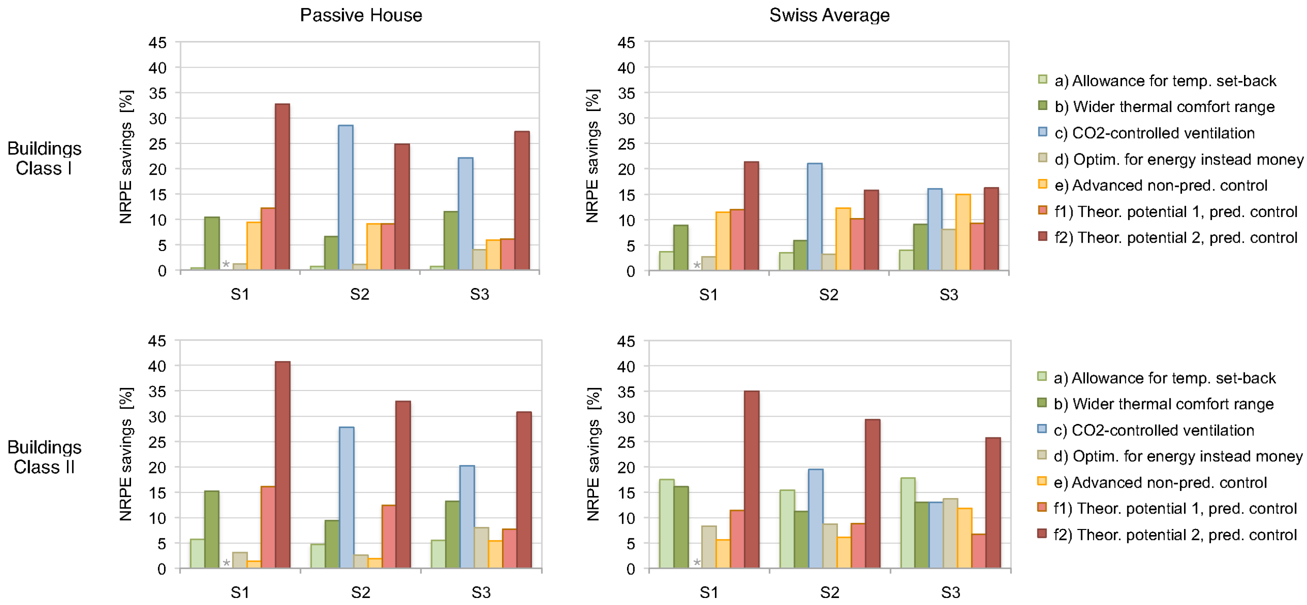

Figure 2. Comparison of average relative savings potentials for annual total Non-Renewable Primary Energy (NRPE) usage. Note, savings potentials *a)–e)* can be realized in practice, whereas *f1)* and *f2)* are theoretical values representing the maximum achievable savings given perfect predictive control. S1–S3: building system variant; *: value not available.

Figure 3 illustrates the individual simulation results from *a)* the set-back (top panels), *b)* the comfort range width (middle panels) and *c)* the ventilation strategy (bottom panels) analyses for the most complex technical building system variant, variant S2. Note that here the absolute NRPE savings potentials are shown, stratified by Building Standard (left vs. right panels) and Buildings Class (yellow vs. blue dots).

It can be seen that there was large variation between the individual building cases, and that there was hardly any correlation between the baseline energy usages and the associated absolute savings potentials. However, a few patterns can be discerned: Firstly, the savings potentials from the set-back (factor *a)*, top panels) and comfort range width (factor *b)*, middle panels) analyses were clearly smaller for the Buildings Class I as compared to Class II. Secondly, consider the set-back effect for the Swiss Average buildings (top right panel): here, the cluster of points with savings exceeding 10 kWh/m^2/a was found to represent corner offices (façade orientations S+E and S+W) of a light construction type. Finally note that the variation of ventilation strategy for the Swiss Average buildings (bottom right panel) yielded two clusters that depended on the internal gains level. The cases with the consistently larger savings potentials were found to be those with the higher internal gains.

Figure 4 compares the found relative savings potentials due to possible improvements in control algorithms, again using building system variant S2 as an example. The x-axis values are given by a measure of average solar heat gains, defined as S·R, where S denotes the product of the window's solar heat gain coefficient with the total area of all transparent window parts divided by the building zone's floor area, and R stands for the annual average of the hourly means of all relevant vertical global radiation components (up to two components for corner offices).

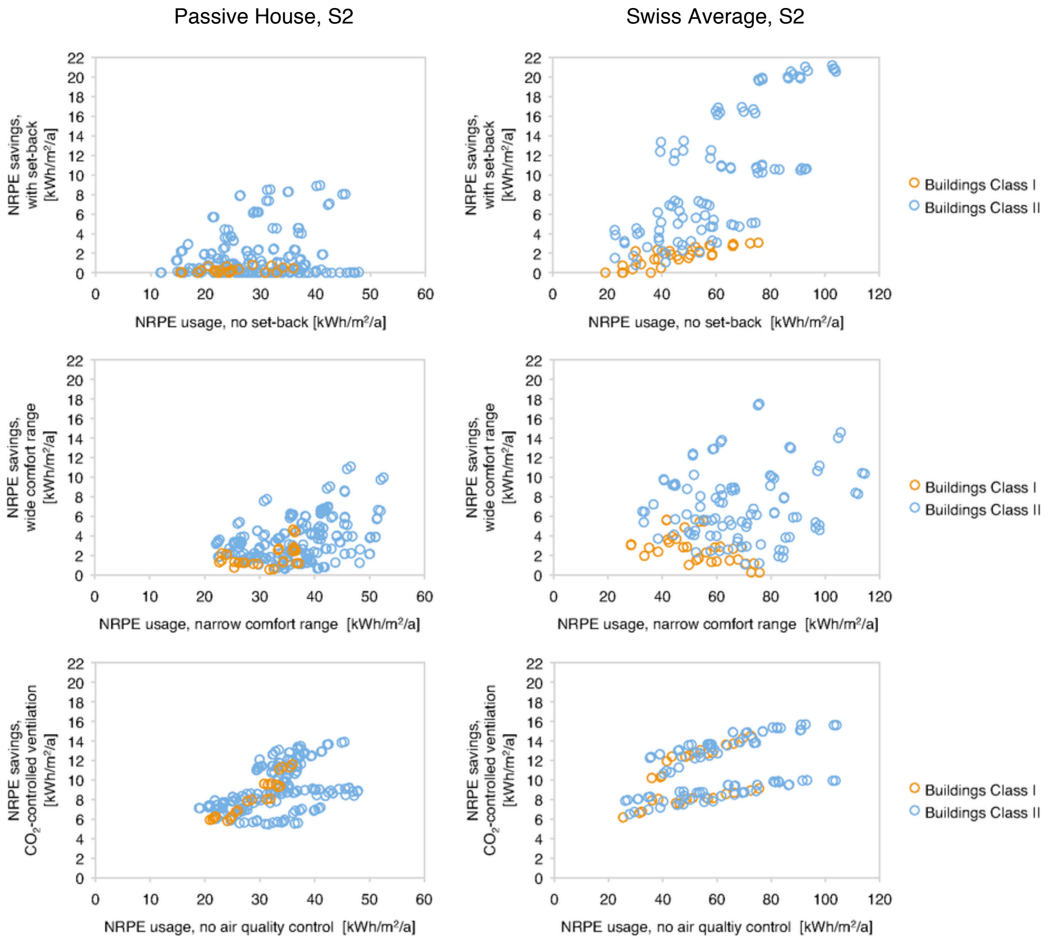

Figure 3. Absolute savings potentials for annual total Non-Renewable Primary Energy (NRPE) usage and building system variant S2 as a function of NRPE base values. Shown are savings due to *a)* allowance for night/weekend room temperature set-back (top), *b)* the widening of the thermal comfort range (middle), and *c)* the use of CO_2-controlled ventilation instead of non-air quality controlled ventilation (bottom).

From Figure 4 can be discerned that the various savings potentials showed in general a positive correlation with the solar heat gains. The savings potentials by *e)* advanced non-predictive control (top panel in Figure 3) were found to be larger for heavy as opposed to light buildings. Quite differently, the highest theoretical savings potentials for the RBC-3 algorithm (factor *f1)*, middle panel) were obtained under high solar heat gains for office zones of heavy construction type. The theoretical savings potentials for RBC-5 (factor *f2),* bottom panel) were generally much higher than the ones obtained for *e)* and *f1)*, and they did not show any clear dependency on construction type.

DISCUSSION & CONCLUSIONS

Our results depended on a series of key assumptions [5] and any variation in those would clearly affect the quantitative estimates (Figures 2–4) reported here. Due to the complexity of the involved models and calculation procedures the quantitative robustness of our results can only be studied with the aid of further simulations. Nevertheless, thanks to the careful, systematic design of our simulation study and the wide range of cases considered we believe that our results provide useful estimates of the various average energy savings potentials and their variability.

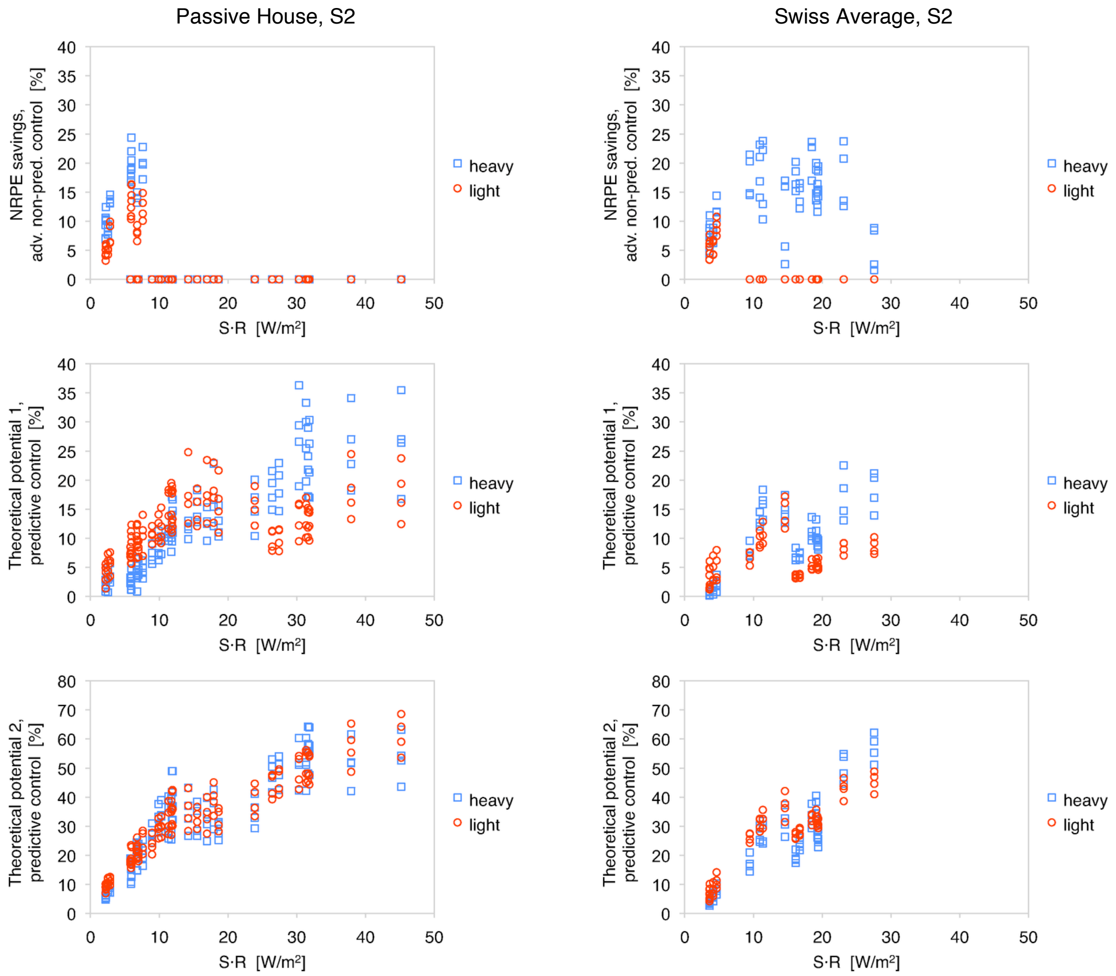

Figure 4. Relative savings potentials for annual total Non-Renewable Primary Energy (NRPE) usage and building system variant S2 as a function of solar heat gains through windows (S·R) and construction type (light/heavy). Shown are relative savings achievable by *e)* advanced non-predictive control (top) and two different theoretical relative savings potentials for predictive control (factors *f1)* and *f2)*, middle and bottom). Note the different y-axis scaling in the bottom panels.

Note that the relative savings potentials reported here refer to annual *total* NRPE usage, i.e they included energy usage for heating, cooling, ventilation and lighting. Higher relative savings would have been obtained if we had excluded the lighting costs from our calculations, as this has often been the case in other studies. Also, here we looked at the individual factors in isolation. It is not clear how the savings interact. If a linear behavior would apply, the relative savings due to simultaneous implementation of n energy saving measures with savings potentials p_i (i=1..n) could be estimated as one minus the product of the terms (1- p_i). Under this assumption the simultaneous implementation of, e.g., factors *a)–c)* and *e)* (Figure 1) would yield average total savings in the order of between 20% and 45%.

Throughout our work we assumed a scant dimensioning procedure for the dimensioning of the building system components [6]. This limited the maximum allowable amplitude for the room temperature set-backs (factor *a)* in Figure 2, and top panel in Figure 3) and thus also the associated energy savings that could be achieved in our simulations.

The large ventilation strategy effect (factor *c)* in Figure 2, and bottom panel of Figure 3) was mainly caused by reduced costs for fan operation. The resulting energy savings are somewhat uncertain due to two opposing effects: On the one hand, for CO_2-based control quite small air change rates were used that actually lead to generally higher CO_2-concentrations as compared to the corresponding non-air quality controlled cases [6]. On the other hand, our simulations also assumed a simplified linear (instead of quadratic or cubic) increase of energy usage with ventilation rate. This probably underestimated the energy usage by the non-air quality dependent control and thus also the energy savings due to its replacement by CO_2-based control.

The found, relatively small effect of the choice of the cost function (factor *d)* in Figure 2) related to the fact that the outcomes of the energy- and monetary cost-based optimizations were strongly correlated in our simulations (see [8]). It remains to be investigated up to what extent this result would also hold for other heat/cold generation systems and other diurnal electricity tariffs than the ones assumed in the present study.

All our investigations of factors *a)–d)* were strictly based on PB calculations. This ensured that the found energy savings reflected the effect of the factor variations alone and were not distorted by the shortcomings of any particular control algorithm. Accordingly, our results only state what differences could be expected to occur if perfect control would apply, whereas the energy savings obtained in reality will also depend on the properties of the particular control solution employed. It can be expected that the more a solution's performance deviates from the PB the less the savings estimates *a)–d)* reported in this work will apply.

Predictive control appears particularly promising (Figures 2 and 4). The theoretical savings potentials *f1)* and *f2)* were assessed using the best-performing, non-predictive RBC algorithms currently known to us, RBC-3 and RBC-5. Both these algorithms were assumed to have perfect control over all subsystems (blinds, radiators, ventilation etc.). This ensured strict comparability with the PB. We are therefore confident that our estimates for the savings potentials *f1)* and *f2)* are on the conservative side.

The found, large differences in these two potentials reflected the enhanced freedom in blind movement granted to RBC-3 as compared to RBC-5. RBC-3 demonstrates how far one could in principle go without using predictions, but since a time-continuous movement of the blinds would hardly be accepted in practice the potential *f2)* is probably more realistic.

The strong dependency of energy savings potentials on solar heat gains (Figure 4) further underlines the importance of bind control in IRA, as also do the results reported in [12]. A closer analysis [13] of the potential *f1)* showed, however, that the PB calculations optimize not only the usage of the blinds, but also of the free cooling and energy recovery subsystems in order to efficiently pre-heat or pre-cool the building structure depending on the expected future variations in weather and internal gains. This behavior was found to minimize the switching between heating and cooling actions and to maximize the free floating of the room temperatures within the thermal comfort range [13].

Even larger potentials for predictive control than reported here could have been obtained if we had allowed for temperature set-back in the corresponding PB/RBC simulation pairs, or if we had considered slowly reacting subsystems (such as floor heating or thermally activated building systems). However, both these measures would have required corresponding state-of-the-art RBC algorithms for comparison that were not yet available in our modeling system by the time the present study was undertaken.

Further studies should be undertaken to clarify in as far the found, theoretical potential of predictive control can actually be exploited in practice. Some related work is reported in two companion papers that deal with predictive rule-based control [12] and Model Predictive Control [14], respectively.

In summary, we conclude that from the factors investigated for the application Integrated Room Automation the use of CO_2-controlled ventilation as opposed to non-air quality controlled ventilation bears the largest immediately accessible energy savings potential. Average energy savings for this measure amount to 13%–28%, depending on the building zone characteristics and the choice of technical building system. Further significant energy savings can be achieved by a widening of the thermal comfort range by ~1.5 ºC (average savings of 6%–16%), and the allowance for night/weekend room temperature set-back (0%–18%).

Advanced control also has a substantial energy savings potential. Average readily achievable savings from improved non-predictive control are 1%–15%. Average theoretical savings potentials for predictive control are 16%–41%. Only part of this potential may be realized in practice, and smaller potentials may apply depending on the allowed freedom for blind movement in the reference control. Predictive control appears particularly promising when high solar heat gains are at disposal. The effect of thermal mass (heavy vs. light construction) on the theoretical potential varies with reference control.

All energy saving measures investigated showed a very high case-to-case variability. Responses to changes in control show complex patterns, such that in general the savings potentials cannot be readily deduced from building, site, or usage characteristics. Appropriate models, data sets and software tools are thus indispensable when it comes to identifying the best combination of energy saving measures for a specific application.

Overall, our findings confirm that control is essential for energy efficient building operation. Future work should address the user acceptance (operators, occupants), the practical applicability (predictive control), and, last but not least, the implementation and operation costs of the various measures investigated.

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