The impact of building automation control systems as retrofitting measures on the energy efficiency of a typical Norwegian single-family house

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Abstract. In this study, the energy savings and cost-effectiveness of building automation measures in a retrofitting context are evaluated for a Norwegian single-family house. In addition, two methods for calculating savings from implementing building automation control systems (BACS) are compared: energy performance simulation and the BACS factor method proposed in EN 15232. Four retrofitting packages and four automation levels are combined to create 16 model versions. This study shows that BACS can increase energy savings and improve indoor comfort when implemented as a retrofitting measure. However, the relative impact on energy savings of building automation decreases when the delivered energy is lower. In addition, the impact of building automation on the energy savings is low compared to the effect of retrofitting the building envelope. When only BACS are implemented, savings up to 21% can be achieved, but when an integrated solution is implemented savings up to 60% can be achieved. Finally, some directions for future work are suggested.

1. Introduction

Buildings consume a large share of the total energy consumption in Europe, mostly due to an inefficient existing building stock [1]. As residential buildings represent around 75% of the existing buildings, it can be concluded that retrofitting offers a significant energy saving potential [2]. The building stock situation in Norway is similar, though it is characterized by its reliance on electricity as the main energy source in residential buildings [3, 4]. A way to improve the energy efficiency of existing buildings, though not often done, is by implementing building automation control systems (BACS). BACS can reduce the operational energy use while maintaining a comfortable indoor climate as highlighted in previous work [5], but system settings can have a significant effect on the achieved energy savings [6]. The system can also reduce peak loads and overall energy costs. This is increasingly important in Norway, as a new grid rent tariff will be introduced by the end of 2020 [7]. If the typical consumption pattern is not changed, it will result in higher energy costs for the consumer [8, 9].

Standard EN 15232 [10] focuses on building automation control (BAC) and technical building management (TBM) functions that can improve the energy performance of a building. The BAC functions are divided into heating, cooling, ventilation, hot water, lighting and blind control; the
TBM functions focus on data monitoring and diagnosis. Four efficiency levels are introduced in the standard based on the implemented functions (see table 1) [10]. These labels are not related to energy performance labels [11], though both are defined by delivered energy. To quickly estimate the effect of BAC and TBM functions on the energy performance of a building, the BACS factor method can be used as presented in EN 15232. Efficiency factors for different building categories are divided into thermal and electrical energy. Thermal energy includes energy used for heating, cooling and domestic hot water. Electrical energy includes auxiliary energy and energy used for lighting. The energy use of appliances is not taken into account. By multiplying the efficiency factors with its associated delivered energy, the expected energy savings are estimated. The efficiency factors assume that the current standard of BACS is level C. However, for this case study it was assumed that there is no automation present (level D). The overall efficiency factors for housing are listed in table 1.

### Table 1. BACS levels with corresponding thermal and electrical efficiency factors to estimate the energy savings from implementing BACS and TBM functions [10]

| Level                        | Thermal | Electrical |
|------------------------------|---------|------------|
| Level D: no automation       | 1.10    | 1.08       |
| Level C: standard BAC for new buildings | 1.00    | 1.00       |
| Level B: advanced BAC with some TBM functions | 0.88    | 0.93       |
| Level A: high-performance BAC and TBM functions | 0.81    | 0.92       |

Several studies discussed the expected outcome from upgrading BACS in residential buildings and concluded that significant energy savings can be achieved [12, 13, 14, 15]. However, the number of studies investigating the effect of BACS in a residential context is limited and does not focus on cold climates. Therefore, the aim of this study is to evaluate the potential of BACS as an energy saving measure for a typical Norwegian house. Previous work highlighted that the effect on the total energy consumption is low compared to savings that can be achieved by upgrading the building envelope [5, 16]. Therefore, four BACS packages are assessed in combination with four retrofitting packages, resulting in 16 models. The packages are based on standards and are not optimized for this building. In the BACS packages, not all functions listed in EN 15232 are included. The combinations of measures are evaluated in terms of energy savings, indoor comfort and cost-effectiveness. In addition, the soundness of the BACS factor method is evaluated by comparing estimated energy savings calculated with this method to the simulation results.

### 2. Case study model

The case study (see figure 1) is a typical Norwegian single-family house as described by Thyholt et al. [17]. The external walls and roof are a timber-frame construction and the walls of the lower floor are constructed with LECA blocks. The ground floor is a concrete slab on grade with no to little insulation. This housing type is located throughout Norway, but for this study the climate of Trondheim, Værnes was used. The house was built according to the building code of 1969. However, higher U-values are used in the simulation model to take into account that the insulation may have worsened over the years due to deterioration. An overview of the electrical loads and internal gains in the house is given in table 2.
Figure 1. Layout and appearance of a typical single-family house, mostly built in the 70s and early 80s, with an area of ca. 170 m$^2$. The east half of the lower floor is partly submerged.

Table 2. Electrical loads and internal gains in the case study. The lighting load in the retrofitting packages, after upgrading to LED, is given in brackets.

| Equipment                                      | Room | Area [m$^2$] | Lighting [Watt] | Heating [watt] |
|------------------------------------------------|------|--------------|----------------|---------------|
| Kitchen                                        |      | 8.5          | 2 x 46 (10)    | 1000          |
| Living room                                    |      | LR 1         | 35.0           | 3 x 46 (10)   | 3800          |
|                                                |      | LR 2         | 21.0           | 3 x 46 (10)   | 2000          |
|                                                |      | LR 3         | 26.6           | 3 x 46 (10)   | 1500          |
| Bedroom                                        |      | BE 1&2       | 11.2           | 46 (10)       | 1000          |
|                                                |      | BE 3&4       | 9.1            | 46 (10)       | 1000          |
| Bathroom                                       |      | BA 1         | 3.5            | 46 (10)       | 500           |
|                                                |      | BA 2         | 1.9            | 30 (6)        | 250           |
|                                                |      | WC           | 1.5            | 30 (6)        | 250           |
| Laundry                                        |      | H 1          | 5.3            | 2 x 30 (6)    | 600           |
|                                                |      | H 2          | 3.6            | 30 (6)        | 250           |
|                                                |      | H 3          | 2.3            | 30 (6)        | 250           |

2.1. Simulation model
The case study building was modeled in IDA-ICE [18]. The aim of this study required a model where all rooms were modeled as individual zones to study the effects of BACS (i.e. individual room control and setpoints). The simulation model was validated by comparing the model with standardized input values and occupancy behaviour [19] to reference values [20, 21]. Occupancy behaviour and distribution of internal gains were adjusted to fit a more realistic scenario. Occupancy schedules were derived from Nord et al. [22], the schedules for lighting and equipment were taken from open-source models by Richardson et al. [23, 24] and the schedule for DHW was taken from Ahmed et al. [25]. These models were adapted to the case study and location.

The effect of four building automation levels was evaluated for four retrofitting packages,
resulting in 16 model versions. The retrofitting packages are based on standards and are not optimized for the building type. The first package (R0) is the building in its current state, without any renovation. Standard values for old buildings as presented in NS 3031 [19] are used. In package R1 (minimum retrofitting) only the windows are improved. As a result, it is expected that the airtightness improves and that thermal bridges around the windows are reduced. To estimate the improvement of airtightness, the method of Ridley et al. [26] was used. In package R2 (moderate retrofitting) the house is upgraded to TEK 17, the current minimum energy requirements in Norway [27]. Package R3 (major retrofitting) is based on the building envelope criteria from the Norwegian passive house standard [28]. The improvements to the energy performance characteristics are listed in Table 3. In packages R1-3 it is necessary to upgrade the ventilation system to ensure proper air quality. Additionally, all lights were replaced by LED lights in R1-3.

| Table 3. Energy performance characteristics in the four renovation packages. |
|---------------------------------------------------------------|
| R0 - no renovation | R1 - minimum | R2 - moderate | R3 - major |
| U-value basement wall [W/m²K] | 1.0 | 1.0 | 0.18 | 0.10 |
| U-value basement floor [W/m²K] | 0.5 | 0.5 | 0.10 | 0.08 |
| U-value timber frame wall [W/m²K] | 0.6 | 0.6 | 0.18 | 0.10 |
| U-value roof (loft insulation) [W/m²K] | 0.6 | 0.6 | 0.13 | 0.08 |
| U-value windows [W/m²K] | 2.8 | 1.2 | 0.8 | 0.8 |
| Air leakage at 50 Pa [h⁻¹] | 6.0 | 1.4 | 0.6 | 0.6 |
| Norm. thermal bridge value [W/m²K] | 0.07 | 0.07 | 0.05 | 0.03 |
| SFP [kW/(m³/s)] | 2.0 | 1.5 | 1.5 | 1.5 |
| Heat recovery [%] | 0 | 80 | 80 | 80 |
| Ventilation system | Mech. exhaust | Balanced | Balanced | Balanced |

The heating system consists of electric radiators and was sized according to the heating demand of the building. The heating capacity includes the additional reheating capacity needed to increase room temperatures from night to day setpoint within one hour, as required in some of the BACS scenarios. Though this house typically has a fireplace, it is assumed that it is not used. There are five occupants that use the whole house apart from the storage rooms (i.e. no heaters and no internal gains). Internal and external blinds and window opening control are added as fixed occupant behaviour to avoid overheating and to provide fresh air. Windows are opened when the operative temperature exceeds a setpoint given by the running mean outdoor temperature or if the CO₂ levels are higher than 1000 ppm. The blinds go down when the indoor temperature exceeds 23.5 °C. These control strategies are only applied when at least one occupant is at home.

2.2. Building Automation Control
Automation levels D, C, B and A were implemented in R0-3 based on their description in EN 15232 [10]. Only HVAC systems and equipment that were already present in level D were automated. An overview of the input parameters is given in Table 4. As the standard describes the type of control but does not give specific input parameters, several assumptions were made.

- The heating temperature setpoints in level D are reference values [19]. The setpoints in
level C, B and A are based on survey data, taken from [29].

- Ventilation air flow rates are based on minimum requirements from TEK17 [27].
- The supply air temperature setpoint, when variable, is increasing with the outdoor temperature as it is mainly used to provide fresh air [30, 31].
- The day/night schedule is based on NS 3031 [19].
- Automation of the domestic hot water system and blinds were outside the scope.
- There is no active cooling system and therefore automation of cooling was irrelevant.

### Table 4. Settings for the BACS and TBM functions for levels A, B, C and D.

| Heating control                  | D [°C] | C [°C] | B [°C] | A [°C] |
|----------------------------------|--------|--------|--------|--------|
|                                   | day / night | occ. / not occ. | day / night | occ. / not occ. |
| Living                           | 22.0   | 21.5   | 21.5 / 19.0 | 21.5 / 19.0 |
| Bedroom                          | 22.0   | 19.0   | 19.0 / 19.0 | 19.0 / 19.0 |
| Bathroom                         | 22.0   | 23.0   | 23.0 / 19.0 | 23.0 / 19.0 |

| Supply air temperature           | D [°C] | C and B [°C] | A [°C] |
|----------------------------------|--------|--------------|--------|
| All rooms                        | 18.0   | 16.0-21.0, depending on $T_{out}$ | 16.0-21.0, depending on $T_{in,op}$ |

| Air flow rate                    | D [L/s m$^2$] | C and B [L/s m$^2$] | A [L/s m$^2$] |
|----------------------------------|---------------|---------------------|---------------|
|                                   | day / night   | occ. / not occ.     |               |
| Living (+)                        | CAV, 0.33$^1$ | 0.33 / 0.19         | 0.33 / 0.19   |
| Bedroom (+)                       | CAV, 0.80$^1$ | 0.19 / 0.80         | 0.80 / 0.19   |
| Kitchen (-)                       | CAV, 1.20$^1$ | 3.50 / 1.20         | 3.50 / 1.20   |
| Laundry (-)                       | CAV, 1.60     | 3.20 / 1.60         | 3.20 / 1.60   |
| Bathroom (-)                      | CAV, 4.40     | 8.70 / 4.40         | 8.70 / 4.40   |
| Toilet (-)                        | CAV, 6.30     | 6.30 / 6.30         | 6.30 / 6.30   |

| Lighting control                  | D and C       | B                   | A                   |
|-----------------------------------|---------------|---------------------|---------------------|
| All rooms                         | Manual on/off | Manual on/off with day/night schedule and daylight control | Automatic presence detection with daylight control |

$^1$ In the baseline scenario (R0,D) the supply air is provided by natural ventilation.

### 3. Energy performance

The delivered energy (see equation 1) and indoor climate (i.e. temperature and CO$_2$ levels) were assessed to evaluate the energy performance of the 16 model versions. There was no energy production on site and all energy was delivered by electricity ($\eta = 1$).

\[
\text{Delivered energy} = \sum \frac{E_{\text{demand,energy source}}}{\eta_{\text{energy source}}} - E_{\text{produced,on site}} \tag{1}
\]

The results from the energy performance simulations are shown in Figures 2 and 3. Figure 2 shows the effect of BACS integrated with building envelope retrofitting on the energy savings. The lines represent different retrofitting packages and the symbols represent the BACS levels from D (left) to A (right). The graph shows the savings from the integrated solutions compared to the retrofitting scenario without BACS. Up to 21% energy savings were achieved only by implementing BACS (see figure 2). The slopes of the trendlines indicate that the effect of automation measures relatively decreases when the delivered energy before implementing...
automation is lower (i.e. level D in packages R1-3). This is consistent with results of other studies [6, 13]. The figure indicates that a similar annual energy consumption can be achieved in R0,A as in R1,D and similar in R2,A as in R3,D.

Figure 3 compares the simulation results with the estimated savings from the BACS factor method and shows the relation between them. Integrating BACS with envelope retrofitting can save up to 60% energy compared to the existing situation. The graph indicates that for this type of housing in the studied climate, the BACS factor method underestimated the energy saving potential of BACS (i.e. the achieved savings are higher than estimated). The savings for detached housing in Trondheim can be estimated by applying a correction factor of: $1.9613 + 1.0698 \times \text{BACS factor estimation}$. This is the correction factor for the overall savings, though it would be more precise to find the correction factors for thermal and electrical energy.

Figure 2. The effect [%] of upgrading building automation measures on the delivered energy in terms of energy savings for different levels of renovation.

Figure 3. Correlation between the simulation results and estimated energy savings according to the BACS factor method.

3.1. Indoor comfort

Many parameters impact indoor comfort, but in this study only the thermal comfort based on overheating hours and indoor air quality in terms of CO$_2$ levels were evaluated. The thermal comfort analysis based on EN 15251 [32] showed that the number of unacceptable hours decreased in R0 and R1 when automation is upgraded, but increased when the house is retrofitted to a higher level (R2 and R3) (see figure 4). For all cases (R0-3) the unacceptable hours were mostly due to overheating. As there was no active cooling system installed, it indicates the assumed window opening behaviour no longer provided sufficient free cooling after retrofitting. In addition, the supply air temperature can be high during the summer (equals outdoor temperature). In the automation packages C-A there were less hours in the best category (category I) due to changed setpoints (i.e. night setback). However, this setpoint is accepted in Norwegian households and therefore the indoor temperature should be assessed with adaptive comfort criteria instead. More detailed analysis showed that the indoor temperature increased after retrofitting and became more stable. CO$_2$ levels improved significantly after renovation, and the best results were achieved with automation level A, because the ventilation is based on demand.
4. Costs and payback period analysis

Discounted payback period (DPP) as given in equation 2 was used to preliminary assess the profitability of the model versions. This method gives the number of years to break even by comparing the yearly energy savings with the initial investment, taking into account the time value of money.

\[
\text{Discounted payback period} = \frac{\ln \left[ \frac{1 - dIC \times ES \times e \times r}{1 + r} \right]}{\ln(1 + r)}
\]

where \(dIC\) is the difference in investment cost between the model version and the original in NOK, \(ES\) is the energy savings in kWh per year, \(e\) is the energy price in NOK/kWh and \(r\) is the real interest rate, as calculated in [33]. The interest rate was assumed to be 3.0% because of the low nominal interest on housing loans, the inflation rate was set to 0.03% and the energy price for electricity including taxes and grid rent was 1.23 NOK/kWh with a yearly price escalation assumed at 3.15% [34]. The investment costs including removal of old elements were taken from Norsk Prisbok [35] and were divided into retrofitting and automation packages (see table 5). Maintenance, replacement and recycling costs were not taken into account.

| dIC     | dIC Included in BACS                                      |
|---------|----------------------------------------------------------|
| Level D | CAV system                                               |
| 34 387  |                                                          |
| Level C | VAV system, weather sensor, general home automation and   |
| 76 126  | thermostat controllers                                    |
| Level B | As R1 + daylight sensors and room control units          |
| 134 967 |                                                          |
| Level A | As R2 + occupancy sensors and temperature sensors        |
| 174 735 |                                                          |

Figure 4. Total occupied hours [%] per comfort criteria as given in EN 15251 [32].
it is more profitable combine a lower level of renovation with the highest level of automation (see figure 6). Though more energy savings are achieved when upgrading to a higher level of building automation, the payback period does not significantly shorten. This is due to higher investment cost for achieving a higher level of automation.

5. Limitations and future work
Not all BACS functions were taken into account because the focus was on those functions that have the most significant impact on energy savings. In addition, this study did not focus on optimizing the setpoints for the different levels of automation. As choosing the setpoint can significantly influence the energy consumption, it may be that higher savings can be achieved when setpoints are optimized. Retrofitting packages R1-3 were not optimized for this building type, and it was not considered how they are implemented. Therefore, they may not be realistic options. In addition, the study focused on electricity as a heating source, but these houses commonly have a fireplace and in retrofitting packages it is common to install an air source heat pump. Future work should focus on optimizing both retrofitting and BACS packages for this building type and should include several heating sources. Only two parameters were chosen to evaluate the indoor climate. Other parameters, such as number of undercooling and overheating hours and humidity levels, should be evaluated as well. The cost of replacement, maintenance and recycling were outside the scope. Therefore, the actual payback period will be longer than presented. When these costs are taken into account, it is more precise to perform a life cycle cost analysis instead. Future work should also focus on different grid rent tariffs to calculate the energy costs instead of a fixed energy price. Though the results look promising, they can only be concluded for a single-family house in the climate of Trondheim. Results may be different for other housing typologies and for other micro-climates in Norway, which should be investigated more.

6. Conclusion
The effect of building automation in combination with retrofitting packages was evaluated for a Norwegian detached house. The study showed that implementing building automation control systems can result in energy savings up to 21% compared to no automation, regardless the renovation level. However, these savings are rather low compared to those that can be achieved by retrofitting the building envelope. By integrating BACS and building envelope renovation, energy savings up to 60% can be achieved. The results indicated that achieved energy savings
from retrofitting to a lower level and upgrading BACS are similar to when the building is retrofitted to a higher level without improving BACS. The former option had a shorter payback period, though more studies and optimization of the packages are needed to assess the full effect of automation on costs, energy and indoor climate.

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