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Optimizing building energy consumption in office buildings: a review of building automation and control systems and factors influencing energy savings

L. Vandenbogaerde[a,*], S. Verbeke[a,b], A. Audenaert[a]

[a]Energy and Materials in Infrastructure and Buildings, University of Antwerp, Faculty of Applied Engineering, Groenenborgerlaan 171, 2020, Antwerp, Belgium

[b]Unit Smart Energy and Built Environment, VITO, Boeretang 200, 2400, Mol, Belgium

[*]Corresponding author. E-mail address: Lukas.vandenbogaerde@uantwerpen.be

Abstract:

Building Automation and Control Systems (BACS) offer promising opportunities to reduce building energy consumption, aligning with the European Union's climate goals. This review critically evaluates the accuracy of energy savings estimation in BACS implementation, with a specific focus on the European standard EN 52120-1. BACS enable effective control of various building services, including heating, cooling, ventilation, lighting, and shading, thereby improving the energy demand-supply balance while maintaining or improving comfort. The review examines energy savings reported in the literature, encompassing field studies and dynamic energy performance simulations, to assess the validity of EN 52120-1's proposed factors. Findings indicate that the factors outlined in EN 52120-1 are not sufficiently accurate in estimating energy savings from BACS implementation. Critical parameters such as occupancy rate, climate conditions, building orientation, occupancy behavior, and control algorithms are often overlooked but significantly influence BACS effectiveness. Additionally, many studies present oversimplified reference cases, leading to overestimated energy savings. While improvements in simulation parameters are necessary, building energy performance simulations appear to be the most reliable method for accurately assessing BACS savings during the design phase. By considering the complexities of building characteristics, climate models and occupant behavior, simulations provide a comprehensive evaluation of BACS performance. This review highlights the limitations of EN 52120-1's factors and emphasizes the importance of considering crucial parameters for accurate estimation of energy savings in BACS implementation. It underscores the need for comprehensive and realistic approaches to assess the energy efficiency potential of BACS in buildings, taking into account various influencing factors.

Keywords:

- Building automation and control systems
- Office buildings
- BAC factor method
- Building energy performance simulations

Abbreviations:

Building Automation and Control (BAC), Building Automation and Control Systems (BACS), Energy Performance of Buildings Directive (EPBD), Technical Building Management (TBM), Smart Readiness Indicator (SRI), Heating Ventilation and Air-Conditioning (HVAC), Domestic Hot Water (DHW), Constant Air Volume (CAV), Variable Air Volume (VAV), Demand Controlled Ventilation (DCV), Air Handling Unit (AHU), Boost Controlled Ventilation (BCV), Building Energy Management Systems (BEMS), Building Energy Performance Simulations (BEPS)

1 Introduction

As the European green deal aims for carbon neutrality by 2050, all sectors must contribute to a severe reduction in energy consumption. Thus, the built environment -the single largest energy consumer in the European Union accounting for 40% of total energy consumption- must contribute its share [1]. In fact, the operation of buildings account for 30% of the energy consumption and 27% of greenhouse gas emissions in the European Union [2]. To reduce the energy demand in this sector, multiple solutions are available for building designers, i.e. reducing thermal transmission, improving the efficiency of HVAC installations, and exploiting renewable energy sources [3], [4]. In recent years, the importance of Building Automation and

Control Systems (BACS) is recognized in reducing the energy demand of buildings. Thus, multiple new provisions are included in the recast Energy Performance of Buildings Directive (EPBD) in 2018. The projected savings due to BACS measures are 450 TWh of annual final energy savings by 2035 within EPBD [5]. Several European standards discuss building energy performance, of which EN 52120-1 explorers the potential of BACS in enhancing building energy performance [6].

BACS typically comprises sensors, controllers, output devices, communication protocols and a user interface for automatic control, monitoring and optimization [7]–[10]. Sensors are responsible for detecting and perceiving input emanating from the physical environment, while actuators execute control actions in adherence to the logical directives established by the controllers [11]. The definition of BACS provided by EN 52120-1 is the following: “System, comprising all products, software and engineering services for automatic controls (including interlocks), monitoring, optimization, for operation, human intervention, and management to achieve energy-efficient, economical, and safe operation of building services” [6]. According to ASHRAE guideline 13-Specifying Building Automation Systems, a Building Automation System (BAS) comprises microprocessor controls that allow for control algorithms, scheduling events, event notifications trend data collection and network communications that can be applied [12]. While such systems require greater attention, they are a vital asset in curbing unnecessary energy wastage through e.g. demand controlled heating, cooling and ventilation or daylight dimming. This way, significant savings can be achieved, in both thermal and electrical energy [13]–[16]. The most profound energy savings, absolute and relative, from BACS are achievable in buildings with relatively high energy consumption [17]–[19]. Prior research exploring a holistic retrofit of BACS in office buildings impacting multiple energy-consuming domains found primary energy savings of up to 50% [20]–[22].

Additionally, BACS can improve the comfort of building occupants through better regulation of IEQ, i.e. temperature, air quality, illuminance levels and noise levels [23]–[27]. One key difference between office buildings and residential buildings is that office buildings often have a designated facility manager who is responsible for managing and implementing energy policies [28], [29]. Facility managers can improve the performance of their buildings by implementing efficient BACS, which can assist by taking over janitorial services and quickly detecting and diagnosing any issues that may arise [30]–[32]. Despite the potential benefits, these systems are more complex than more traditional ways of saving energy, e.g. insulating the building envelope [33], [34].

In addition to the complexity of BACS, the high investment and operating cost can also be a deterrent to widespread adoption [35]–[37]. Despite the initial investment, the payback period for building automation is relatively short, typically between 0-5 years, according to building automation market players Siemens and Priva [38], [39]. The European building automation controls association (eu.bac), an association of different building automation and control systems manufacturers, assumes a payback time between two and six years depending on the complexity of the system [40]. The EPBD recast states that the monitoring of technical building systems should be the most cost-effective alternative to inspections in large non-residential buildings and, thereby, allow a payback period of under three years [41]. Cheng et al. show in a review paper that the payback periods for Building Energy Management Systems (BEMS) in commercial buildings were shortened from 5.4 to 0.7 years between 1977 and 2017 [42]

However currently, the large-scale adoption of BACS is hampered by certain challenges. Due to the complexity of the systems, it is unclear which energy savings and when the return on investment can be realized. The interaction between different systems further complicates this [43]. In addition, gaps in knowledge and potential problems specific to these building automation systems are the life expectancy of the different components, obsolescence of hardware or software parts, vendor lock-in and cybersecurity [8], [44]–[48]. The European standard EN 52120-1 endeavors to address this gap in energy savings by the proposal of general saving factors to estimate energy savings resulting from BACS upgrades. In this method, BACS are divided into seven categories [6]:

- Heating control
- Domestic hot water supply control
- Cooling control
- Ventilation and air-conditioning control
- Lighting control
- Blind control
- Technical home and building management

This standard prescribes two methods for estimating the reduction in energy consumption: a detailed energy performance analysis and a simplified calculation for estimating, i.e. the BAC factor method. The BAC factor method breaks down the seven domains of BACS into specific systems where automation is feasible. Thus, the section lighting control is further specified into occupancy control and daylight harvesting. For each of these classes, ranging between no control and full automation, the BAC efficiency class can be determined. Class D corresponds to non-energy efficient BACS, class C is the reference scenario (standard BACS), class B represents advanced BACS and some specific Technical Building Management (TBM) functions and lastly, class A corresponds to high-energy performance BACS and TBM functions.

This review paper will provide a state-of-the-art of literature discussing energy savings and influential parameters of BACS implementation in office buildings. This way, this review can serve as a foundation for future research in assessing energy savings in a design phase. For this purpose, various studies are listed by domain relevant to office buildings. The consulted references differ in methodology: there are both (laboratory) field studies and simulations in dynamic software. The advantages of simulations are the predictive capabilities and the convenience of easily simulating a large variety of cases, however, such simulations require detailed information about building design, climate and occupancy profiles which limits accuracy [49]. Thus, a 'performance gap' may occur which indicates the difference between the simulated results and the effective situation, the main reasons being weather data and occupancy patterns [50]–[53]. The research of O'Grady et al. shows that EnergyPlus is commonly used in the academic context, though, validation through case studies is limited [54]. Field studies have the advantage of a realistic reference case, although the research is limited to a particular situation and climate [55]. For each section, a conclusion will be drawn on the estimated energy savings and, where possible, a comparison with the BAC efficiency classes of the standard EN 52120-1.

First, the method of this review paper is discussed. Next, the BAC factor method of EN 52120-1 is reviewed after which the selected references are reviewed in a structured manner. Decisive parameters are identified by analyzing variations between references, and general conclusions are drawn whenever possible.

2 Methods

This review paper aims to identify research on the energy savings that can be achieved by implementing BACS in office buildings. For this, relevant papers were sought on various channels e.g. Google Scholar, Web of Science, IEEE Xplore, Springer and ResearchGate. The following keywords were combined to find relevant papers: 'office building', and 'energy savings' combined with the various domains of building control e.g. 'smart shading', 'heating control', 'ventilation control' and 'occupancy detection'. The results were further filtered by year; only post-2015 references were used due to the rapid evolution of the building automation market. The final selected references are a combination of studies with field experiments and Building Energy Performance Simulations (BEPS).

Most literature applies a particular automation system in an office building e.g. demand-controlled ventilation, occupancy detection for lighting and occupancy sensors for heating demand. The distribution in the total energy consumption of the different domains also varies strongly in offices [56]–[60]. Therefore, this review paper will distinguish the main domains in office automation for a structured overview. Thus, the next section will first discuss energy savings for heating and cooling control. Next, savings by automated ventilation are reviewed. Hereafter, the control of office lighting will be reviewed. Lastly, the control of blinds in offices is evaluated. Control of Domestic Hot Water (DHW) supply is deliberately not included in this review as its share in office energy consumption is rather negligible, unlike residential buildings [61]–[64]. The category of technical home and building management concerns the ability to adapt operations easily to the user's needs [6]. This includes correcting extreme values of set points, controlling the interlock between heating and cooling and alarming and monitoring functions. Although this is a key part of a Building Management System, this is only discussed shortly as it does not always lead directly to energy savings. Other common control types, not discussed because not relevant to energy consumption, are fire alarms and security systems [65].

3 Energy savings according to literature

As discussed in *methods*, the savings that can be achieved by (1) heating and cooling control, (2) ventilation control, (3) lighting control and (4) blind control are discussed in this section. The selected references are a combination of field studies and dynamic energy simulations to quantify energy savings. Before doing so, the benchmark for the classification of energy savings will be discussed, i.e. the BAC factor method of EN 52120-1.

The standard concerns the contribution of BACS to the energy performance of buildings through listing BAC functions contributing to the energy performance, other building automation standards do not quantify the impact on energy consumption and are therefore left out of this review paper:

- EN 16484: Building automation and control systems (BACS).
- EN 17609: Building automation and control systems - Control applications.
- EN 14908: Open Data Communication in Building Automation, Controls and Building Management - Control Network Protocol).
- EN 22510: Open data communication in building automation, controls and building management - Home and building electronic systems - KNXnet/IP communication).

- EN 13321-1: Open data communication in building automation, controls and building management - Home and building electronic system) do not quantify the impact on energy consumption and are therefore left out of this review paper.
- CEN 16946: Energy Performance of Buildings - Inspection of Building Automation, Controls and Technical Building Management).
- CEN 52127: Energy performance of buildings - Building management system.

3.1 EN 52120-1 BAC factor method

The standard divides the building types into office, lecture hall, education buildings, hospital, hotel, restaurant, wholesale and retail trade service buildings and other types, i.e. sports facilities, storage and industrial building. As discussed above, the European standard EN 52120-1 describes two methods for estimating energy savings by implementing BACS. In the simplified BAC factors, Class C, i.e. a building with standard BACS, is the reference for an estimate of the reduced energy consumption in the simplified method. The BAC factor method determines factors that estimate energy savings when upgrading the control systems to a higher automation class. The BAC efficiency class changes if all systems meet the requirement of the new class if relevant to the building. Table 1 below provides an overview of the BAC efficiency factors of offices by class, both overall (thermal and electric) and classified by heating, cooling, DHW, lighting and auxiliary. The BAC classes are discussed earlier and the efficiency factor for class C is 1 since this is considered the reference class. Although, some studies consider class D as the reference class if no form of BACS has yet been introduced in the building. The BAC factor is a simple tool that can be used to estimate savings but according to literature, estimated savings are not always accurate [66]–[68]. EN 52120-2, explanation and justification of EN 52120-1, mentions that the BAC factor should only be used for a rough estimation of the saved energy when changing from one BAC class to another, low-quality estimations are reached in post estimation of the saved energy based on the measured energy consumption after class changes [69].

Table 1 Overview of the BAC efficiency factors of offices according to EN 52120-1 [6]

		D	**C**	**B**	**A**
Overall	$f_{BAC,thermal}$	1.51	1	0.80	0.70
	$f_{BAC,electric}$	1.10	1	0.94	0.89
Detailed	$f_{BAC,heating}$	1.44	1	0.79	0.70
	$f_{BAC,cooling}$	1.57	1	0.80	0.57
	$f_{BAC,DHW}$	1.11	1	0.90	0.80
	$f_{BAC,llighting}$	1.10	1	0.85	0.72
	$f_{BAC,auxilary}$	1.15	1	0.86	0.72

The BAC factor method only considers the reference building automation class, without the need for specific control functions and provides simple energy efficiency factors when upgrading [6]. The factors are based on a simple one-zone model where different fixed schedules are adopted for the building types. Due to this simplified approach, literature suggests that these factors are insufficient as highly influential parameters are not considered [22], [66], [70], [71]

It is worth noting that plug loads are a significant source of electricity consumption in offices, i.e. up to 20% of office electricity use and likely more in energy-efficient office buildings, the control of these loads through smart outlets can lead to energy savings [60], [72]–[75]. The control of plug loads by smart outlets can turn off certain devices by absence. Despite the potential benefits in offices, often with plenty of electric devices e.g. computers, monitors, printers, vending machines and projectors, this is not included in the BAC factor method. Other methods are available besides the BAC factor method, i.e. the eu.bac classification and the Smart Readiness Indicator (SRI) [76], [77]. The eu.bac is a methodology for the auditing and certification of BACS based on EN 52120-1. A grade from E to AA can be achieved through a points-based assessment of the entire life cycle of a building automation system. A case study was used to determine the rule of thumb that a drop of 10 points introduces a 5% saving [78]. Recently, the EPBD involves smart building technologies in its focus areas. Thus, the SRI is used as a tool to rate the smart readiness of a building. The goal is to raise more awareness about the potential of incorporating BACS into buildings, the reviewed domains are heating, cooling, DHW, controlled ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging and monitoring and control [79], [80]. The SRI exceeds in energy-consuming domains by dynamic building envelope, electricity, electric vehicle charging and monitoring and control, this review will merely focus on the domains provided by EN 52120-1. The review paper of Van Thillo et al. provides a more comprehensive explanation of various BACS assessment models in addition to the potential energy savings of BACS in residential buildings [81].

3.2 Heating and cooling control

In Europe, heating and cooling systems are widely used in office buildings to maintain thermal comfort, including radiators and air climatization [82], [83]. The latter category includes combined HVAC systems that offer heating, cooling, and ventilation, as well as passive chilled beams that solely manage air temperature. EN 52120-1 has divided heating and cooling into several control functionalities, i.e., emission control, control of distribution network supply or return hot/cold water temperature, control of distribution pumps and sequencing of different heat generators/chillers. Although the significance in energy consumption and comfort, EN 52120-1 does not specify control algorithms [6]. Rule Based Control (RBC) is a common strategy for building control, which utilizes rules and heuristics to manage temperature control [84]. Towards manual temperature control, e.g. thermostatic valves on radiators, a rule-based strategy can ensure energy savings due to better scheduling. However, poorly tuned RBCs can lead to comfort issues and energy inefficiency. In contrast, Model Predictive Control (MPC) calculates optimal control inputs based on a mathematical model that considers current state measurements and forecasts, ensuring more efficient temperature control [85]. Model Predictive Control (MPC) can ensure more efficient temperature control by calculating optimal control inputs based on a mathematical model which takes current state measurements and forecasts into account [86]–[88]. The literature review of Blum et al. concerning MPC implementation in office HVAC systems concludes energy or cost savings between 10% and 70% with building construction, ambient conditions and reference case conditions as influential parameters [89]. Though MPC has received greater attention in research, the majority of buildings still adopt RBC [86]. The reviewed articles in this section regarding heating and cooling control are rule-based as well as model predictive control, summarized in table 2 below. As mentioned above, the EN 52120-1 standard divides heating and cooling control into distinct functionalities, though, this review concentrates solely on emission control in office buildings.

Emission control for heating and cooling control is divided into no automatic control and centric automatic control (D), individual room control (C), individual room control with communication (B) and individual modulating room control with communication (and occupancy detection) (A). Zhao et al. developed a control strategy for a multizone VAV air-conditioning system based on occupancy and thermal comfort in an office floor in Shanghai, China [90]. The case study for TRNSYS simulations was a 16-zone office floor located in Shanghai with a multi-zone VAV air-conditioning system. The proposed method optimized the temperature set point for each zone in real-time according to occupancy levels, resulting in energy savings of 7.4%, 9.4%, and 12.4% for occupancy rates of 25%, 50%, and 75%, respectively. The reference case was a temperature setpoint-based control strategy that did not consider occupancy levels or the thermal sensation of occupants. Peng et al. investigated a demand-driven cooling control strategy for six offices over two months [91]. The control module of this method defines the air temperature set point based on the predicted occupancy, resulting in energy savings of 21.2%-39.4% for occupancy rates ranging from low to medium. The research found that the energy savings of the system are inversely proportional to its occupancy rate. Brooks tested a VAV box control algorithm in a university setting based on real-time occupancy measurements [92]. The baseline control was a dual-maximum control scheme, the proposed RBC controller differentiates through unoccupied mode and no fixed minimum air flow rates. The field study is performed for 6 days in April and found a reduction of 37% of HVAC energy. Wang et al. simulated a medium-sized office building with VAV systems controlled by occupancy information [93]. The control method based on occupancy information sets the airflow to zero in unoccupied private offices and conference rooms, resulting in energy savings of 13% in the Baltimore climate. However, savings were partly due to occupancy-based lighting control. Kong converted two laboratory rooms into open-floor offices to test the effectiveness of occupancy-centric control in offices [94]. The HVAC system of the controlled office space had three modes, occupied, unoccupied, and standby, and was based on actual occupancy information. The comparison of the two rooms showed weekly averaged savings in HVAC energy between 17% and 24%, depending on weather conditions and sensor accuracy.

As previously mentioned, MPC has the potential to achieve greater energy savings while simultaneously maintaining or improving occupants' comfort. To this end, several studies have been conducted to investigate the effectiveness of MPC in various office buildings. For instance, Freund et al. examined the implementation of MPC in a large-sized, low-energy office building located in Hamburg, which serves as the headquarters for local ministries of energy and environment [95]. The building, which comprises 1,250 offices and spans 46,500 m², is heated using thermally activated building systems such as thermoactivated ceilings. The authors found that MPC resulted in a 30% reduction in heating energy compared to the use of a Rule-Based Control (RBC) heating schedule based on outdoor air temperature between February and April. MPC was found to be superior to RBC in slow-response heating systems. Similarly, de Coninck et al. implemented MPC in a medium-sized office building in Belgium [96]. The reference control algorithm was RBC, and the building was heated using two heat pumps and a boiler that supplies radiators, fan coil units, and an air handling unit. The authors found that MPC saved between 20% and 30% of primary energy use while achieving similar or better thermal comfort levels than RBC. The savings in energy consumption were achieved through the optimal and increased use of heat pumps, an early start-up for preheating, and the significant reduction of water supply temperature as soon as the desired comfort level was achieved.

Multiple studies report energy savings by class A emission control which corresponds to Individual modulating room control with communication. Savings with these measures range between 7% and 37% of HVAC energy. The studies introduce occupancy-centric control algorithms to ensure energy savings while maintaining comfort. EN 52120-1 describes this as upgrading from class D “central automatic control” to class A “individual modulating room control with communication”. Model predictive control even ensures greater savings, up to 30% of primary energy, depending on the controlled variable. To define absolute energy savings, climate does play an important role. Climate determines the heating or cooling load of buildings and influences the behavior of occupants. Older research by Persily et al. also describes the climate as well as occupancy schedules as important parameters [97].

Table 2 Overview of the references concerning heating and cooling control

Study	Location	Methodology	Description	Control algorithm	Control system EN 52120-1	Energy savings
Zhao et al. (2023) [90]	Shanghai	Simulations in TRNSYS	16 zone office floor of 720 m^2	RBC	Class A: Individual modulating room control	7.4–12.4% in cooling energy in summer
Peng et al. (2017) [91]	Singapore	Field study	Office space of 550 m^2	RBC	Class A: Individual modulating room control	20% cooling energy during 2 months
Brooks et al. (2015) [92]	USA	Field study	University campus of 3700 m^2	RBC	Class A: Individual modulating room control	37% of HVAC energy for six days in April
Wang et al. (2020) [93]	USA	Simulations in EnergyPlus	3-floor office building of 4950 m^2	RBC	Class A: Individual modulating room control	< 8–13% in total energy
Kong et al. (2022) [94]	USA	Laboratory field study	2 open floor offices of 66 m^2	RBC	Class A: Individual modulating room control	17-24% HVAC energy during 5 weeks
De Coninck et al. (2016) [96]	Belgium	Simulations in Modelica	2-story office building of 960 m^2	MPC	-	20–30% of total primary energy
Freund et al. (2021) [95]	Germany	Field study	Office building of 1250 offices, area of 46 500 m^2	MPC	-	30% of heating energy

3.3 Ventilation control

Demand-controlled ventilation (DCV) can result in significant energy savings for office buildings by avoiding unnecessary ventilation caused by varying occupancy. Several studies have shown energy savings achievable through DCV, as presented in Table 3 below. DCV systems help reduce electricity consumption by fans and lower the amount of conditioned air extracted from rooms in comparison to Constant Air Volume (CAV) systems. EN 52120-1 specifies control of not only supply air flow but also free mechanical cooling. Control configurations for free mechanical cooling include night cooling, free cooling, and H,x directed control.

Son et al. examined the application of enthalpy-based free cooling (taking into account temperature and humidity conditions) in a Korean office building [98]. The researchers compared this approach to a reference case in which the outdoor air flow rate was set at the minimum legal requirement for the entire simulation, and no economizer was used. The simulations revealed that significant energy savings were possible during the cooling period (April-October), with a 5.5% reduction in electric chiller energy compared to the reference case. Similarly, Stasi et al. investigated hybrid ventilation strategies in a former industrial shed that had been retrofitted into housing units and office spaces [99]. One of the proposed strategies involved free cooling in mechanical ventilation based on temperature conditions. The researchers estimated that total savings in cooling electricity ranged from 0% to 7.7% between April and October, depending on the climate (with Palermo showing no savings, and Bari, Roma, and Milano achieving savings of 7.7%, 6.6%, and 7.5%, respectively).

DCV (Demand-Controlled Ventilation) can reduce air flow in unoccupied or partially occupied zones, as noted previously. Ahmed et al. conducted a study that simulated the indoor climate and energy performance of a Finnish low-energy office building when implementing DCV [100]. The study found that the average occupancy rate during office hours was only 55%, making it suitable for introducing DCV. The DCV system coupled with cooling saved around 10% of primary energy compared to a CAV (Constant Air Volume) system with a flow rate of $1.6\ m^3/s.m^2$, and the total HVAC energy consumption was reduced by 41%. The DCV controller used a CO2 setpoint of 700 ppm, a heating setpoint of 22.5 °C, an AHU (Air Handling Unit) cooling setpoint of 24 °C, and an active chilled beam cooling setpoint of 26 °C. Even greater energy gains are described in the literature, Hackel et al. found a reduction of up to 49% in energy consumption for HVAC [101]. As this office was heated and cooled by a ground-source heat pump, electricity was the energy carrier for heating, cooling, and ventilation. The CO2 setpoint is set following the guidelines of Appendix A of ASHRAE standard 62.1. Besides an office, also an art gallery, libraries and art centers were tested. The office building may have high relative energy savings, but the cost savings are limited due to the installed ground source heat-pump and energy recovery ventilation system. Implementing DCV also greatly affects the energy consumption of fans. Chenari et al. also studied the implementation of DCV in an office building [102]. The reference in this study was a CAV fan system with occupancy control (class B) but not considering the number of occupants. The deviations from the reference included VAV (Variable Air Volume) systems with DCV based on the number of occupants (still class B) and DCV based on a CO2 setpoint (class A). The study found that the realized savings amounted to 22% of fan energy for the DCV based on the number of occupants and 28% of fan energy for the DCV with a CO2 setpoint. Greater savings were achieved by ventilation based on the number of occupants, though this was still class B as the reference. Merema et al. calculated the reduction in fan energy as well as in heat losses by implementing DCV in an office building of the Catholic University of Leuven [103]. The reference was a CAV system where the air flow rate was based on occupancy, providing a default flow rate of 29 m³/h.pers. The study found that reductions of 50% fan energy were achieved, and heat losses decreased by 34%, which ensures great savings when no heat exchanger is installed. However, because of the high fixed heating setpoint, the reduction in heat losses was less substantial than in a kindergarten and lecture room, both of which were also tested in this research. The reason the savings here are significantly higher than in the study of Chenari et al. was the use of a CAV system with an on/off control compared to a CAV system with occupancy control. Kohtaniemi et al. compared a CAV system to DCV as well as Boost Controlled Ventilation (BCV) [104]. The DCV system saved up to 25% of fan energy in the small simulated office, which reached up to 53% in the meeting room where a lower occupancy rate was favourable. The lower savings in the office were due to occupancy schedules, with the office occupied between 9 am and 5 pm, except for a one-hour lunch break. Although the DCV system provided the greatest energy savings for fan energy, the BCV provided the greatest energy savings overall when taking electric cooling energy into account. Finally, Delwati et al. studied three landscape offices with a ventilation system for three rooms in a laboratory study [105]. The research was focused on the cooperation of the fan and the valves on the room VAV systems. Ventilation demand was determined from 24h measurements of three landscape offices in a real building under normal conditions, two measurement campaigns were carried out with the flow rate being higher in set 1. The reference CAV system will constantly provide the peak demand while with DCV with a constant static pressure point, variations in flow rate are supplied. The difference in fan energy between the CAV system and the DCV system was between 64% and 84%, depending on the profile settings, the greatest savings were achieved for the smaller office. Simulations in modelling were also carried out and confirmed the results of the laboratory study. The reference is the university building with 40 offices with a CAV system which is always on between 6:30 and 18:00.

The studies included in Table 3 typically involve upgrading ventilation systems in office buildings from class D, which entails no automatic control, to class A, which relies on demand-based control. Electricity savings fall into the wide interval of 25%-85% which is due to the reduction in the frequency of fan usage. The ventilation flow is usually delivered through a CAV system which is activated during office hours as a reference case. As a result, the greatest savings occur in offices with a highly variable occupancy rate. Class D represents a constant airflow which is manually turned on and off, a more common system in offices is a VAV system with time control (class B). HVAC savings can reach up to 49% as a lower outside air flow leads to a lower extraction of conditioned air, though, this strongly depends on the occupancy rate. Also, climate plays an important role in when free cooling is of interest and in the amount of energy necessary for reheating or cooling outside air.

Table 3 Overview of the references concerning ventilation control

Study	Location	Methodology	Description	Control system EN 52120-1	Energy savings
Son et al. (2016) [98]	Korea	Simulations in EnergyPlus	Three-story office of 5,576 m²	Class A: H,x- directed control	5.5% of chiller electric energy during the cooling period
Stasi et al. (2022) [99]	4 climates	Simulations in EnergyPlus	2-story building with residential and office spaces	Class B: Free Cooling	0–7.7% of electric cooling energy
Ahmed et al. (2015) [100]	Finland	Simulations in IDA ICE	Skanska Finland’s head office of 9,100 m²	Class A: Individual modulating room control	41% of total HVAC energy
Hackel et al. (2015) [101]	USA	Field study	Office in Minnesota of 929 m²	Class A: Individual modulating room control	49% of total HVAC energy
Chenari (2016) [102]	Portugal	Simulations in Energyplus	Test office in a university lab of 47 m²	Class B: Occupancy detection Class A: Demand-based control	22% of fan energy 28% of fan energy
Merema (2018) [103]	Belgium	Field study	Office building KU Leuven	Class A: Demand-based control	50% of fan energy
Kohtaniemi et al. (2022) [104]	France	Simulation in IDA-ICE	Small office room of 22 m²	Class A: Demand-based control	25-53% fan energy
Delwati (2018) [105]	Belgium	Laboratory field study	Three landscape offices of 12 m² each	Class A: Demand-based control	69-85% fan energy

3.4 Lighting control

Lighting is a significant contributor to energy consumption in office buildings, accounting for around 17-25% of electric energy and about 10% of total building energy use [106]–[108]. In the lighting control domain, building automation systems are available for occupancy detection and daylighting. According to previous research conducted by Roisin et al., occupancy or presence detection is particularly useful in offices with variable occupancy, and the effectiveness of daylight dimming is influenced by factors such as orientation and location [109]. Although it is possible to achieve substantial energy savings in lighting by sacrificing comfort, it is important to maintain visual comfort to ensure employee satisfaction [110]. Chew et al. reviewed energy savings of occupancy detection, daylight harvesting and the combination. The reviewed references are from pre-2015, general findings of his research are a reduction between 3-50% for the use of occupancy detection exclusively, between 20-92% for daylight dimming and the studies with a combination of the two control techniques find savings between 21.9-73.2% [111]. The studies regarding lighting control in offices are summarized in table 4 below. The reference is usually a situation where lighting is always on during office hours. Although this scenario is more realistic in an office building compared to residential buildings, still some form of occupants behavior is expected in office buildings regarding manual lighting control [112], [113].

Measuring occupancy is a key component for reducing lighting energy. Besides using the commonly used PIR sensors to detect presence, using a mobile application together with BLE beacons is a possibility too [114]. The implementation led to a 15.3% saving of lighting energy in an office with 10 employees where one light per two workers was designated in a study by Choi et al. [115]. The area managed by a particular occupancy sensor, also referred to as sensor resolution, has an impact in offices with highly variable occupancy. In addition, savings of 32% are found when the PCs and monitors are also controlled. As a reference, the lighting and device's energy consumption are calculated from real measured data from smart plugs. The timing of the field study was three months during spring. This field study considers one case, simulations allow more variation in input parameters. Thus, Lowcay found savings between the wide interval of 12-91% with the reason for the spread being dependence on the relative occupancy, available daylight, glazing ratio and sensor resolution [116]. Window shades were also considered, it is assumed that employees close the blinds at 2000 lx for the remainder of the workday. The setpoint for the lighting system was 400 lx, the luminaires will complement the daylight to achieve this illuminance. All luminaires are at full brightness each day for 16h in the reference case. In this research, location and glazing ratio has less importance. However, sensor resolution, referring to how many cubicles are controlled per sensor, is of great interest. For the Los Angeles case with 25% occupancy, the savings differ from 91%, 69% and 31% for respectively high, medium and low resolution. This varies between 1, 4 and 16 cubicles controlled for respectively high, medium, and low resolution. The effect of the resolution is clear, though, a higher resolution is achieved by additional sensors and therefore greater investment. The effect of occupancy detection and daylight dimming is investigated by Cheng et al. as well, savings of about 36% were observed in a field study [117]. The office consists of three zones, a zone for leisure time and two working zones where one zone is near windows. Occupancy detection is used in the leisure time zone and the zone that lacks natural daylight. Daylight dimming combined with occupancy detection is used in the zone near the window. Furthermore, a widely used software package for lighting calculation is DIALux, which is used by Wagiman et al. and Shankar for energy savings [118], [119]. An intelligent controller with the capability to learn from experience is implemented in an office by Wagiman et al. for daylight dimming which resulted in savings of 36% [118], [119]. The reference case is the non-retrofitted office with T8 luminaires, the retrofit consists of LED luminaires and the control systems. In the simulations by Shankar, daylight dimming has an impact of up to 48%, an occupancy schedule can even achieve an additional 19% savings [119]. The base case is LED luminaires running at full illumination and a clear sky, savings of 22% are achieved in a cloudy situation. Finally, Beccali et al. recreated a small office in a laboratory to test the efficiency of different systems [67]. Three different control systems were tested, i.e. no automatic control (reference case), an automatic on/off control and daylight dimming. Automatic on/off control had a limited impact of 6%, and daylight dimming control has a more substantial impact of 32%. The laboratory is also used for a residential case where the rooms were assigned another function, the main difference between these cases was the occupancy schedule. The results are compared to the BAC factors, no substantial differences are found for the upgrade to automatic on/off control, in contrast to the class A upgrade which shows significant deviations.

EN 52120-1 subdivides lighting control into occupancy control and daylight control. Savings in lighting energy range between 12%–91% when occupancy, as well as daylight control, is implemented. This is considered an upgrade to class A where class D manual on/off control is the reference in the research. Occupancy plays a major role in the case of lighting systems based on presence detection, climate affects the performance of daylight control. The resolution of the sensors to measure occupancy is also an impactful parameter. Thus, fewer sensors per area cause the lighting control to control a larger area and therefore, reduce the possible savings by a lower occupancy.

Table 4 Overview of the references concerning lighting control

Study	Location	Methodology	Description	Control system EN 52120-1	Energy savings
Choi et al. (2015) [115]	/	Field study	Office space with ten employees	Class A: Occupancy detection	15% of the lighting energy

Lowcay et al. (2020) [116]	USA	Simulations in DAYSIM and MATLAB	Single floor office of 576 m²	Class A: Occupancy detection and daylight dimming	12–91% of the lighting energy
Cheng et al. (2020) [117]	China	Field study	Office of 1400 m²	Class A: Occupancy detection and daylight dimming	36% of the lighting energy
Wagiman et al. (2018) [118]	Malaysia	Simulations with DIALux	Single office of 160 m²	Class A: Daylight dimming	34% of the lighting energy
Shankar (2020) [119]	India	Simulations with DIALux	Office of 108 m²	Class A: Daylight dimming	48% of the lighting energy
Beccali et al. (2017) [67]	Italy	Laboratory field study	Test office in a laboratory of 106 m²	Class C: ON/OFF control Class A: Daylight dimming	6% of the lighting energy 32% of the lighting energy

3.5 Shading control

Solar shading in offices affects heating and cooling loads, however, improper use of shading control systems can lead to an increased energy demand [120]–[123]. Besides energy savings, control of solar shading can provide increased productivity by enhancing thermal and visual comfort in offices [124]–[126]. EN 52120-1 describes manual operation or manual control as class D, Class A can be achieved by a combined light, blind and HVAC control. Because of the substantial internal gains in office buildings, a control system that takes all parameters into account is desirable [127]–[129]. Table 5 provides an overview of the references discussing blind control in offices.

In Belgium, Garzia et al. simulated an automated shading system on the middle floor of an office building [125]. The control system is based on illuminance levels and indoor temperature. Because this automation system does not control the lighting level and HVAC settings, this is considered class C in office buildings (B in residential buildings). The reduced required heating energy is rather limited, i.e. 1.4%. This minimal saving is due to occupants not allowing all useful solar gains at the manual control reference. However, this control system can greatly improve the undesirable high illuminance and the occupants are less exposed to unwanted high indoor air temperatures, a cooling system is not simulated. Other studies review control systems with a higher degree of automation. The research of Lamano et al. simulated automated blinds combined with an auto-dimming function of the lighting system, the reference cases are always open and always closed blinds between 10:30 and 18:00 [130]. This saves up to 54% of lighting energy, between 2 and 5% of electricity for air-conditioning and around 9–10% of the overall building energy consumption. Kang et al. also have a combined control system in laboratory testing [131]. This system takes the heat gains and illumination into account of the sun and the lighting. This way, the cooling load will reduce when the blinds are closed yet the lighting energy will increase. The reference is a set-point temperature control with always open blinds and an on/off lighting system. The savings achieved compared to the baseline were 41% of cooling energy, 20% of lighting energy and overall, a reduction of 30% was realized. Another laboratory investigation is conducted by Kunwar et al. where an automated shading system is implemented in test rooms with different orientations [132]. The control system harvests the optimum amount of daylight while minimizing glare. This way, an average of 25% of the cooling energy is saved and 49% of the lighting energy. The lighting in the baseline scenario was not adjusted or dimmed, also no solar shading was installed. An efficient shading control system can induce significant savings in cooling energy in certain climate zones, e.g. in Qatar where Al Touma et al. simulated an office space of 30 m² with a fully glazed façade with an automated shading system with a set point of the Daylight Glare Index (DGI) [133]. This resulted in 21.9% less energy consumption, though this is a class C control system. When combining the shading control with lighting control, a reduction of 38% in lighting energy and 26% in overall energy consumption is achieved. Besides simply opening or closing the blinds, Venetian blinds allow to adjust the slat angle. Kwon et al. evaluated the control of the slat angle of Venetian blinds assuming an office building with different window-to-wall ratios and different window orientations [134]. The control strategy aims for a minimum of heating, cooling, and lighting energy combined while maintaining 500 lux indoors. The control strategy led to energy savings of 21% in the cooling period and 12% in the heating period. The different window-to-wall ratios have a significant impact on savings from building automation, savings increased by up to approximately 70% as the window-to-wall ratio increased in the cooling period and approximately 50% in the heating period.

There are three ways according to EN 52120-1 to control window shading; manual control (class D), automatic control (class C) and a combined system that takes HVAC, blinds, and lighting into account (class A). The savings that an upgrade to system A represents are scattered in heating, cooling, and lighting energy. The reference case in the studies is usually blinds which are always on or off, only Garzia et al. have simulated the behavior of office employees in the reference case. The reference case where employees' interaction with outdoor parameters is neglected is unrealistic. Climate plays a significant role in the effectiveness of building automation and control systems. In tropical climates, automated shading is essential to prevent overheating and save cooling energy, while in moderate climates shading control should primarily balance allowing useful solar radiation and preventing glare on work planes.

Table 5 Overview of the references concerning blind control

Study	Location	Methodology	Description	Control system EN 52120-1	Energy savings
Garzia et al. (2022) [125]	Belgium	Simulations in Energyplus	Middle floor of an office building of 1080 m²	Class C: Automatic control	1.4% of heating energy
Lamano et al. (2018) [130]	Singapore	Simulations in Energyplus	Office of 93 m²	Class A: Combined control	54% of lighting energy 2–5% of air-conditioning energy
Kang et al. (2015) [131]	Korea	Laboratory field study	Office of 60 m²	Class A: Combined control	41% of cooling energy 20% of lighting energy
Kunwar (2020)	USA	Laboratory field study	Office with six test rooms of 25 m² each	Class A: combined control	25% of cooling energy 49% of lighting energy
Al Touma et al. (2017) [133]	Qatar	Simulations in Energyplus	Office of 30 m²	Class C: Automatic control Class A: Combined control	21.9–26.1% of total cooling and lighting energy
Kwon et al. (2017) [134]	Korea	Simulations in Energyplus	Office building of 4850 m²	Class A: combined control	21% of the total energy cooling period 12% of the total energy heating period

3.6 Technical Home and Building Management

The last domain EN 52120-1 distinguishes in building automation is technical home and building management, including setpoint and runtime management, automated fault detection and diagnosis, information reporting, local energy production and renewable energy, heat recovery and heat shifting and smart grid integration. The REHVA guidebook *Introduction to building automation, controls and technical building management* describes Technical building management as the core of an integrated facility management system which provides information on the total run time and condition of equipment and which monitors and provides feedback on energy targets [135]. While these functions are crucial for a well-functioning BMS, it is difficult to directly link them to energy savings. Nevertheless, the research of G. Lin et al. shows that Fault Detection and Diagnosis (FDD) saves around 8%, based on 26 organizations containing 550 buildings with FDD [136]. Correctly functioning FDD can lead to energy savings by preventing abnormal HVAC system operation, which can result in increased energy consumption and poor environmental quality.

4 Discussion

A comprehensive assessment of various building automation components is conducted by merging data from field studies and Building Energy Performance Simulations (BEPS). The control system described in the studies is converted into an automation class according to EN 52120-1. The discussion of this review paper will further elaborate on the BAC factor method, field studies and dynamic energy simulations, the control of heating, cooling, ventilation, lighting and shading and, lastly, the influential parameters.

4.1 BAC factor method

The BAC factor method provides saving factors for the following domains: heating, cooling, domestic hot water, lighting, and auxiliary. However, these factors are limited as the domains are further subdivided. The control of heating, for example, is further divided into emission control, control of supply or return water temperature, control of the distribution pumps, control of the heat generator, the sequencing of different heat generators and the control of thermal energy storage. Factors that estimate the savings of such a single intervention are not available, only broad estimates when upgrading from an efficiency class. Further detailed factors, based on multiple case studies, may be of interest since not always all components are installed in one building. The BAC factor method considers buildings with class C as reference which represents basic BACS. These factors do not directly represent energy consumption, therefore they are only of use when a benchmark is provided. Since the parameters are defined by a simplified “shoebox” model with an identical occupancy and differencing heating and cooling set points, the factors provided by this method are too limited as a framework for a dynamic energy simulation. In practice, a single zone model with a fixed daily occupancy pattern and without taking occupancy behavior at all into account is unrealistic and insufficient for assessing energy savings. For a more realistic reference model and thereby also more realistic estimations of the savings by BACS, a much more elaborate model is necessary.

4.2 Field studies and dynamic simulations

Energy savings can be assessed by measurements (field or laboratory field studies), where automation systems are implemented. This ensures that savings can be measured in real-time, though the measurement period is often limited in time. If the reference case and the retrofitted scenario are not in the same time frame, the reported energy savings may not be an accurate representation. The weather as well as the behavior of the occupants can differ significantly over time. Occupancy behavior depends on several parameters e.g. comfort, climate, personal preferences and culture making it difficult to compare. Constant climate changes ensure that a field study differing in time encounters validation issues. Additionally, only a short measurement period is considered in some cases giving an incomplete picture of performance through all seasons. Field studies do remain useful for the validation of results and for identifying human behavior, however, they are unsuitable for early design energy calculations.

Dynamic energy performance software, e.g. EnergyPlus, is commonly used for assessing energy savings in buildings. These software packages make it easier to simulate longer periods and allow easier testing of the impact of different parameters, however, the quality of the output depends on the level of detail of the input parameters. The input of a simulation is always a simplification of reality and therefore, deviations will occur which creates a performance gap. This way, the accuracy of these dynamic energy simulations will be influenced as occupancy behavior, e.g. opening windows, thermostat set points, lighting switching and the usage of blinds is a highly uncertain parameter causing a great variety. This behavior which is included in field studies (less in laboratory tests) is difficult to simulate. Sometimes a deterministic estimation is attempted of the reaction on certain occurrences e.g. glare on computer screens. However, usually, a simple reference case is assumed in the aforementioned studies where human behavior is of no importance e.g. blinds always open or closed, no interaction with windows or lighting on and undimmed during office hours. More realistic models are the probabilistic models where distributions represent the likelihood of different outcomes or actions given certain inputs although little literature has been found where these models serve as a reference for determining the performance of Building Automation and Control Systems. Dynamic energy performance simulations can assist BACS manufacturers in product development by easily generating useful data for different scenarios.

Incorporating occupancy behavior in dynamic energy simulations would increase accuracy, as occupancy behavior has a major impact on energy consumption [137]–[139]. Although the accuracy may increase, including occupancy behavior is complex and not straightforward. The researchers of Annex 66, Definition and Simulation of Occupant Behavior in Buildings, mainly oversimplified static schedules are used [140]. Challenges are quantifying the relationship of occupants with outdoor parameters, in addition to the impact of comfort, culture and economy [141].

Both field studies and dynamic energy simulations are a more elaborate method to assess energy savings of BACS relative to the simple BAC factors method, as BACS are implemented or upgraded in a real case in field studies and dynamic energy performance simulations demand input regarding influential parameters. Dynamic energy simulations have the advantage of assessing the energy performance in advance, which can assist in decision-making.

4.3 Temperature, ventilation, lighting and shading control

Most studies discussing heating and cooling control consider the impact of individual modulating room control, a form of emission control depending on effective occupancy instead of general time programs. According to EN 52120-1, thermal energy savings are around 54% by upgrading the control system from class D to A. The selected references in this review paper stated savings between 7% and 34% in HVAC energy. Therefore, the standard seems to overestimate the possible savings for thermal energy savings. This broad interval of savings in the studies is due to key parameters such as occupancy rate which seems to be an important parameter as in office buildings with a high occupancy rate, occupant-centric control is less effective. Climate and the control algorithm (e.g. CO_2 setpoint, but also RBC or MPC) also play a role in energy efficiency and savings for heating and cooling energy savings. The BAC factor method does not take any of the foregoing parameters into account.

Introducing DCV in offices relative to a CAV ventilation system has great potential for both thermal and energy savings. This way, the ventilation flow rate is usually based on a CO_2 setpoint allowing the setpoint to be drastically reduced during periods of low occupancy. According to the standard, an upgrade from a CAV system to DCV ventilation is an upgrade from class D to class A. The savings from the literature show significant differences and are in the range of 22% to 85% of fan energy. The BAC factor method describes a saving of 38% for an upgrade of class D to A for auxiliary energy. Added to this are savings in heating and cooling energy, up to 49%. Again, savings are influenced strongly by the occupancy rate. Free cooling in office buildings can save up to 8% in chiller energy but strongly depends on climate.

In the case of lighting systems, the reference in literature is typically a class D system where the lighting is mostly enabled during office hours. The upgrade of automatic detection of occupants and automatic dimming for daylight illuminance is considered case A. The BAC efficiency factors prescribe a reduction of around 35% upon upgrading from class D to class A for lighting which also ignores the influence of parameters i.e. occupancy patterns, sensor resolution, orientation and location of the building. The references consist of field studies where offices were retrofitted and simulations in DIALux and DAYSIM.

The BAC factor does not accurately reflect savings but even in literature, the reference scenarios of the simulations are usually too simple. For instance, it is often assumed that during office hours all lighting is on at full brightness though this forgets that employees themselves interact with lighting and that they usually turn off the lights when leaving the office. The Lightswitch-2002 model of Reinhart for manual and automatic control is a much more realistic approach to modelling human interaction [142].

Where occupancy control and daylight dimming mainly affect the lighting energy, automated solar shading influences the lighting level as well as the heating and cooling consumption of a building. When the control system manages the lighting levels in the offices as well as optimizing the HVAC and lighting energy, the system is considered class A. The control system is considered class C when the solar shading is only controlled by the level of illuminance. A reduction between 20% and 54% is obtained by upgrading to class A. The savings of cooling and heating energy differ significantly from one another though, key parameters are climate, set-points, window-to-wall ratio, and reference case. As discussed above, EN 52120-1 shows savings of 35% for the lighting system by upgrading from class D to A. Most of the studies have no solar shading as a reference case which is, in fact, worse than class D (still manual control of shading). There is a certain overlap between lighting control and blind control, daylight harvesting, and advanced automation of the blinds influence the required lighting energy.

4.4 Influential parameters

The occupancy rate is widely recognized as a crucial factor in determining the energy performance of office buildings, particularly when considering the implementation of BACS. The ability of BACS to effectively align energy supply with the actual energy demand is most pronounced in cases where the occupancy rate is reduced. Conversely, an oversimplified approach to the reference case can have a profound impact on the simulated energy performance of office buildings. By oversimplifying the case study parameters and assuming constant activity of energy-consuming technologies without manual adjustments, the initial excessive energy consumption becomes over-susceptible to the influence of BACS. The assessment of BACS efficiency entails careful consideration of the following parameters:

- Occupancy rate: the energy demand reduces as the occupancy rate reduces. BACS can control temperature, air flow, lighting and shading to reduce energy consumption during unoccupied periods.
- Occupancy behavior: the behavior of occupants plays a significant role in influencing the effectiveness of determining energy consumption in the reference case with manual control. If occupants with manual control are already economical in their choices of setpoints, setbacks, window and shading operations, the potential savings will be less significant. Furthermore, occupants have the potential to affect the effectiveness of BACS by manually overriding automated setpoints.
- Climate: temperature control is affected by climate as control systems have a greater impact in extremer climates, this also applies to shading control where offices in hot climates benefit greatly from automated shading. Daylighting control will also be more effective in hot and sunny climates.
- Setpoints: setpoints of controlled variables, i.e. indoor temperature, airflow, illuminance level and shading illuminance setpoints do greatly affect the energy saving potential. These setpoints can be defined by comfort requirements, this way, comfort requirements are also influential to the energy-saving potential of BACS.
- Control algorithm: MPC can adjust by prediction and therefore lead to even greater savings compared to RBC which is based on simple rules and current measurements. Predictions include weather, occupancy and heating or cooling load.
- Sensor resolution: the area that a sensor addresses, a greater resolution allows for more precise control.
- Orientation: the effectivity of daylight and shading control depends on the orientation of windows as solar radiation and illuminance are not equally distributed among the different orientations.
- Window-to-wall ratio: the effect of daylight and shading control is dependent on the window-to-wall ratio as this also affects solar radiation and illuminance levels.

5 Conclusion

In conclusion, this review paper has analyzed the implementation of building automation and control systems in the context of regulating heating, cooling, ventilation, lighting, and shading in office buildings. Through this examination, several limitations and gaps in the literature have been identified, necessitating their resolution to optimize energy savings and enable an accurate assessment of BACS efficiency. One significant limitation revealed in this review pertains to the simplified approach employed in the influential factors outlined by the European standard EN 52120-1. While this standard serves as a foundational framework for evaluating energy savings derived from BACS, it fails to adequately consider pivotal factors that exert a substantial influence on energy consumption. Factors such as occupancy rate, occupancy behavior, climate conditions, setpoints, control algorithms, sensor resolution, orientation, and window-to-wall ratio have been found to be critical determinants but are overlooked within the standard. To overcome this limitation, the utilization of building energy performance simulation emerges as a more viable approach for assessing the efficiency of BACS implementation. Nonetheless, it is imperative to ensure the accuracy of climate files, building characteristics, occupancy behavior, setpoint schemes, and other associated parameters in the simulation process. Neglecting the consideration of these parameters may result in an overestimation of energy savings due to an oversimplified reference case. This review paper strongly emphasizes the need for future research endeavors to enhance the accuracy of simulation parameters. Such endeavors would enable a comprehensive evaluation of the impact of BACS on energy savings, facilitating more precise predictions regarding potential savings in office buildings. Moreover, it is of utmost importance to extend research beyond energy savings and delve into the exploration of the co-benefits derived from BACS implementation. This entails investigating the influence of BACS on maintenance practices, facility management, occupant comfort, and other pertinent aspects. To comprehensively understand the impact of BACS, a holistic assessment should include a life cycle cost analysis, providing a broader perspective on the long-term benefits and economic viability associated with BACS integration. In conclusion, this review paper underscores the criticality of considering influential factors and incorporating them into the assessment of BACS implementation. By addressing the limitations illuminated through this study and conducting further research, stakeholders can make informed decisions and effectively optimize energy consumption in office buildings while simultaneously maximizing the potential benefits afforded by building automation and control systems.

Declaration of competing interest :

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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