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Review

Meeting User Needs through Building Automation and Control Systems: A Review of Impacts and Benefits in Office Environments

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Abstract: Smart building technologies and building automation and control systems (BACS) can offer a range of additional benefits beyond energy savings, in particular by improving building responsiveness to user needs. Although in recent years these technologies have gained popularity as a means of reducing energy consumption and improving building performance, a clear picture of the role of BACS in providing a wider range of benefits is still missing. This review identifies and collects BACS impacts in office buildings with a special emphasis on improving indoor environmental quality by adapting building operation to changing conditions and guaranteeing feedback and real-time interaction with occupants. The resulting benefits, such as increased employee productivity, fewer occurrences of sick leave, and lower rates of absenteeism are highlighted. Offices represent an interesting field of application, as small improvements in the built environment can have a significant impact on labour costs which are the predominant share of the total operating costs. Furthermore, quantitative relationships between physical factors of the indoor environment and benefits have been displayed where available. This literature review aims at establishing an approach that comprehensively evaluates BACS across their entire spectrum, leading to the promotion of novel business cases.

Keywords: BACS; non-energy benefits; office; comfort; health and well-being; productivity; absenteeism

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1. Introduction

The term "smart building" refers to a building that is capable of sensing, interpreting, communicating, and actively responding to changing conditions related to building systems or the external environment (e.g., energy grids). At a global level, the smart buildings market is expected to grow at a Compound Annual Growth Rate (CAGR) of 10.9% by 2026, reaching USD 121.6 billion [1]. The use of smart building technologies and building automation and control systems (BACS) is becoming more popular as a means of reducing energy waste. However, a significant portion of energy efficiency measures have been found to not be cost-effective enough if only energy savings are considered [2], thus investors have started to look into the additional benefits of these measures. It can be stated that non-energy benefits, often referred to as multiple benefits or co-benefits, are those outcomes created apart from or in addition to energy savings associated with an energy efficiency improvement and include, e.g., positive impacts on occupant comfort, health, and well-being, as well as energy flexibility. With the Energy Performance of Buildings Directive 2010/31/EU (EPBD Recast) [3] establishing the principles of cost-optimal and nearly zero-energy performance levels, policymakers started to emphasise the co-benefits of energy efficiency measures [4]. A progressive shift towards nearly zero-energy buildings (nZEB), as enforced by this legislation, requires significant adjustments to the existing structures of the building market, which means including added values beyond energy savings [5]. Smart building technologies and BACS assessment should undergo the same approach, as these can provide additional benefits, besides the positive energetic impacts, for many actors and stakeholders within the construction sector, i.e., building occupants, facility managers, owners, tenants, and smart service providers. BACS can help design healthier and more comfortable buildings and will play a role in facilitating the integration of renewable energy sources (RES) into future energy systems that will have a significant share of renewables and distributed energy supply, thus requiring a higher degree of demand-side flexibility (DSF). At the European level, one of the objectives of the 2018 EPBD amendment (directive 2018/844 of the European Parliament and of the Council of 30 May 2018 [6]) is to make the aforementioned benefits more tangible. Therefore, with the delegated regulation [7] and an implementing regulation [8], the Smart Readiness Indicator (SRI), a voluntary EU scheme for rating building smartness, was introduced. In particular, seven impact categories were defined in the SRI scheme to evaluate how a smart ready service can influence the building, its users, and the energy grid: energy efficiency, comfort, health, well-being and accessibility, maintenance and fault prediction, convenience, information to occupants, and energy flexibility and storage.

Although a 2016 review of BACS concepts and technologies noted that there were few references to the topic [9], in the following years, scientific literature showed a rising interest. Aste et al. [10] proposed a framework for the analysis of BACS potential for building performance optimization to tackle the gap between the designed and measured performance of nZEBs. Al Dakheel et al. [11] discussed smart buildings' features, functions, and technologies. Furthermore, the article reviewed existing key performance indicators associated with these technologies. O'Grady et al. [12] identified research trends and patterns about the current state of building automation. The article covers building automation architecture, benefits, and interactions with occupants. The present paper elaborates on the subject of BACS benefits, as a lack of literature that explores the wide range of BACS impacts on the built environment and the corresponding non-energy benefits has been identified.

As people spend the majority of their time indoors [13], poor indoor environmental quality (IEQ) can cause a series of negative effects. Therefore, among non-energy benefits, those related to a user-centric perspective such as comfort, health, and well-being, have been given particular emphasis in accordance with current research trends. According to O'Grady et al. [12], these are the second most researched topics in the BACS sector, with 34% of publications addressing perceived comfort and indoor air quality's (IAQ) effects on occupant health. Together with academic papers related to healthy buildings, there is a rising number of dedicated certification systems such as WELL, Fitwel, Healthy Building Certificate, and Living Building Challenge [14,15].

Finally, for the analysis, this study selected the office sector, which accounts for a large share of floor space. In Europe (EU27 + UK), about 24% of service buildings are offices [16]. The benefits of having a positive impact on office users are particularly interesting, as the cost of labour for office buildings is significantly higher than the cost of energy; it typically accounts for around 90% of business operating costs [17]. Therefore, employees' wellbeing and productivity as a result of comfortable and healthy conditions in the workplace is a key aspect. Conversely, there has been evidence that negative conditions can equally affect concentration and productivity [18]. Additionally, both short-term and long-term health problems can be accounted for as well. Short-term reversible effects such as headache, eyes and nose irritation, respiratory difficulties, and lethargy fall under the name of Sick Building Syndrome (SBS) [19].

The research question guiding the literature review was, "What are the main non-energy impacts and benefits associated with BACS in office buildings, in particular when responding to user needs?". The literature review has been conducted first by defining a specific nomenclature and indicating the criteria for publication selection in the materials and methods section. Then, BACS impacts on the built environment have been covered with a specific focus on the response to user needs. Finally, the benefits arising from these positive impacts have been analysed, highlighting mathematical relationships between physical factors and the specific benefits where available.

The main conclusions highlight how BACS can play a role in the creation of a comfortable and safe work environment. As a result, benefits in terms of improved productivity, reduced sick leave, and reduced SBS symptoms are placed under the spotlight and linked to building automation impacts on the built environment.

2. Materials and Methods

2.1. Nomenclature

As this review paper explores non-energy benefits of BACS, nomenclature issues have been addressed first. Starting with the term "BACS", there are several comparable terms that can be utilized to reference building automation, including Building Management System (BMS), Building Control System (BCS), Building Automation System (BAS), and Building Energy Management System (BEMS). BMS and BCS are generally used as overarching terms for systems that manage buildings, although they do not specifically denote automation systems. BEMS is focused on energy management. In this review, the term BACS has been chosen to identify systems that monitor and control building services, as defined by EN ISO 16484-2:2004 [20].

Secondly, the nomenclature related to "non-energy benefits" has been addressed. A 2012 report from the International Energy Agency (IEA) discussed the economic and social benefits of energy efficiency measures, as these have proven to have numerous benefits for the economy, society, and end-users well beyond the immediate results in terms of energy and cost savings. The term "multiple benefits" was employed to describe the wider socioeconomic outcomes that can result from energy efficiency improvement [21,22]. A similar concept was presented in the 2011 report "Assessing the Multiple Benefits of Clean Energy" from the US Environmental Protection Agency [23]. Later, the International Energy Agency Energy in Buildings and Communities Programme (IEA EBC) Annex 56 [24] worked on a new methodology for the cost-effective renovation of existing buildings and included a comprehensive definition of so-called "co-benefits". Co-benefits were defined as "the effects (either positive or negative) beyond the energy savings and the reduction of carbon emissions that may arise from high efficiency energy buildings and from an energy-related building renovation" [25].

In the present study, a database search was conducted, combining different keywords to understand which is the prevalent nomenclature. In combination with the word "building", the following keywords have been searched: "co-benefits", "multiple benefits", "multiple impacts", and "added values". Although the first two keywords are slightly predominant, no universally accepted nomenclature for non-energy benefits has emerged. For instance, a study dealing with energy efficiency investments analysed the corresponding "co-benefits", also defined as ancillary benefits [26]. Another study adopts a broader view, identifying co-benefits as a result of built environment strategies that promote climate change mitigation [27]. In addition, no clear distinction between "benefit" and "impact" could be found. As a general rule, the words "co-benefits" and "multiple benefits" refer to additional benefits with regard to an overarching perspective such as green building design or energy efficiency measures, which are seen as the "main benefit". Whereas the terms "multiple impacts" and, more in general, "impact" refer to the effects on specific areas of the built environment, such as comfort, energy flexibility, well-being, etc.

Therefore, after reviewing the state of the art, a specific nomenclature has been defined. On the one hand, the definition of "impact categories" was selected to identify those aspects of the built environment impacted by a certain technology, as proposed by the SRI assessment framework as well. The SRI assessment divides the impacts into three main areas: (1) Energy saving and operation; (2) Response to user needs; (3) Response to the needs of the grid. Al Dakheel et al. [11], in conducting a review of smart buildings features and key performance indicators, propose a similar breakdown, with a fourth area called "monitoring, control, and supervision" [11]. The pathway adopted by the SRI assessment has been chosen in this study, considering the fourth area integrated into the previous three.

On the other hand, the word "benefit" was selected to identify a positive outcome of impacting a specific category or area. For example, a well-designed and well-operated ventilation system positively impacts IEQ, in particular the IAQ levels, of a building. Stakeholders benefit differently from improved IAQ., i.e., for an office employee, reduction of SBS, stress, or better concentration are major benefits. These nomenclature choices are aimed at better clarifying and distinguishing terms that often are mixed or used interchangeably. Figure 1 summarizes the proposed approach, reporting impact categories, a further division in subcategories, and some examples of related benefits.

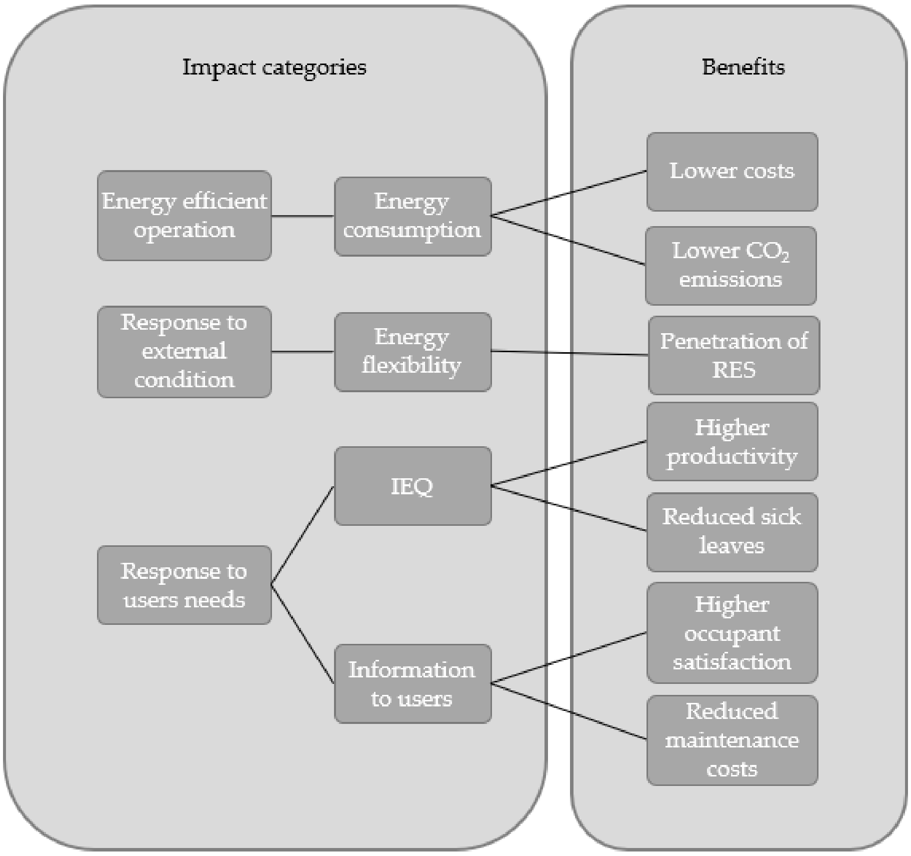

Figure 1. Nomenclature—impacts and benefits.

Energy efficient operation refers to the use of technologies that maximise energy savings. Reducing energy waste lowers costs and carbon dioxide (CO_2) emissions. The capacity to respond to external conditions relates to the ability to interact with the electricity grid in a flexible and dynamic manner. This allows a building to adjust energy use based on grid conditions, demand, and production. Response to user needs refers to the ability of a smart building to adjust its functions and systems to meet the specific needs and preferences of the person living or working there. Needs include factors such as having a high-quality indoor environment, being informed on building performance and management, and ensuring a safe and efficient operation and maintenance.

2.2. Literature Search

The publications were searched through various databases, e.g., Scopus, Web of Science, Google Scholar, Institute of Electrical and Electronics Engineers (IEEE), Xplore, and ResearchGate. The literature search carried out to identify the impacts and benefits of BACS in office buildings has been structured around two major blocks. On the one hand, technologies and systems have been reviewed based on the impacts areas. To this aim, the keywords “BACS” and “building automation” have been searched in combination with the impacts: energy efficiency, flexibility, the single subcategories of IEQ (thermal comfort, visual comfort, acoustic comfort, IAQ), and information to users. On the other hand, benefits resulting from improved impact categories have been searched. Keywords such as “thermal comfort” or “IAQ” or “visual comfort” have been searched in combination with the keywords “productivity”, “SBS”, “sick leaves”, and “absenteeism”.

The results have been filtered, discarding those not related to office buildings and focusing on the most recent ones. After the screening, 112 publications have been reviewed in depth (Figure 2). A significant 70% have been released within the last 10 years, while a notable 40% stem from the most recent 5 years. However, there is a set of studies, mainly from the US, published between 2000 and 2006 that examined the intersection of productivity, SBS, and work performance in office buildings. The majority of significant contributions to this topic emerged within these years, and these remain the most valuable references, as no major subsequent studies have supplanted their significance.

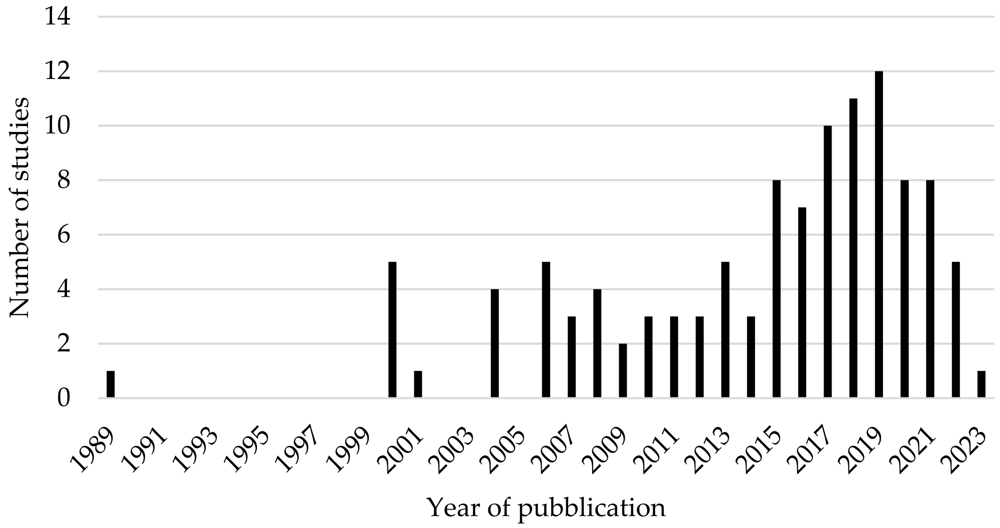

Figure 2. Yearly distribution of the reviewed literature.

3. BACS Impacts

3.1. Energy Efficient Operation

Energy efficient building operation has always been the main objective of several building technologies. This consideration is true for BACS as well; O’Grady et al. [12] reviewed studies on building automation systems and showed that the energy efficiency impact category is the most prominent; out of 79 scientific publications analysed, 73 target energy efficiency aspects. Non-residential buildings are responsible for 8% of global final energy consumption [28], and in the office sector, Heating, Ventilation, and Air Conditioning (HVAC) represents 33% of all energy use in the US [29]. Therefore, research efforts often focus on improving automation and control of HVAC generation, distribution, and emission systems. For instance, forecasting algorithms combined with an optimizer [30], or the integration of real-time weather responsiveness [31], are proposed to enhance BEMS functionalities. Two BACS retrofit options were evaluated in a Danish office case study, reporting energy savings up to 29% [32]. Model Predictive Control (MPC) for HVAC and lighting equipment instead of the conventional Rule-Based Control (RBC) has been studied in a Swiss office, showing 17% energy savings for MPC [33]. Thermostat control based on air temperature and operative temperature has been explored for fan-coil and radiant systems [34], showing energy savings in case of operative temperature control (up to 8.3%). Different control strategies for smart glazing have been analysed with and without daylight sensors. RBC using thermal load controls allows up to 9% energy savings, and optimised hourly settings save up to 20% of the yearly energy consumption [35]. Since workplaces consume more than 45% of their total electrical energy to provide adequate lighting [36], research on BACS tackled this topic intending to optimise energy use without compromising visual comfort. A fuzzy logic control system reduces energy waste by 30% without reducing occupant comfort [37]. A review focused on lighting control in open office spaces points out how control strategies that are occupant-dependent can reduce energy consumption by up to 60% [36]. Energy savings in the range of 45 to 61% are found for a control strategy based on daylight [38]. A meta-analysis study analysing multiple lighting control strategies found a potential for a 24% energy saving for occupancy-based approaches, a 28% energy saving for daylighting, a 31% energy saving for individual tuning, a 36% energy saving for institutional tuning, and a 38% energy saving for multiple approaches [39].

3.2. Response to the External Condition

The growth of renewable energy generation challenges the power grid balance due to its intermittent nature. Providing flexibility with higher power plant capacity or with energy storage are capital-intensive solutions; therefore, alternative power flexibility resources such as DSF need to be considered. Buildings are potential actors in DSF, as their energy flexibility can be determined by parameters such as thermal mass, HVAC and lighting systems characteristics, and occupant behaviours [40]. The BACS commonly available in office buildings and their large thermal inertia enable them to participate successfully in grid response activities [41,42] by shaving peak loads and maximising economic benefits. In a study reviewing the potential and building performance implications of DSF, power flexibility characteristics (shed-ability, controllability, and response time) for key office building loads are reported with corresponding literature [43]. Requirements for coordinating the interaction between building flexibility and the grid are reviewed and, for a reference case, the useful energy is also quantified [44]. Multi-agent systems are proposed instead of traditional BMS to coordinate the interaction with smart grids [45]. A control framework based on MPC is tested in office buildings, providing 19.5% and 10.6% of additional photovoltaic self-consumption and building self-sufficiency, respectively, compared to two baseline controls with constant setpoints [46]. Overall, improvements in the area of energy flexibility need to be achieved without compromising other building performances. Therefore, in addition to parameters such as energy capacity, response time, or load shift potential, occupants' dissatisfaction with indoor comfort and poor indoor air quality should also be considered when evaluating flexibility [41].

3.3. Response to User Needs

Response to user needs means providing high IEQ by adapting operations to changing conditions and ensuring feedback and real-time interaction with occupants. The TAIL scheme for rating IEQ in offices and hotels undergoing deep energy renovation (EU ALDREN project) [47], divides IEQ into thermal environment, acoustic environment, IAQ, and luminous environment (TAIL). By improving these categories, it is possible to enhance physical (comfort sensation) and psychological (occupant satisfaction) well-being. According to U.S. data, people spend a large amount of their time in buildings (90% of the time according to data [48,49]), so it is not surprising that comfort, health, and well-being are increasingly investigated topics, not only as a side-effect of energy efficiency measures [50]. Results from a 2022 study that investigated building professionals' experience and interest in occupant health in buildings [51] show that the number of studies published in the last six years on healthy buildings has been increasing. The COVID-19 pandemic has also significantly influenced professionals' perspectives on the impact that buildings have on occupants' health. Despite the growing attention, an analysis of temperature satisfaction of 52,980 office occupants in North America revealed that only about 38% are satisfied [52]. In another survey, a percentage of satisfaction of 80% or more was found in only 11% of buildings for thermal comfort and in 26% of buildings when IAQ was investigated [53].

Furthermore, evidence shows that green-certified buildings do not necessarily perform better [54,55].

BACS can respond to user needs in office buildings by optimising temperature control, the rate of air exchange, and the use of daylight by providing personalized settings and room scheduling. In this section, BACS' impacts on the different categories related to response to user needs are analysed. In the following section, the main benefits associated with these impacts, such as productivity and health benefits, are investigated.

3.3.1. Thermal Comfort

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55, the concept of thermal comfort refers to the mental feeling of being comfortable in a particular temperature range [56]. It is a highly subjective state dependent on numerous physical, physiological, and psychological factors, such as age, gender, metabolism, clothing, physical activity, location, posture, and mental state [56]. Research suggests that large variations in daily temperature beyond an acceptable range affect long-term thermal comfort more than the average experience over time. Continuous monitoring technologies can be used for evaluating long-term thermal comfort based on this evidence [57]. However, energy savings take precedence over thermal comfort in the building control literature [58]. Often, innovative control strategies are proposed and analysed to improve energy efficiency while maintaining comfort levels. Various MPC algorithms are applied to a BMS in an office for the purpose of optimising both indoor comfort and energy consumption [59,60]. According to the first study, the MPC achieved a higher level of comfort satisfaction during working time compared to a programmable thermostat (97.4% vs. 77.2%) and a 19.4% reduction in energy consumption. In another case, a neural network temperature predictor is combined with a fuzzy controller to maintain indoor thermal comfort in an office building by controlling the ventilation rate [61]. Hybrid MPC performed better than RBC in terms of energy consumption and percentage of discomfort hours for dynamic façades with electrochromic glazing [62]. Automatic window controls based on temperature and CO_2 sensors reduce the risk of overheating in office buildings by 64% and improve IAQ in highly occupied environments by 90% compared to manual control [63]. These works evaluate thermal comfort using the Predicted Mean Vote (PMV) method. Nevertheless, smart building technologies are showing how it is possible to improve thermal comfort, linking it to controllable building parameters. BMSs act on adjustable parameters such as air conditioning setpoint or ventilation air flows, whereas PMV factors cannot be directly controlled since these factors result from the interaction between HVAC settings and building internal and external conditions. Machine learning (ML) techniques and neural networks (NNs) are applied to bridge the gap between controllable building parameters and thermal comfort modelling [64]. As a result of the availability of Internet of Things (IoT) environmental sensors, a hybrid approach based on machine learning and building dynamic simulation was developed for the prediction of indoor thermal comfort feedback in an office building in France [65]. Lastly, IoT and ML are leveraged to learn individual comfort requirements directly from data collected in the indoor environment [66].

3.3.2. Visual Comfort

The European standard EN 12665:2018 defines visual comfort as "a subjective condition of visual well-being induced by the visual environment" [67]. Visual comfort is usually assessed using factors linking the light environment and occupant needs, such as the quantity, quality, and uniformity of light, and the presence of glare. Studies reviewing parameters used to assess the quality of the indoor environment of offices identify illuminance levels and daylight factor as the most used indicators to define luminous comfort [68,69]. These indicators are common across certification schemes and standards as well [70]. Lights, switches, dimmers, and different types of movable blinds and shading systems are meant to provide flexibility towards the changing needs of illumination.

However, office occupants often actively close blinds or switch lights on when discomfort arises, but tend to forget to turn off the lights or open the blinds when negative conditions end [71].

Hence, the role of BACS in visual comfort is investigated with the objective of optimising daylight and artificial illumination, while reducing energy consumption at the same time [72–74]. For instance, the lack of physical connections with the outside environment is a major source of dissatisfaction in offices [75,76], but excess daylight and proximity to windows can cause glare. A study on glare-based control strategies for automated blinds in office buildings points out that glare prevention should be the main priority of these systems since glare is the main reason occupants interact with shading devices. The study proposes MPC based on daylight simulations to prevent glare without excessive use of sensors. The lack of real-time daylight simulation tools and computational requirements are major challenges [77]. A simulation and field study evaluated visual comfort and energy savings by implementing 10 different control strategies for lighting and shading [78]. The study concluded that, if glare protection is not necessary, a blind slat angle of 0° or dynamic shading is preferable in winter. However, in summer, a blind slat angle of 30° or dynamic shading is the optimal configuration. An adaptive lighting and blind control algorithm was developed and tested, resulting in −25% electric lighting use without affecting comfort. Based on occupants' light switching and blind closing behaviour, the algorithm learns their preferred illumination level. This information is used to calculate photosensor setpoints for lighting and blinds [71]. Finally, occupants' satisfaction with blinds and ceiling lights has been tested in relation to two different control strategies: fully automatic and manual. Results showed that higher visual and thermal discomfort was reported by participants testing fully automatic control, although the measured average operative temperature was similar in both cases [79]. These results are relevant in relation to the BACS impact area "information to occupant" and the relationship between control perception and comfort.

3.3.3. Indoor Air Quality

Indoor air quality refers to the quality of an indoor environment's air as determined by chemical, biological, and physical contaminants. Although it has often been overlooked in favour of other topics such as energy efficiency, sustainability, and outside air quality [80], its importance has gained momentum in the last decade, as evidence supporting its effect on health, quality of life, and the working environment has been discovered [81]. The TAIL scheme for rating IEQ selected the most relevant indicators to describe IAQ from the EN 16798-1 standard [82], the guidelines published by the World Health Organization [83] and Level(s) framework [84]: carbon dioxide, ventilation rate, air relative humidity, visible mould, benzene, formaldehyde, PM2.5, and radon [47].

On the one hand, increasing ventilation rates guarantees better IAQ, but this happens at the expense of energy consumption. On the other hand, lowering the energy consumption associated with ventilation systems can increase the risk of deteriorating IAQ. BACS and sensing technologies have the potential to tackle both aspects at the same time [85] by providing demand controlled ventilation (DCV) [86]. Measurements collected from case studies showed that DCV is of particular interest in rooms which have a wide range of occupancy rates such as open offices [87]. A study integrated the CO_2 mass balance equation with CO_2 sensors to reduce energy consumption, maintaining indoor pollutants within recommended ranges [88]. Furthermore, with advancements in IoT and ML, an office desk can be customised to meet an individual's needs, going beyond existing BMS, which provides centralised control or control at the zone level, not considering individual preferences [89].

3.3.4. Information to the Users

Real-time and historical information regarding indoor environmental conditions, warnings, performance evaluation, forecasting, and benchmarking are functionalities that can be implemented with BACS and thus delivered to building users. The achievement of the performances foreseen at the design stage is a recognized issue. Brager et al. [90] report how extensive field research has identified widespread low occupant satisfaction with indoor thermal environments. The main identified causes are building over-conditioning and lack of individual control over the environment by occupants. Higher user awareness and higher perceived control over the building operation have been proven to have effects on thermal sensation and comfort. This leads to higher satisfaction with the indoor environment [91–94]. On the contrary, a fully automated control system that removes occupant control over the environment leads to lower satisfaction levels [95,96]. A similar negative outcome can result from conditions such as inaccessibility and poor location of environmental controls [97]. A post-occupancy evaluation carried out on a green building, which had more control options compared to a conventional design, showed that the lack of responsiveness and relevant feedback and limited user understanding may have contributed to poor comfort conditions. Findings from the study indicate that users wish to learn more about how buildings work and how comfort can be provided [98]. A field study on the effect of BACS on perceived comfort found that participants in the test reported improved perceived comfort when adaptive opportunities (e.g., movable blinds, operable windows, thermostats) were available. Furthermore, even though occupants preferred less automation, digital control technologies such as mobile apps were acceptable [96]. A study proposes a prototype user-interactive system integrated with a model predictive HVAC controller in office buildings to counteract energy consumption associated with occupants' control overrides. Results show that MPC can underestimate HVAC energy consumption by up to 55% if manual interventions are not taken into account. The proposed user-interactive system allowed for the recovery of 36% of the additional energy consumption while maintaining occupant satisfaction [99].

A study [100] analysing a LEED-certified office building in North America pointed out that, as most green building rating systems (such as LEED, Green Globes, and BREEAM) focus on predicted performance at the design stage, actual performances are rarely verified. Thus, sustainable design depends on measuring and monitoring the in-use performance of "green" buildings [101]. Another study compared IAQ and SBS in green and standard buildings, concluding that poorly maintained green buildings do not have any added advantage [102]. In this context, BACS can play a role in reducing the performance gap between the design and operation phases of a building. Knowledge and automation systems can enable climate-responsive architectural design, making efficient use of mechanical systems [90] and improving building resilience in addressing unexpected scenarios such as power outages, new habits of users, heat islands, and new constructions [103].

From the perspective of a building owner or a facility manager, BACS provide control tools to building management staff to detect and resolve system issues. This prevents unexpected equipment breakdowns and business disruptions and ensures building equipment operates correctly. As a result, BACS have the potential to lower maintenance costs and extend equipment life by reducing demand and start/stop cycles [104,105]. Further, BACS data can be used to establish benchmarks and to support the valuation of assets in real estate transactions.

4. Benefits

4.1. Productivity

Improving thermal and visual comfort, enhancing IAQ, or delivering feedback and control are ways of providing an adequate response to user needs. The role of BACS in this context has been highlighted in the previous sections. These impacts can give rise to a variety of benefits, depending on the stakeholder perspective. For office buildings, salaries are considerably higher than energy and maintenance costs [106]. Therefore, any action that results in improving employee productivity has strong effects on an organisation's financial performance [107]. For the same reason, measures to reduce sick leave can have an effective return on investment [76]. For instance, a 2000 study tried to estimate the impact on U.S. GDP deriving from direct productivity improvements, reduced respiratory disease, reduced allergies and asthma, and reduced sick building syndrome symptoms [108].

Research indicates that job performance and satisfaction are both affected by the physical environment in the workplace [95,109]. Thermal comfort has a strong influence on occupant productivity. A total of 82.7% of interviewed office occupants in Chile confirmed that their productivity is affected by the thermal environment [110]. In the same way, in Japan, a positive correlation was found between thermally satisfied office workers and their self-estimated performance [111]. Several studies have shown that productivity and IEQ are causally related [107]. A 3% increase in execution speed with a reduction of air temperature from 25.5 °C to 23.5 °C was observed in a study describing a methodology to evaluate IEQ and its effects on comfort and performance [112]. A review of temperature control for health and productivity in offices reports an average 2% productivity loss per degree °C above 25 °C of indoor temperature [113]. Another study by the same author proposed a relationship between air temperature and relative performance [114], later confirmed by Lan et al. (2011) as well [115]. Based on Equation (1) elaborated by [114], Figure 3 shows the relationship between productivity relative to maximum value (P) and indoor temperature. This study places the optimum not on the neutral thermal sensation but slightly on the cold side (PMV between −0.5 and 0).

$$P = 0.1647524 \times T - 0.0058274 \cdot T^2 + 0.0000623 \times T^3 - 0.4685328 \quad (1)$$

Productivity increases in a comfortable visual environment as well. BACS can optimise daylight, provide correct artificial illumination, and prevent glare. Findings indicate that occupants prefer illumination levels between 300 and 450 lux for the indoor working environment and show a preference for daylight. Kaushik et al. (2021) point out that illumination has a "positive" effect on visual comfort and productivity from 225 lux and a "very positive" impact from 325 to 450 lux [116]. Researchers found that using a shading system improved an individual's performance on tasks requiring sustained attention, for instance, colour-naming tasks. In other tasks requiring velocity and vigilance, no effects were found [117]. Furthermore, visual comfort and high daylight levels have been associated with tenants willing to pay 5–6% more for renting an office with these characteristics under the market conditions of Manhattan, U.S. [118]. Epidemiological studies have investigated the relationship between daylight and absenteeism. A study from Norway found that adding 1 h of daylight increases the sickness recovery rate by 0.8% [119].

The relationship between occupant productivity and IAQ includes several contributions. Numerous studies have demonstrated that an increase in outdoor ventilation rates can improve productivity at the workplace. Not only are CO_2 levels associated with attention levels but also odour perception leads to experiencing secondary effects, such as sensory irritation, distraction, and deteriorating performance [120]. An experimental study looked at work performance when subjects were exposed to high levels of VOC and different ventilation rates. Work performance was observed to increase by 2.5–5% as the ventilation rate increased from 5 to 20 l/s per person [121]. Two studies examined work performance in a call centre. The first study could not find a strong relationship between ventilation rate and performance [122], whereas the second one found a 6% decrease in talk-time in a call centre with an enhanced flow rate and a newly installed supply air filter in place [123]. In an office experimental setup, five groups of six employees have been observed at three ventilation rates: 3, 10 and 30 l/s per person. As the ventilation rate doubled, productivity increased by about 1.7% [124]. A review conducted in 2005 statistically analysed data from laboratory experiments and field measurements of multiple studies, finding an average performance improvement of 1–3% per 10 l/s-person increase in ventilation rate. Over 45 l/s-person, no further performance increase was observed [125,126].

As a result of [126] statistical analysis, [127] developed Equation (2), which can be used to calculate the relative performance:

$$RP = \exp\left[\left(-161.822 \cdot x^{-1} - 0.368\mathrm{Ln}(0.472x) + 1.827x - y_0\right)/1000\right] \quad (2)$$

Equation (2) is displayed in in Figure 3, in addition to the relationship between relative performance and indoor temperature. For instance, the curve corresponding to an initial ventilation rate of 14 l/s per person is displayed; y_0 is the coefficient (20.1553) associated with the initial ventilation rate as reported in [127].

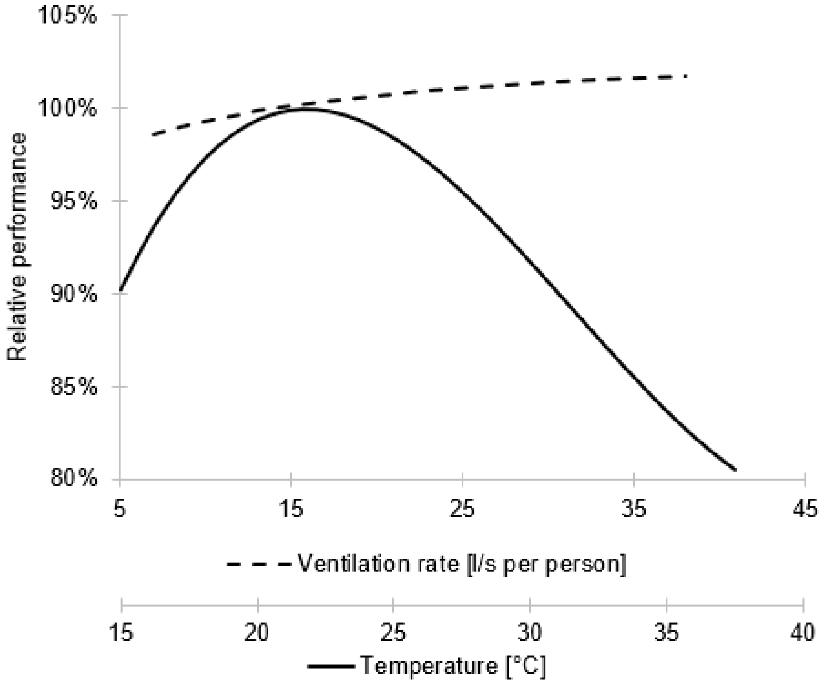

Figure 3. Relative performance vs. indoor temperature and ventilation rate.

Evidence of benefits in terms of productivity resulting from the BACS impact category "information to occupants" has been recorded as well. Human productivity is maximised in offices with many possibilities for personal control and a feedback system with complaint monitoring [128]. Finally, a complete overview of the relationship between IEQ parameters and office productivity has been collected by a comprehensive review that looked at 300 journal and conference articles and books [129].

4.2. Health and Well-Being

Moving on to health-related issues, such as SBS symptoms, allergies, and respiratory irritation [130], an association with lower IAQ emerged from several studies. Reduced sick absences can be accounted for as one of the main benefits of reducing these negative effects. Connecting ventilation rates and health-related aspects is fundamental to quantifying this benefit. It was observed that the prevalence of selected symptoms might decrease by up to 70–85% with large increases in ventilation rate and/or improvements in ventilation effectiveness [131]. An airborne transmission model and published field data have been combined to statistically estimate a quantitative relationship between ventilation rate and sick leaves [132]. Apart from being responsible for odours and deteriorating performance, as mentioned above, VOCs can cause sensory irritation and even pulmonary effects [120]. The quantitative relationship between SBS symptoms and ventilation rates can be estimated with the following Equation (3) based on a statistical analysis of published data from 8 studies and 43 data points [133]:

$$\mathrm{RSP} = \exp[(-0.0541901 + 0.0008939 \cdot \mathrm{x}) \cdot \mathrm{x} + 0.452511] \tag{3}$$

where RSP is the SBS symptom prevalence, relative to a ventilation rate of 10 l/s per person. In Figure 4, the relationship between sick leave prevalence and ventilation rate is displayed as reported by [132] and based on the data of [134]. At the same time, the relationship between SBS symptoms and ventilation rate has been displayed as well [133].

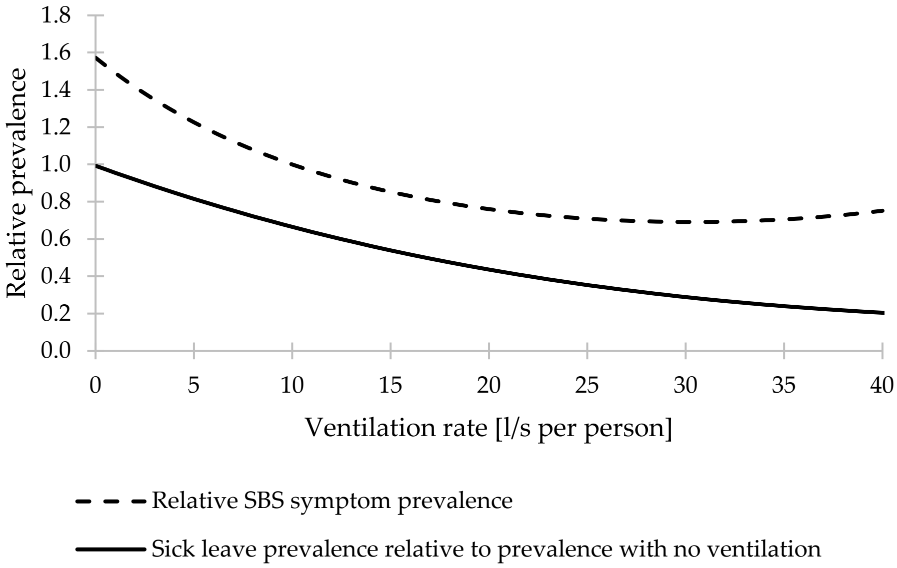

Figure 4. Sick leave in offices and SBS symptom relative prevalence vs. ventilation rate.

Fisk et al. (2012) [135] put together different quantification methods to estimate annual economic benefits associated with changing ventilation rates for office buildings in the United States. The study found that the costs of lowering the ventilation rate from 8 to 6.5 l/s per person largely outweighed the energy savings. A recent work proposes a novel complementary approach to estimate IAQ costs in offices associated with pollution and SBS. Costs of Disability Adjusted Life Years (DALY) are calculated as a function of pollutants concentration and the number of workers [136]. Finally, specific literature reviews have been conducted on the impact of IEQ on health and productivity [137,138].

5. Discussion

BACS have been analysed considering the different impacts on the office built environment and the associated benefits. These technologies have proven to be a cost-efficient solution to achieve energy efficient building operation as they quickly pay for themselves via reduced utility expenses. Recent research efforts have been focused on the optimization of various strategies, such as implementing forecasting algorithms, real-time weather responsiveness, MPC, sensor networks, thermostat control based on operative temperature, smart glazing control, and occupancy-based lighting control. These strategies have been shown to achieve energy savings of up to 29% for heating and cooling and up to 60% for lighting. Offices and buildings in general have the potential to respond to external conditions and to be involved in DSF by using building automation and thermal inertia to increase coordination with the grid, reduce peak loads, and maximise economic benefits. MPC strategies have been tested in office buildings, providing additional photovoltaic self-consumption and building self-sufficiency.

A systematic analysis of dissatisfaction in office buildings conducted using post-occupancy evaluation from over 600 buildings showed that a total of 81% of respondents expressed dissatisfaction with at least one aspect of their workspace, while 67% expressed dissatisfaction with more than one [139]. However, three decades of public health studies have shown that better IEQ leads to healthier and more satisfied workers, making it crucial for employers, building owners, and managers. IEQ effects on productivity and health-related aspects are the most cited benefits. Table 1 collects the main studies addressing these benefits.

Table 1. Quantification of benefits—literature overview.

Type of Study	Impact Area	Benefit	Correlation	Source
Review	Thermal comfort	Performance/productivity	−2% of productivity for each +1 °C above 25 °C	[113]
Review	Thermal comfort	Performance/productivity	Performance increase with temperature below 22 °C and decreases above 25 °C	[114]
Experimental	Thermal comfort	Performance/productivity	Optimum around 22 °C and PMV between 0 and −0.5	[115]
Field intervention	Thermal comfort	Performance/productivity	+3% in execution speed when T from 25.5 °C to 23.5 °C	[112]
Review and statistical analysis	Thermal comfort	Health	+12% intensity of SBS-symptoms each +1 °C above 22.5 °C	[140]
Review	IEQ	Performance/productivity	+0.5–5% of productivity at building stock level by improving indoor environment	[108]
Simulation + market analysis	Visual comfort	Higher rent	+5–6% rent for offices with high daylight values	[118]
Empirical analysis	Visual comfort	Reduced sick leave	+1 h of daylight = +0.8% of recovery rate from sickness	[119]
Experimental	IAQ	Performance/productivity	+2.5–5% of work performance as ventilation rate from 5 to 20 l/s-person	[121]
Experimental	IAQ	Performance/productivity	+1.7% productivity for a 100% ventilation rate increase between 3 and 30 l/s-person	[124]
Review	IAQ	Performance/productivity	+1–3% productivity per 10 l/s-person. Negligible over 45 l/s-person	[125,126]
Empirical analysis	IAQ	Health	Symptoms prevalence decrease by up to 70–85% with large increases in ventilation rate	[131]
Review and statistical analysis	IAQ	Health	Risk of short-term sick leave = 35% for low ventilation rates	[134]
Review and statistical analysis	IAQ	Health	+23% SBS symptoms for ventilation from 10 to 5 l/s per person; −29% from 10 to 25 l/s per person	[133]

BACS can address user needs by creating a healthier and more productive work environment in office buildings by maintaining an optimal indoor temperature. The relationship between thermal comfort and productivity in buildings has been extensively reviewed [141,142]. However, studies outlining mathematical relationships between physical factors of the indoor environment and productivity are limited [142]. Literature agrees in associating a 2% productivity decrease for each temperature degree above 25 °C, with an optimum around 22 °C. Nevertheless, a high degree of uncertainty needs to be considered, due to the different conditions and activities where productivity can be analysed [141]. To date, the PMV method has been commonly used to evaluate thermal comfort, but BACS and smart building technologies are allowing us to bridge the gap between comfort modelling and controllable building parameters through the implementation of ML techniques and NNs. The deployment of IoT environmental sensors has been used to learn individual comfort requirements and has been coupled with building dynamic simulation for predicting indoor thermal comfort.

In the field of visual comfort, according to a 2021 report by the American Society of Interior Design, 68% of workers have complaints about building lighting. BACS can control natural and artificial lighting levels, ensuring that the environment is not too bright or too dim, which can help improve visual comfort and reduce eye strain. Control of shading devices can preserve the connection with the outside environment while preventing glare and overheating. Furthermore, adjusting artificial light is required to optimise dimming and colour temperature control, guaranteeing the correct illuminance levels based on the performed tasks. Optimal illumination has been shown to improve mood, energy, alertness, and overall productivity, although mathematical relationships with visual comfort parameters need to be further investigated. On the health side, it was proven that daylight reduces absenteeism. Estimates found that adding one hour of daylight increases the daily entry rate to absenteeism by 0.5% and the corresponding recovery rate by 0.8% [119].

In an effort to provide adequate ventilation rates and to reduce energy consumption at the same time, demand controlled ventilation managed by BACS and sensing technologies have an edge in optimising these two aspects. Ventilation rates are proportionally related to productivity, ranging from around 3 to 30 l/s per person [124]. In this range, a productivity increase of 1–3% is expected for each additional 10 l/s per person [125]. Finally, higher user awareness and control lead to higher satisfaction levels, while fully automated control systems result in lower satisfaction.

Some studies analysed productivity in simulated office environments. In this case, one of the main limitations is that the tasks analysed were simple ones. As a result, it is unclear whether the data are representative of actual office performance. Another research path used questionnaires in real conditions, but in this case, the inaccuracy is related to the limited control over the experimental conditions. In terms of health and well-being benefits, the literature review reveals a clear link between sick leaves and ventilation rates [131,134], with SBS symptom prevalence increasing for ventilation rates below 10 l/s per person [133].

Future research is needed to improve the understanding of the connection between controllable environmental parameters and the achievable benefits of specific automation systems and control strategies. Furthermore, the exploration of analysis and reliability of quantification methods is recommended as well.

6. Conclusions

Building automation and control systems can have multiple impacts on the office built environment in addition to energy related ones. BACS can improve overall comfort by controlling temperature, daylight, artificial lighting, and ventilation. By acting on ventilation rates, BACS can enhance IAQ, reducing pollutants and controlling the presence of VOCs. Maintenance can be improved by monitoring and controlling equipment, making it easier to identify and fix problems before they cause downtime. It can facilitate communication and remote access to building systems, providing increased flexibility and reducing the need for on-site maintenance. Safety and security can be enhanced by monitoring building access, response to fire, and other safety alarms.

As a result, a variety of non-energy benefits need to be taken into account when evaluating the role of BACS. In the case of office buildings, meeting user needs and providing a comfortable and safe work environment can improve employee productivity; reducing pollutants has a positive effect on sick leaves and the appearance of SBS symptoms. Thanks to BACS, these positive outcomes can be achieved by optimising energy consumption, which is often a competing interest.

Singular BACS impacts on the built environment and benefits derived from an improved IEQ are two topics with already established coverage in scientific literature. However, studies that bridge the gap between these two aspects are still missing. This literature review tried to link these two topics by introducing an approach that aimed at evaluating the multiple impacts and related benefits that BACS can offer. Establishing common ground on this topic has the potential to be beneficial for investors, paving the way for the promotion of novel business cases for BACS implementation.

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