Co-benefits of building automation and control systems: an analysis of smart office buildings

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Abstract. The more and more widespread availability and implementation of building automation and control systems (BACS) is revealing how building monitoring, control, and real-time data, can support building users' well-being, providing additional co-benefits, besides the positive energetic impacts. Therefore, these technologies will play an important role in the transition towards a smart built environment, reducing energy consumption, enhancing comfort and interacting with a smart grid and building users. The Standard EN15232 with the BAC factor method introduces smart control efficiency classes and provides quantitative data for estimating the energy savings associated with the installation of smart controls. Although this method is not very detailed, it aims to provide a rough estimation in the early design stages. Assessment methods for BACS (such as the European Smart Readiness Indicator, the French SBA 'Ready to Service label') also stress the importance of non-energetic impacts of BACS. At present, these methods mostly rely on qualitative assessments or use ordinal scores, since investigation on non-energetic benefits and quantitative data are largely lacking. This paper analyses the multiple co-benefits of smart controls in office buildings in greater detail. By means of data reported in literature and building simulations, the most important co-benefits are identified and to the extent possible also quantified. A contemporary office building is used as case study to apply and demonstrate the proposed analysis framework.

Keywords. Smart buildings, BACS, co-benefits.
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1. Introduction

In 2019, commercial building sector accounted for 12% of the energy consumption in the United States [1]. In Europe office buildings represent 25% of the non-residential floor space and 26% of the energy consumed in tertiary sector [2]. The European energy performance of buildings directive (EPBD) and the directive 2012/27/EU on energy efficiency are the main policy instruments to promote a phase-out of inefficient buildings. In particular, the 2018 amendment of the EPBD (directive 2018/844 of the European Parliament and of the Council of 30 May 2018 [3]) promotes the implementation of building automation and electronic monitoring of technical building systems to support building digitalization and the improvement of energy efficiency. Real estate industry lags behind in adopting new technologies compared to other sectors, nevertheless according to a recent market report, the global smart buildings market is expected to grow with a compound annual growth rate (CAGR) of 32%, reaching $43 billion USD by 2022 [4]. A wider implementation of Building Automation and Control Systems (BACS) which can provide technical management and monitoring is expected to produce energy savings in a cost-effective way and to improve comfort and indoor air quality (IAQ), adjusting the indoor environmental conditions to occupant needs. Furthermore, in a future energy system with a large share of distributed renewable energy generation, smart buildings will be the cornerstone for an efficient demand-side energy flexibility and an optimized self-consumption [5, 6], with BACS being key enablers of the building integration within the so-called "Smart Grid" [7].

Despite the growing attention on BACS multiple benefits, a review and meta-analysis performed by O'Grady et al. (2021) [8] highlighted that the most investigated trend by far in this field is the impact on energy reduction (92% of the reviewed publications). The European standard EN 15232:2017 [9] focuses on this aspect by providing an estimation of the impact that these systems have on energy performance and introducing a classification of the building control systems and functionalities. However, further co-benefits of smart technologies are for many actors and stakeholders within the construction sector still unclear or unknown, therefore, the 2018/844 directive introduced the Smart Readiness Indicator (SRI), a voluntary EU scheme for rating building smartness and the ability to interact with the occupants and the grid [10]. The SRI tackles the lack of awareness of the benefits associated with smart building technologies and functionalities, aiming at making these benefits more tangible for building users, owners, tenants, and smart service providers. Another example is the Ready2Services (R2S) label set up by the French Smart Building Alliance (SBA) with the Certivéa certifier for non-residential buildings. The R2S reference framework describes the key requirements for communication between the building systems and services with the objecting of providing more services, optimizing operating costs, improving flexibility and scalability and enhancing attractiveness. Nevertheless, the SRI scheme as well as the R2S are qualitative appraisals which aim at raising awareness of possible smart technologies implications and co-benefits beyond energy savings without providing insights on the real entity of these co-benefits. For this reason, more mixed method (qualitative and quantitative) insights to capture the human experience are needed [8], as well as quantitative approaches that can be implemented as early design stage assessments [11].

This paper proposes an approach which considers the energetic and non-energetic benefits of BACS, focusing on office buildings. This building typology was chosen due to the higher permeability to smart technologies and the relevant impacts that these promise to achieve [12]. Major market players highlight how a smart office can leverage BACS to deliver a better user experience of the workplace, meeting in this way evolving employees' needs as recorded for instance during COVID-19 pandemic. Employees are increasingly aware of the importance of having a better work environment in terms of comfort and health aspects. These systems, combining several data-driven and digitally-enabled services, have an impact on employee well-being and performances by managing lighting, heating, ventilation, and air conditioning systems, office desks, and elevators, up to whole office spaces. Defining and quantifying the benefits of BACS in office buildings will allow to decrease the risk perception associated to the adoption of smart technologies. The proposed approach collects and analyzes main smart office co-benefits and presents an application on a case study. A reference office building was modeled within EnergyPlus simulation engine and a shading control has been selected for the assessment of energy savings in combination with co-benefits. A proper adjustment of daylight not only has a direct impact on building internal gains, which in turn influence the heating and cooling consumption, but also on thermal and visual comfort, attention restoration, and stress reduction.

2. Smart office building co-benefits

Nowadays, considering not only energy efficiency, but also co-benefits is gaining more and more relevance when it comes to evaluating innovative solutions for built environment. Smart building technologies are no exception as demonstrated by the SRI scheme, which assesses the impacts that a smart ready service can provide to the building, its users, and the energy grid by defining a set of seven categories: energy efficiency, comfort, health, well-being and accessibility, maintenance and fault prediction, convenience, information to occupants and energy flexibility and storage.

Co-benefits in the field of comfort, health and well-being, are the second most investigated topic in BACS sector after energy efficiency, with 34% of the publications that are related to the impacts of perceived human comfort in the built environment, and the effects of IAQ on health and productivity of building occupants [8]. Nevertheless, there are still many questions on how to effectively measure and quantify impact of BACS on occupant comfort and in general on indoor environmental quality (IEQ); aspects that play a key role in improving the conditions of an office environment. Smart technologies can manage heating or cooling generation and emission systems to influence thermal comfort sensation. Controls managing shading devices can influence internal gains and visual comfort. To quantify those impacts common metrics such as indoor temperature, daylight factor and illuminance need to be taken into account [13]. In case of IAQ, BACS can manage the control of ventilation systems based on sensors such as CO_2 sensors which connect the environment variables with building systems. A systemic review of their influence in managing energy savings, thermal comfort, visual comfort, and IAQ in the built environment is reported by Dong et al. (2019) [14]. Visual contact to nature was investigated due to its positive effects on concentration, stress, and cognitive performance [15]. Some studies tried to link IEQ with higher occupant satisfaction [16] or with employee health and productivity [17, 18] in green rated buildings. Others focused on indicators specific for office buildings and related to co-benefits such as increased productivity, reduced sick leaves, reduced employee turnover [19–21]. The opposite perspective can be found as well, linking negative impacts of poor IEQ with direct medical costs or indirect costs related to poor employee performance, which could either cause higher absenteeism, reduce work effectiveness and employee recruiting and retention. The benefits of an improved IEQ are related to containing the mentioned negative effects [22]. One of the main barriers that makes these benefits hard to calculate, is that the figures required should be obtained from the accountability and human resources departments of the companies.

Smart functions such as automated fault detection and diagnosis of building equipment operation are strongly connected to an optimized building functioning as well. Article 2 of the 2018 EPBD amendment places the focus on the functionalities of continuous monitoring of energy use, efficiency benchmarking and communication which have the potential to improve operation and maintenance activities of technical building systems, as performances, and device failures are monitored in all systems. In this way, the directive recognizes that a good design only, cannot avoid a performance decrease over the building operating life. Building operation presents several inefficiencies compared to project conditions. The performance gap caused by these inefficiencies can be reduced by installing monitoring and diagnosis systems. For instance, in case of heat pumps, an energy performance gap can be identified with the system performance degradation over time [23] or in case of controlled ventilation, filters fouling is responsible for an increased energy consumption. A second benefit in this area is related to lower maintenance and replacement costs [24, 25].

Finally, another set of benefits is related to the ability of BACS to provide information on building operation, such as IEQ parameters, electricity production from renewable sources, storage capacity, services availability and other building performances to occupants or to facility managers. This information can positively influence user interaction with the building, as occupant behavior is one of six influencing factors of building energy performance [26]. In case of commercial buildings, approaches have been proposed to decrease energy demand by improving occupants' energy-consuming behaviors [27]. In addition, an informed user is key for the acceptance of BACS. A study showed that occupants' comfort feeling was correlated to control perception over the indoor environment, as they were not satisfied with the implemented automation, and wanted a more direct control [28]. Inkarojrit (2005) [29], for instance, carried out a study among 25 office users in Berkeley, finding that more than half of the participants preferred either a manual window blind control or a smart one with the override possibility. Similar results were found in a more recent study [30], also focused on comparing manual and automated blind control strategies in office buildings.

3. Methods

The present study proposes an approach which includes both energetic and non-energetic benefits in the assessment of BACS impacts in an office environment. The approach is illustrated using a reference office building model set up using the dynamic simulation engine EnergyPlus. This tool, further than performing a building energy simulation, allows including thermal comfort modeling and simplified control strategies. As a case study for the analysis of BACS impacts on the selected reference building, two different control strategies of a sun shading system have been modeled: a manual control versus an automated control.

3.1 Building model description

The selected building model is the office division of the Flemish research organization VITO in Berchem, Belgium (Fig. 1). This model was chosen as representative of office buildings at European level. In order to simplify the analysis, out of the whole model, one floor located in the middle of the building was considered.

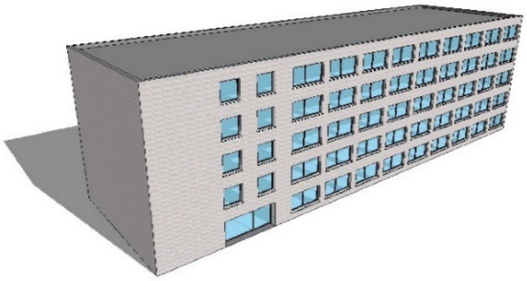


Fig. 1 – Model of Berchem office division.

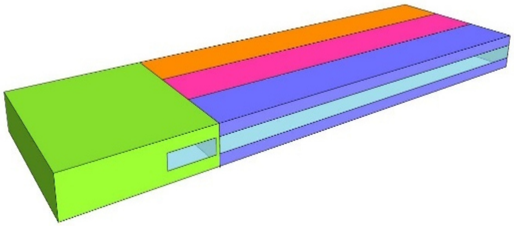


Fig. 2 – Model of the middle floor.

Its interior dimensions are 60x18x3.4 m and it is divided in four zones (Fig. 2):

1. Right zone (45x6 m - purple): office area
2. Left zone (45x6 m - orange): office area
3. Corridor (45x6 m – pink)
4. Auxiliary zone (15x18 m - green)

Floor and ceiling are considered to have identical thermal conditions, therefore adiabatic. The surfaces in contact with the external environment are the south facing façade (right and auxiliary zones), the north facing façade (left and auxiliary zones) and the two side surfaces which have no windows. Shading on the façade caused by obstacles is not considered. Tab. 1 reports main characteristics and relative U-values of the construction elements such as ceiling, floor, external and internal walls. Tab. 2 reports the characteristics of the windows such as U-values and g-value. An internal mass due to walls and furniture is also considered (left zone and corridor: 100 m^2; auxiliary zone and right zone: 50 m^2).

Tab. 1 – Construction materials.

	Ceiling/Floor	Int. wall	Ext. wall
Materials	Carpet Pad	Gypsum board	Façade brick
	Air	Air	Air
	Concrete	Gypsum board	Insulation
	Gypsum board		Brick
			Plaster
U-value [W/m^{2}K]	1.53	2.58	0.21

Tab. 2 – Windows properties.

	Values
U-value window [W/m^{2}K]	1.2
U-value frame [W/m^{2}K]	1.8
g-value	0.39

A gas boiler feeds a hot water loop. All zones are heated by fan coil units and a controlled ventilation system provides the air change. The outdoor air flow rate is 0.000944 m^3/s (per floor area). The natural infiltration rate was assumed to be constant to 0.0001111 m^3/s (per exterior surface area). Moreover, air mixing between zones is also taken into account: 0.000315 m^3/s between offices and corridor, 0.00009 m^3/s between corridor and auxiliary zone. User behavior and system schedules are reported in Tab. 3. Occupancy schedule does not take into consideration intermediate steps between no employees at workplace and full occupancy.

Tab. 3 – User behavior and system schedules.

Typology	Schedule
Occupancy	100% weekdays between 8:00 a.m. and 12:00 p.m. and 2:00 p.m. and 5:00 p.m.
Ventilation	Weekdays at 100% (=0.001389 m^3/s per floor area) from 6:00 a.m. to 8:00 p.m., else 25%
Heating setpoint	21°C from 6:00 a.m. and 5:00 p.m. on weekdays, else 15.6°C

Internal loads associated with lights and electric equipment follow the occupancy schedule and are reported in Tab. 4. Although, it is important to underline that daylight is the only responsible for office illuminance levels, since no artificial lighting is simulated. A typical metabolic rate of 120W per person has been selected for office activities.

Tab. 4 – Internal loads.

Typology	Values
People [m^2/person]	10
Activity level [W/person]	120
Lights [W/m^2]	10
Electric equipment [W/m^2]	7.5

3.2 BACS model description

Control of solar protection shadings has been chosen to be modeled and investigated within the proposed approach. The solution implemented is an external shading system which main characteristics are reported in Tab. 5.

Tab. 5 – Shading characteristics.

	Shading
Thickness [mm]	5
Solar transmittance	0.21
Solar reflectance	0.43
Visible transmittance	0.14
Visible reflectance	0.8

Two control strategies have been compared to determine their impact on the building: on the one side a basic manual control, on the other side an automatic control. Manual control means that employees can open or close the shadings according to the circumstances: glare, thermal discomfort, need for more light, etc. This control has been approximated by making the assumptions that employees close the blinds whenever the illuminance exceeds 2000 lux for at least 20 minutes or the indoor temperature is above 26°C (thermal discomfort sensation). Work plane illuminance is the most cited and studied parameter when it comes to visual comfort [31] and 2000 lux is considered a limit value above which visual discomfort perception arise (glare or scarce visibility of computer screens) [32]. Besides, the assumption that shadings are forgotten close for the rest of the day and opened again the next working day (if temperature is below 24°C and illuminance below 2000 lux) has been made. The automatic control is based on sensors which take into account irradiance, illuminance and temperature levels [33, 34]. Opening and closing strategies are displayed in detail in Fig. 3 and Fig. 4. The displayed control strategies have been modeled within the Energy Management System (EMS) feature of EnergyPlus, which allows implementation of custom control strategies and calculation routines that go beyond standard modeling processes provided by EnergyPlus.

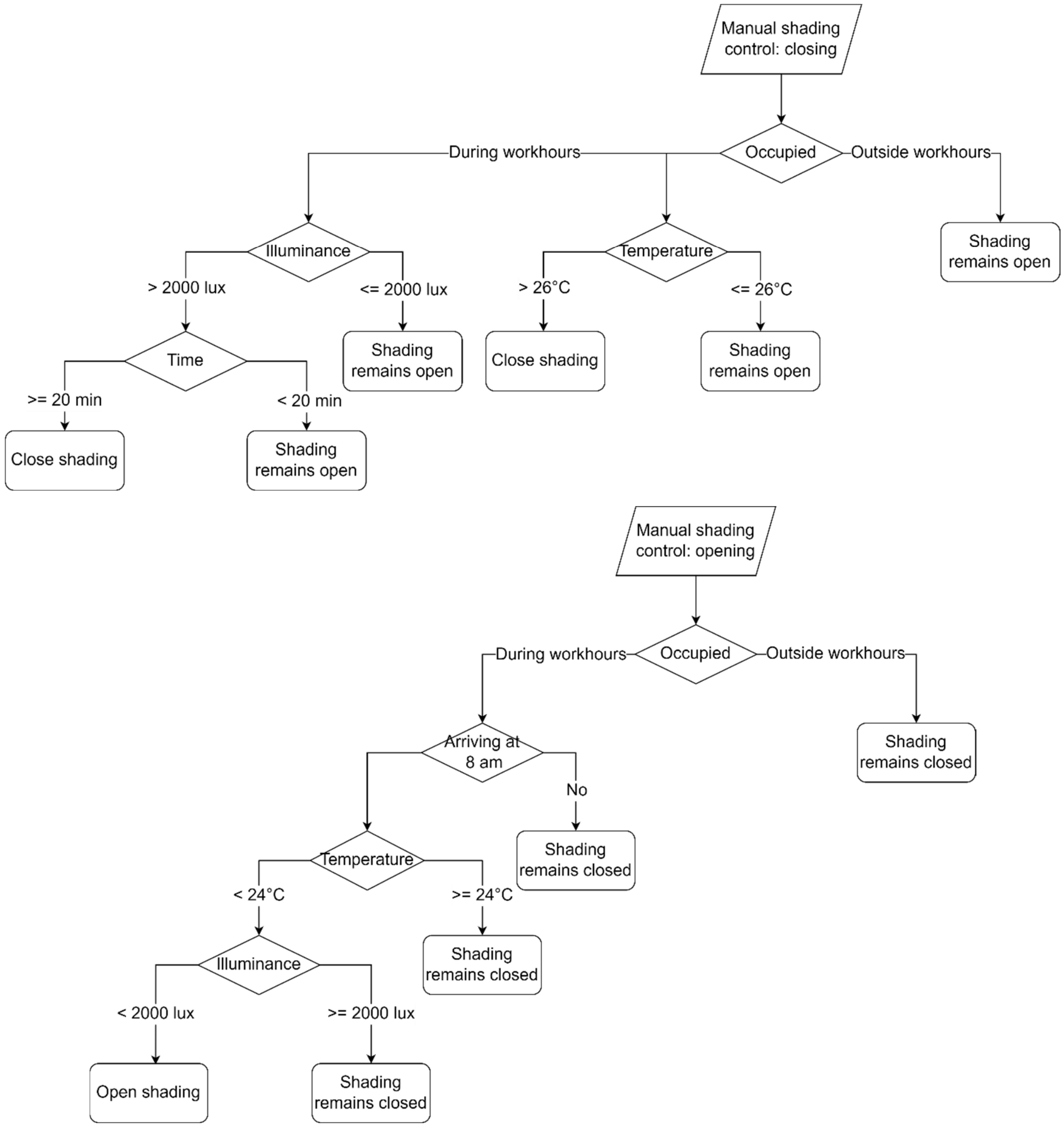
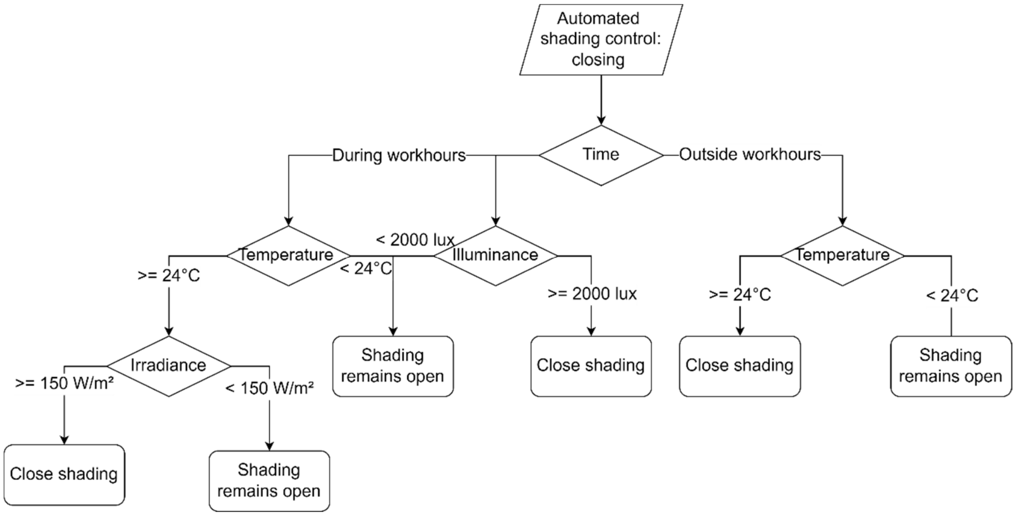


Fig. 3 – Overview of the manual shading control: closing and opening strategy.



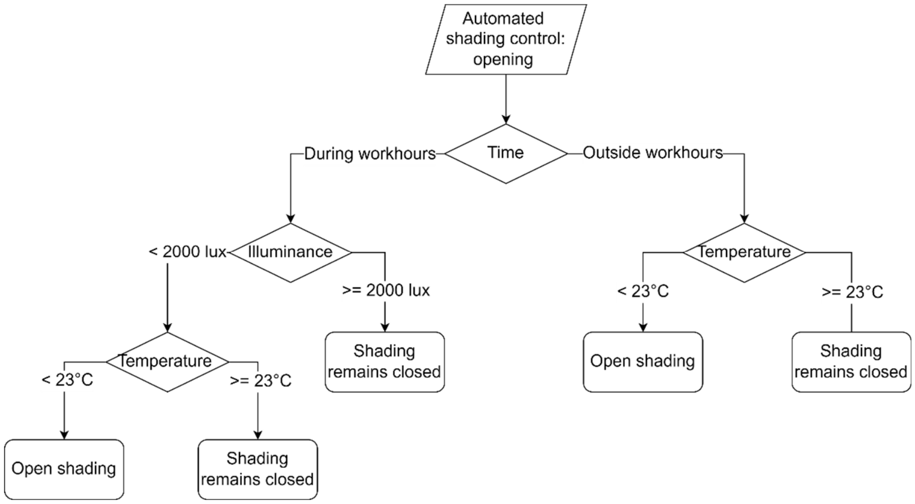


Fig. 4 - Overview of the automated shading control: closing and opening strategy.

4. Results and discussion

Main output parameters resulting from the simulation are:

- Heating energy consumption: the yearly energy use associated to heating gas boiler.
- Zone operative temperature (OT): is the average of the Zone Mean Air Temperature (MAT) and Zone Mean Radiant Temperature (MRT). In particular the total number of working hours where the OT is above 26 °C was computed in order to highlight discomfort conditions. The EN 16798-1:2019 sets IEQ criteria divided in 3 categories. In case of office buildings in summer, the comfort range corresponding to category II is 23-26 °C.
- Zone reference point illuminance: the measurement point is placed at desk height (0.8 m) located 1 m away from the window. In this case the cumulated number of working hours for different illuminance ranges was computed.

The results in Tab. 6 show that the implementation of both control strategies leads to a similar heating consumption (1.4% difference). The number of working hours where the OT reports values above 26 °C do not show significant differences either, being 6% higher for the automatic control strategy.

Tab. 6 – Results.

	Auto	Manual
Heating energy consumption [kWh/m^{2}a]	71.6	72.6
OT > 26°C, cumulated hours	350	330
illuminance > 2000 lux, cumulated hours	53.5	93.2

Finally, the illuminance parameter highlights the impact of the automated control strategy on the visual comfort. In this case, employees are exposed to an illuminance level higher than 2000 lux for 53.5 hours only, 43% less than manual control. This is visible in Fig. 5, where histograms represent the cumulative working time (hours) of illuminance levels binned per 500 lux intervals. In addition, under the premise that no artificial lighting is simulated, manual control leads to spend more hours in the interval 0-500 lux (scarce illuminance). EN 16768-1:2019 and EN16464-1 defines 500 lux as minimum illuminance level for office buildings.

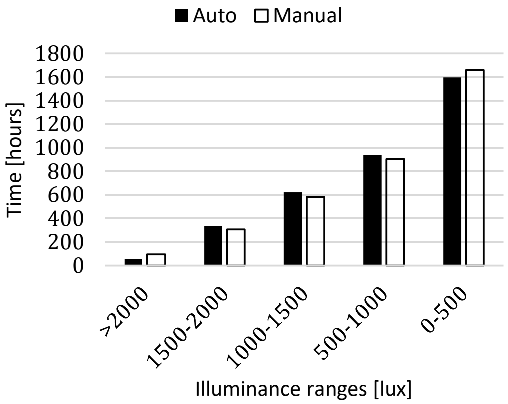


Fig. 5 - Cumulated working hours for different illuminance ranges.

Under the conditions defined in this simplified approach, the automated shading control does not provide appreciable benefits in terms of energy efficiency, although it is important to underline the positive impact on visual comfort. As pointed out in paragraph 2, visual comfort is directly related to attention restoration, stress reduction, and a better cognitive performance, which in turn impact on employee's productivity and the amount of sick leave each year. Furthermore, an automated control that provides detailed information to the occupants as well, giving the possibility to be aware of the current environmental conditions and to interact with them if needed, is proven to further enhance thermal and visual comfort sensation of the occupants.

5. Conclusions

To facilitate the transition to smart buildings, the multiple advantages that BACS offer need to be made more visible and to be considered altogether. An analysis framework for the evaluation of BACS co-benefits in office buildings has been introduced, outlining main benefits of automation systems for this building typology. Furthermore, a contemporary office building case study has been modeled within EnergyPlus to quantify the improved benefits associated to building automation, focusing on the analysis of a shading automated control system compared to a manual one. Control of movable elements such as openings, blinds and other sun shading solutions has a specific domain within the SRI scheme which is called "dynamic building envelope". Improving the control level of a shading system can not only reduce heating and/or cooling needs but also improve thermal and visual comfort of employees, enhancing the office experience. In turn, this has an impact on health related aspects such as stress reduction and productivity.

An approach that considers all the impact spectrum, highlights how often building design should put together competing interests. Minimizing energy consumption, can be in contrast with enhancing visual comfort or indoor air quality, nevertheless BACS can provide a solution to this issue, as these can be the cornerstone of a multi-objective optimization process, aiming at an optimal trade-off between opposite targets. Main limitations of this study are due to the reduced building model, the control strategies simplification, and the limited possibilities offered by the EnergyPlus EMS to model real controls. The aim of this analysis was to approach the evaluation of added values and benefits associated with an improved control level in office buildings. More research should be carried out to further develop this approach and test it on more BACS.

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References

1. Energy Information Administration, Energy Department. Annual Energy Review: Primary energy consumption by source and sector: Government Printing Office; 2019.
2. Lapillonne B, Sebi C, Pollier K, Mairet N. Energy Efficiency Trends in Buildings in the EU—Lessons from the ODYSSEE MURE project. ADEME. Retrieved December. 2012;30:2014.
3. Directive (EU) 2018844 of the European Parliament and of the Council of 30 May 2018 amending Directive 201031EU on the energy performance of buildings and Directive 201227EU on energy efficiency.
4. Smart Building Market. 2018 Global Trends, Market Share, Industry Size, Growth, Opportunities and Forecast to 2023. 2018.
5. Martirano L, Habib E, Parise G, Greco G, Manganelli M, Massarella F, Parise L. Demand Side Management in Microgrids for Load Control in Nearly Zero Energy Buildings. IEEE Transactions on Industry Applications. 2017;53:1769–79. doi:10.1109/TIA.2017.2672918.
6. Ożadowicz A. A New Concept of Active Demand Side Management for Energy Efficient Prosumer Microgrids with Smart Building Technologies. Energies 2017. doi:10.3390/en10111771.
7. Fan Z, Kulkarni P, Gormus S, Efthymiou C, Kalogridis G, Sooriyabandara M, et al. Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities. IEEE Communications Surveys Tutorials. 2013;15:21–38. doi:10.1109/SURV.2011.122211.00021.
8. O'Grady T, Chong H-Y, Morrison GM. A systematic review and meta-analysis of building automation systems. Building and Environment. 2021;195:107770. doi:10.1016/j.buildenv.2021.107770.
9. European Technical Standard. EN 15232 Energy Performance of Buildings: Impact of Building Automation, Control, and Building Management 2012. Brussels.
10. Verbeke S, Dorien A, Reynders G, Ma Y, Waide P. Final report on the technical support to the development of a Smart Readiness Indicator for buildings; 06/2020.
11. Märzinger T, Österreicher D. Extending the Application of the Smart Readiness Indicator—A Methodology for the Quantitative Assessment of the Load Shifting Potential of Smart Districts. Energies 2020. doi:10.3390/en13133507.
12. Billanes JD, Ma Z, Jørgensen BN. Consumer central energy flexibility in office buildings. Journal of Energy and Power Engineering. 2017;11.
13. Zhang W, Liu F, Fan R. Improved thermal comfort modeling for smart buildings: A data analytics study. International Journal of Electrical Power & Energy Systems. 2018;103:634–43. doi:10.1016/j.ijepes.2018.06.026.
14. Dong B, Prakash V, Feng F, O'Neill Z. A review of smart building sensing system for better indoor environment control. Energy and Buildings. 2019;199:29–46.

doi:10.1016/j.enbuild.2019.06.025.
15. Ko WH, Schiavon S, Zhang H, Graham LT, Brager G, Mauss I, Lin Y-W. The impact of a view from a window on thermal comfort, emotion, and cognitive performance. Building and Environment. 2020;175:106779. doi:10.1016/j.buildenv.2020.106779.
16. Altomonte S, Schiavon S, Kent MG, Brager G. Indoor environmental quality and occupant satisfaction in green-certified buildings. Building Research & Information. 2019;47:255–74.
17. Singh A, Syal M, Grady SC, Korkmaz S. Effects of Green Buildings on Employee Health and Productivity. American Journal of Public Health. 2010;100:1665–8. doi:10.2105/AJPH.2009.180687.
18. Purdey B. GREEN BUILDINGS AND PRODUCTIVITY. Environment Design Guide. 2005:1–9.
19. Berggren B, Wall M, Weiss T, Garzia F, Pernetti R, editors. LCC analysis of a Swedish net zero energy building–including co-benefits; 2018.
20. Bleyl J, Bareit M, Casas M, Coolen J, Bruyn BD, Hulshoff A, Robertson M, editors. Building deep energy retrofit: Using dynamic cash flow analysis and multiple benefits to convince investors; 2017.
21. Brew JS, editor. Finding the Value in Deep Energy Retrofits; 2017.
22. Brager GS, editor. Benefits of improving occupant comfort and well-being in buildings; 2013.
23. Yoon SH, Payne WV, Domanski PA. Residential heat pump heating performance with single faults imposed. Applied thermal engineering. 2011;31:765–71.
24. Loureiro T, Gil M, Desmaris R, Andaloro A, Karakosta C, Plesser S, editors. De-Risking Energy Efficiency Investments through Innovation; 2020.
25. Dobson DW, Sourani A, Sertyesilisik B, Tunstall A. Sustainable Construction: Analysis of Its Costs and Benefits. American Journal of Civil Engineering and Architecture. 2013;1:32–8. doi:10.12691/ajcea-1-2-2.
26. Bastida L, Cohen JJ, Kollmann A, Moya A, Reichl J. Exploring the role of ICT on household behavioural energy efficiency to mitigate global warming. Renewable and Sustainable Energy Reviews. 2019;103:455–62. doi:10.1016/j.rser.2019.01.004.
27. Rafsanjani HN, Ahn CR, Alahmad M. A Review of Approaches for Sensing, Understanding, and Improving Occupancy-Related Energy-Use Behaviors in Commercial Buildings. Energies. 2015;8:10996–1029. doi:10.3390/en81010996.
28. Tamas R, Ouf MM, O'Brien W. A field study on the effect of building automation on perceived comfort and control in institutional buildings. Architectural Science Review. 2020;63:74–86. doi:10.1080/00038628.2019.1695573.
29. Inkarojrit V. Balancing comfort: occupants' control of window blinds in private offices: University of California, Berkeley; 2005.
30. Sadeghi SA, Karava P, Konstantzos I, Tzempelikos A. Occupant interactions with shading and lighting systems using different control interfaces: A pilot field study. Building and Environment. 2016;97:177–95. doi:10.1016/j.buildenv.2015.12.008.
31. Correia da Silva P, Leal V, Andersen M. Influence of shading control patterns on the energy assessment of office spaces. Energy and Buildings. 2012;50:35–48. doi:10.1016/j.enbuild.2012.03.019.
32. Reinhart CF, Mardaljevic J, Rogers Z. Dynamic Daylight Performance Metrics for Sustainable Building Design. LEUKOS. 2006;3:7–31. doi:10.1582/LEUKOS.2006.03.01.001.
33. Karlsen L, Heiselberg P, Bryn I, Johra H. Solar shading control strategy for office buildings in cold climate. Energy and Buildings. 2016;118:316–28. doi:10.1016/j.enbuild.2016.03.014.
34. Thalfeldt M, Kurnitski J. External shading optimal control macros for 1- and 2-piece automated blinds in European climates. Building Simulation. 2015;8:13–25. doi:10.1007/s12273-014-0194-3.

Data Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.