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Understanding the opportunities and challenges of building automation and control systems to support facility management – an extensive literature review

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Sophie van Roosmale, Amaryllis Audenaert and Jasmine Meysman
Faculty of Applied Engineering, University of Antwerp, Antwerp, Belgium

Abstract

Purpose – This paper aims to highlight the expanding link between facility management (FM) and building automation and control systems (BACS) through a review of literature. It examines the opportunities and challenges of BACS for facility managers and proposes solutions for mitigating the risks associated with BACS implementation.

Design/methodology/approach – This paper reviews various research papers to explore the positive influences of BACS on FM, such as support with strategic decision-making, predictive maintenance, energy efficiency and comfort improvement. It also discusses the challenges of BACS, including obsolescence, interoperability, vendor lock-in, reliability and security risks and suggests potential solutions based on existing literature.

Findings – BACS offers numerous opportunities for facility managers, such as improved decision-making, energy efficiency and comfort levels in office buildings. However, there are also risks associated with BACS implementation, including obsolescence, interoperability, vendor lock-in, reliability and security risks. These risks can be mitigated through measures such as hardware and software obsolescence management plans, functional requirement lists, wireless communication protocols, advanced feedback systems and increased awareness about BACS security.

Originality/value – To the best of the authors' knowledge, no prior academic research has been conducted on the expanding link between FM and BACS. Although some papers have touched upon the opportunities and challenges of BACS for FM, this paper aims to provide a comprehensive overview of these findings by consolidating existing literature.

Keywords Building automation and control systems, Facility management, Risks, Sustainability, Opportunities, Challenges

Paper type Literature review

1. Introduction

Facility management (FM) is crucial for ensuring the functionality, comfort, safety, sustainability and efficiency of a building (CEN, 2018). A facility manager's goal is to follow the strategy of an organisation to facilitate the core operations of the organisation. Therefore, strategic planning and decision making related to maintaining building relevance in the long term are required skills (Pun *et al.*, 2017). In addition, the strategic decisions relate to minimising the operating costs of building assets with the right investment decisions to prevent breakdowns and exceed the designed lifespan (Atkin and Bildsten, 2017); see Figure 1. Furthermore, facility managers are responsible for implementing services like

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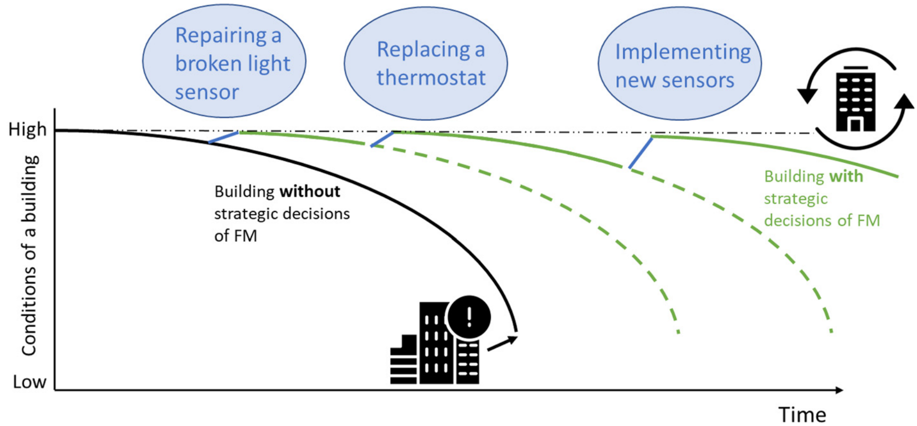

Figure 1.
Examples of strategic decisions of FM related to the building condition

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maintenance, cleaning, security, catering and watering plants (CEN, 2021; Pun *et al.*, 2017). An ongoing and escalating challenge for facility managers are the consequences of climate change on managing buildings in a more sustainable way (Curtis *et al.*, 2017). The European Green Deal aims for carbon neutrality by 2050, requiring facility managers to significantly reduce building energy consumption (European Commission, 2020).

building automation and control systems (BACS) have the capability to support facility managers in achieving an elevated level of sustainability within buildings. This is accomplished through enhanced energy efficiency throughout the operation phase, along with other responsibilities such as maintenance and guaranteeing comfort (Osma *et al.*, 2015). BACS can identify areas for improvement or maintenance; they enhance thermal comfort and air quality through sensor-based management of heating, cooling and ventilation (Garzia *et al.*, 2022; Martirano and Mitolo, 2020). While BACS adds value to a building, which increases the return on investment, they also complicate FM because of insufficient understanding of operational and maintenance implications (Domingues *et al.*, 2016; Mayer *et al.*, 2017; Ramsauer *et al.*, 2022; Zucker *et al.*, 2015). Furthermore, BACS introduces risks like obsolescence, interoperability, vendor-lock-in, reliability and security risks in the domain of building management (Bowlds *et al.*, 2018). These risks form a threat for the greater uptake of BACS by facility managers in general.

A considerable amount of research has been conducted on BACS, but each study has a specific focus and method, which hinders an optimal use of BACS for FM. This paper is the first step towards a better understanding of BACS for FM by investigating the expanding link between FM and BACS described in the literature. The aim is to explore the positive influences, challenges and best practices of BACS for facility managers to encourage greater BACS implementation by facility managers.

2. Methodology

A qualitative systematic literature review, based on a thematic analyses, was conducted to make an overview of the opportunities and challenges of BACS for facility managers (Snyder, 2019). The research strategy consists of defining search terms, the scope and selecting different data sources to identify candidate articles. The used databases are Web of Science, Google Scholar, JSTOR and Emerald Insights. The search terms, Building

Automation and Control Systems/BACS and Facility Management, were placed in a Boolean string, and they form a combination of "Facility Management" AND "BACS" NOT "SMART CITIES", but this resulted in too few relevant articles, as BACS is a very broad umbrella term. The focus in this paper is BACS in office buildings, so the relevant categories of BACS in combination with" Facility Management" were used. This resulted in strings of "Facility management" AND "smart lights", "Facility management" AND "smart blinds", "Facility management" AND "smart HVAC", "Facility management" AND "Intelligent Building" and "Facility management" AND "Building automation" AND "Control systems". The selection criteria are only publications written in English because English is the primary language of scientific publications. In addition, only publications that define or discuss BACS or smart technologies (like heating ventilation airconditioning HVAC, lighting and so on) in an FM context are included. The exclusion criteria are publications that cannot be located and publications earlier than 2010 because they are outdated due to the rapid technological developments in BACS (with one exception regarding an important development in BACS). The relevance of the collected papers was ensured by the title, keywords and abstract to define the subject. This search resulted in 169 relevant findings and an additional 116 papers were included using the snowballing technique (Wohlin, 2014). See Figure 2 for a summary of the process. Subsequently, all selected articles were processed and bibliographic data such as title, authors, publishing year, keywords, topics, description of the paper and the conclusions were indexed. In the next chapters, the results of this literature study will be explained.

3. Opportunities of building automation and control systems for facility management according to literature

Facility managers face challenges in balancing energy performance, comfort and (maintenance) costs. BACS offers valuable support by enabling data-driven strategic decisions and optimising maintenance activities in buildings. BACS can collect real-time and

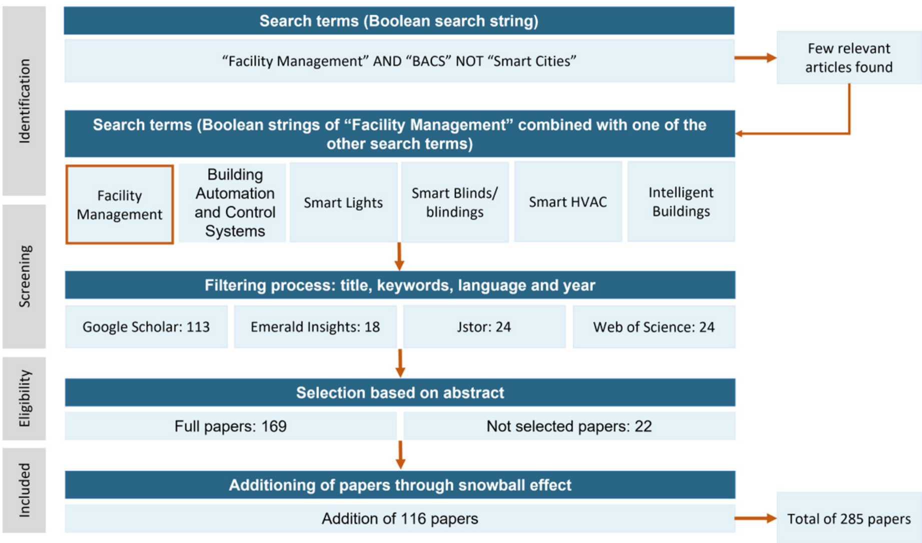

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Figure 2. Summary of the literature review process

historical data, analyse weather data and user behaviour and inform decisions related to adjusting setpoints and prioritising maintenance. The following chapters discuss the opportunities of BACS in detail.

3.1 Strategic decision-making

BACS can support facility managers with data-driven strategic (investment) decisions to maintain the long-term relevance and functionality of buildings, by collecting and comparing data (Atkin and Bildsten, 2017). Real-time data, including temperature, daylight, airflow and air quality, combined with project information, historical data, weather data and analysis results from condition monitoring, can inform decisions such as adjusting setpoints, prioritising maintenance and avoiding unnecessary maintenance (Domingues *et al.*, 2016; Pun *et al.*, 2017). Monitoring users' behaviour through sensors is important because users impact building performance, so this provides insights to predict future behaviour (Liu *et al.*, 2010; Pettersen *et al.*, 2017). Facility managers face a challenge balancing energy performance, economic efficiency (of maintenance) and users' preferences while considering the building's context (Mayer *et al.*, 2017). Shen *et al.* developed a loosely coupled system to assist facility managers in decision-making that collects and integrates all information from different systems and vendors with varying communication protocols (Shen *et al.*, 2012).

Facility managers must prioritise goals in BACS, as conflicts can arise between optimal comfort and ideal energy performance and the economic efficiency of maintenance (Mayer *et al.*, 2017; Pun *et al.*, 2017). Yang *et al.* focus on finding a balance between energy consumption and comfort through a decentralised control system using algorithms to calculate the best compromise. It uses a central coordinator agent to communicate between the user and three local controller agents to make decisions in BACS based on user preferences and data collected from the local controller agents like temperature, air quality and illumination (Yang and Wang, 2012).

3.2 Reactive, proactive and predictive maintenance

Facility managers conduct maintenance on the building to ensure efficiency and extend its service life. This includes observing and monitoring the facility, fault localisation, (planning of) cleaning, maintenance and repairing defects or replacing components, as well as checking defect resolutions and component performance (British Standards Institution, 2018). These activities ensure optimal and safe operation of the building for the building's users. Efficient FM requires strategic planning and organisation.

There are different types of maintenance, reactive and preventive maintenance. Reactive maintenance involves repairing an item to restore its function and is implemented when a defect or malfunction is detected (British Standards Institution, 2018). BACS support facility managers with providing real-time monitoring and notifications of defects, enabling faster response and minimising potential hazards (Villa *et al.*, 2022). However, reactive maintenance can be costly as it requires urgent and unexpected repairs or replacement and it disrupts the optimal operation of the building (Fialho *et al.*, 2022).

Preventive maintenance, or proactive maintenance, is executed before defects are reported to prevent malfunctions (Villa *et al.*, 2022). Components will be replaced before reaching their projected end of life. BACS combined with preventive maintenance has advantages over reactive maintenance, as it sends timely notifications based on schedules or usage to facility manager for checks, repairs or replacements. However, it can be time-consuming because of regular physically checking the building, which is often not budgeted for in FM plans (Bouabdallaoui *et al.*, 2021). Further research is needed to assess the potential cost savings from implementing preventive maintenance in BACS in comparison to reactive maintenance.

Additionally, BACS enables predictive maintenance, which uses historical and real-time data along with advanced statistical methods to predict the timing of a failure based on deviations. Then, it notifies the facility manager of needed maintenance before a defect occurs (Casini, 2022). Predictive maintenance is similar to preventive maintenance as it aims to prevent defects and faults (such as a misplaced sensor or incorrect setpoints). However, predictive maintenance avoids unnecessary replacements and allows for proactive identification of the cause of defects.

Fault detection and diagnostics techniques use data collected by BACS to monitor the building and repeatedly analysing it for anomalies, reducing the need for emergency repairs and improving maintenance efficiency (British Standards Institution, 2018; Chew and Yan, 2022; Gunay and Shi, 2020). Various fault detection and diagnosis methods exist. Model-based fault detection involves an algorithm constantly checking the output of BACS against its predicted behaviour to identify faults. However, these algorithms may not always be available. Signal-based systems generate notifications when data does not align with BACS's "healthy" data, but it can malfunction with unknown failures. Knowledge-based fault detection compares large amounts of historical data from BACS with real-time data. However, these amounts of historical data create computational burdens. The active fault detection injects test signals into BACS to evaluate its performance, but the added signals may obstruct the performance of BACS (Lazarova-Molnar *et al.*, 2016).

Predictive maintenance could enhance system reliability and decrease reliance on reactive maintenance (Peng Au-Yong *et al.*, 2014). However, this technique is still under development due to the complexity of the system to autonomously analyse the data and determine the need for preventive maintenance (Bouabdallaoui *et al.*, 2021).

3.3 Sustainability

Sustainable buildings prioritise reduced emissions and waste (environmental pillar), improved user comfort (social pillar) while minimising water and energy consumption throughout its life cycle (economic pillar of sustainability) (Mayer *et al.*, 2017). Facility managers ensure this through predictive maintenance strategies in which the service life of the materials and installations are extended and aligning the building's function with the company's core operations. They promote retrofits to reduce energy usage and emissions without strongly increasing the costs. Optimising BACS is another viable option for enhancing sustainability (CEN, 2017; O'Grady *et al.*, 2021; Osma *et al.*, 2015).

BACS uses real-time and historical data on luminescence and temperature to optimise lighting, blinds and HVAC, enhancing energy efficiency. Light sensors measure luminescence, reducing the unnecessary use of electric lights (Osma *et al.*, 2015). Thermostats can also reduce energy usage by providing feedback on local air temperatures for system adjustments. However, the potential benefits of integrating lighting, HVAC and blinds to reduce energy consumption, like closing blinds in summer to reduce cooling energy and opening blinds in winter to maximise natural lighting and heating, are often overlooked (Osma *et al.*, 2015). BACS should also have low energy consumption, and today BACS can respond to changes in electricity prices, further enhancing energy efficiency (O'Grady *et al.*, 2021).

Human interactions with BACS significantly impact a building's energy performance (Osma *et al.*, 2015; Weerasinghe *et al.*, 2022). However, motion sensor data for occupancy levels, users' needs and simulations of energy consumption are often inadequately analysed for benchmarking and setpoint selection (Kučera and Pitner, 2018; Mayer *et al.*, 2017). Neglecting user needs can increase energy use through manual setpoint overrides.

Increasing user awareness and understanding of energy consumption through feedback and responsibility can result in energy savings of 10% (O'Grady *et al.*, 2021).

A lesser addressed yet significant aspect of the sustainability of BACS is the repairability of components or systems such as lighting and HVAC. Repairability refers to the component's repair potential; highly repairable components are preferred from a sustainability standpoint as they minimise waste and reduce the need for new parts. However, components that have infrequent breakdowns but need to be completely replaced in case of failure fall into a grey area in terms of sustainability (Villa *et al.*, 2022).

3.4 Comfort

Facility managers influence building occupants' comfort levels by selecting and monitoring the optimal setpoints in BACS. Higher comfort levels result in increased satisfaction, better health and improved productivity (Halhoul Merabet *et al.*, 2021). BACS can influence different aspects of comfort, such as thermal comfort, through HVAC's functions that regulate temperature within a preset range (Gunes *et al.*, 2015; Yang and Wang, 2012). Indoor air quality can also be influenced by ventilation through HVAC, having a significant impact on the health and productivity of occupants (Gunes *et al.*, 2015; O'Grady *et al.*, 2021; Salamone *et al.*, 2017; Yang and Wang, 2012). Lighting, including natural daylight and electric lighting, along with blinds, contributes to visual comfort by managing natural light and preventing glare on computer screens (Yang *et al.*, 2021).

Correct operation of BACS is important for occupant comfort because discomfort leads to increased complaints for a facility manager. User input helps adjust lighting, blinds and HVAC settings, but comfort is subjective, making it challenging to meet everyone's preferences (Gunes *et al.*, 2015; Klein *et al.*, 2012). Systems that collect users' feedback through ticketing or platforms are often used, though they are time-consuming for facility managers to analyse and implement the feedback (Yang *et al.*, 2021). Thus, Ramsauer *et al.* devised a system, "Human perception and Building Automation System" (HumBAS), that analyses feedback and adjusts BACS settings to enhance comfort and productivity (Ramsauer *et al.*, 2022).

Another aspect a facility manager needs to consider is the trade-off between increased comfort and higher energy demands (O'Grady *et al.*, 2021; Yang and Wang, 2012). Balancing comfort and energy efficiency is a priority, and BACS can support this by collecting data about the thermal, lighting and air quality levels from sensors and using this data to support facility managers in decision-making (Araszkiewicz, 2017; Ramsauer *et al.*, 2022; Yang *et al.*, 2021). Hence, the accuracy of the sensors is of significance (Gunes *et al.*, 2015). Interactions between lighting, blinds and HVAC have an impact; e.g. around 30% of energy used for cooling is caused by heat gain through windows (Yang *et al.*, 2021). For example, optimising blinds based on sunlight can reduce the need for additional cooling in summer and heating in winter (O'Grady *et al.*, 2021). Ensuring proper integration and settings of HVAC, blinds and lighting are essential for both energy efficiency and occupant comfort (Yang *et al.*, 2021).

4. Challenges of building automation and control systems for facility management according to literature

BACS offer benefits for facility managers, but also provide challenges, including increasing complexity because of growing expectations and their ability to control more systems (Domingues *et al.*, 2016; Osma *et al.*, 2015). Other challenges are data management (Pašek and Sojková, 2019), high investment costs for installation and maintenance costs (Osma *et al.*, 2015). The following chapters discuss specific challenges in detail.

4.1 Obsolescence

The construction industry is constantly evolving with the introduction of new BACS technologies, increasing the risk of obsolescence in existing applications (Lomakin and Murav'ev, 2016; Pašek and Sojková, 2019). Obsolescence refers to the lack of maintenance support for components or systems, because of the development of new technologies, product unavailability, discontinuing support due to market competition or company closure (Alelyani *et al.*, 2019; British Standards Institution, 2018).

Lomakin and Murav'ev (2016) described three types of obsolescence of systems: economic, functional and degradation of resource resilience (Lomakin and Murav'ev, 2016). Economic obsolescence occurs when newer and cheaper versions of a system become available, leading to discontinuation of older versions. Functional obsolescence arises when the operation of the "old" system no longer meets current needs because additional features are required. Degradation of the resource resilience refers to a lack of replacement components or skills for repair, resulting in fatal failures of the system. Alelyani *et al.* (2019) described three types of obsolescence similar to Lomakin's but not identical. Functional obsolescence occurs when there are functional changes to the software within the same system. Technological obsolescence happens when the vendor no longer supports the software product. Finally, logistical obsolescence occurs when the hardware is no longer compatible with a new version of the software (Alelyani *et al.*, 2019).

Commercial software and hardware components often have a shorter lifespan than the expected lifespan of the entire system (Bowlds *et al.*, 2018; Wu *et al.*, 2022). Rapid software evolution requires frequent updates and increases costs (Alelyani *et al.*, 2019). Considering obsolescence in planning is crucial, as 70% of commercial off-the-shelf technology will be unavailable within 20 years (Robinson *et al.*, 2015).

One way to mitigate obsolescence is purchasing a lifetime supply of components, however this is challenging because it requires accurate estimation of the required parts and storage space, and it does not effectively address software obsolescence (Sandborn, 2013). Emulation offers a better solution by replacing the obsolete component of BACS with hardware or software that imitates the same function, communication protocol and mechanical characteristics as the original (Baker, 2013; Robinson *et al.*, 2015). However, emulation can be time-consuming because it demands a thorough analysis of the original functions, especially for software obsolescence, making it challenging for facility managers to implement their obsolete components of BACS (Robinson *et al.*, 2015). Hence, other solutions may be more suitable, but completely predicting and preventing obsolescence in BACS is impossible (Robinson *et al.*, 2015). Having a hardware and software obsolescence management plan assist in addressing the uncertainties associated with obsolescence (Sandborn, 2013; Schmid *et al.*, 2016). The plan includes a material risk index (MRI), which evaluates components based on time-dependent risks that may impede their functioning because of obsolescence. These evaluations can be used to formulate an action plan and a cost analysis, but MRI can be time-consuming (Sandborn, 2013). The next step is to create a design refresh planning (DRP), aiming to identify the optimal timing and scope of BACS to mitigate future costs (Sandborn, 2013), based on market analysis and surveys with different vendors. However, DRP often produces insufficient results, particularly for software applications.

Facility managers need to be aware of the remaining obsolescence challenges by preparing a strategic plan to respond effectively to the possible obsolescence of BACS and ensure the building's flexibility (Baker, 2013; Pašek and Sojková, 2019).

4.2 Interoperability

Facility managers deal with various hardware and software systems in BACS. So, interoperability for information exchange and collaboration is required (Declercq *et al.*, 2021; Domingues *et al.*, 2016; Shen *et al.*, 2012). Manufacturers develop protocols for BACS to create interoperability, with a specific goal, sales price and timeframe for the development (Declercq *et al.*, 2021). However, manufacturers are unable to predict all future-needed functions of BACS, leading to new interoperability challenges (Domingues *et al.*, 2016). Other challenges include confusion about protocols due to a lack of awareness of the technical complexity of BACS and cybersecurity concerns because of connections in BACS devices from several vendors (Declercq *et al.*, 2021; Verbeke *et al.*, 2022). There are four types of interoperability. Technical interoperability concerns the connectivity between components because of the translation of messages from one protocol to another (Domingues *et al.*, 2016; Giao *et al.*, 2022; Verbeke *et al.*, 2022). Syntactical interoperability refers to the packing and transmission of data (Giao *et al.*, 2022; Verbeke *et al.*, 2022). Semantic interoperability is addressed to how concepts from different technologies are interchanged, understood and processed (Giao *et al.*, 2022; Verbeke *et al.*, 2022). Finally, organisational interoperability relates to business objectives and regulatory frameworks (Verbeke *et al.*, 2022).

Interoperability in BACS can be improved by using open communication protocols. Although open protocols, such as BACnet and LonWorks, provide broad functionality and are able to communicate with some products from different vendors, they are still not able to communicate with all devices and components (Domingues *et al.*, 2016; King and Perry, 2017; Verbeke *et al.*, 2022). Furthermore, adding specific functions to open protocols can hinder interoperability with other systems or components (Declercq *et al.*, 2021).

Layered communication models, like the open system intercommunication (OSI) model or the transmission control protocol/internet protocol (TCP/IP) model, can enable partial interoperability on devices and software from different vendors (Declercq *et al.*, 2021). Physical or software gateways are another solution. A physical gateway is able to translate between protocols used by different hardware components, whereas a software gateway translates between protocols in the same communication layer (Declercq *et al.*, 2021). Service-oriented architecture (SOA) is an example of a gateway that acts as a communication gateway between different devices, based on architectural principles and patterns to reuse services from different components of vendors, or combines several independent services to perform a task (Giao *et al.*, 2022; Shen *et al.*, 2012). Other solutions are semantic taxonomies and standardised ontologies, which are able to find similarities in the content of different protocols and in data points, like an application programming interface (Declercq *et al.*, 2021). An example of this is smart appliances REFerence ontology (SAREF) (Verbeke *et al.*, 2022).

Facility managers should develop a strategy before implementing these solutions, which includes functional requirements and required connections in BACS, to avoid unnecessary complexity and costs (Declercq *et al.*, 2021).

4.3 Vendor lock-in

Vendor lock-in is often seen as part/result of interoperability (Kiss, 2022; Opara-Martins *et al.*, 2016), yet there is a clear distinction. Vendor lock-in refers to the difficulties faced by facility managers when switching software and hardware vendors due to technologically complex underlying (cloud) infrastructures and a lack of universal standards (De Oliveira *et al.*, 2017). It is time-consuming and costly for facility managers to transition to another vendor. Vendor lock-in can occur for products and services tied to a vendor (Verbeke *et al.*, 2022), resulting in competitive market positions (van der Zeeuw *et al.*, 2022). Customers may change or combine different vendors for several reasons, like price increases, technical issues or the need to improve their BACS. Ensuring the adaptability of BACS to new developments is crucial given their long service life (Kastner *et al.*, 2005).

Vendor lock-in can occur in four areas: data transfer, application transfer, infrastructure transfer and human knowledge (Kiss, 2022). Data transfer challenges arise from incompatible data storage solutions or differences in writing patterns, resulting in service failures and loss of application functionality (Opara-Martins *et al.*, 2016). Application transfer is difficult when a system relies on specific standards not supported by another vendor. Infrastructure transfer can happen when fieldbuses are used as a standard solution for communication in BACS, but the data exchange protocol is different or proprietary (Bangemann *et al.*, 2014). Calculating cost reductions for a different vendor can be complex because of the pricing and context of the vendor. Human knowledge lock-in refers to the time-consuming and costly process of training an operation team to learn the new vendor's infrastructure formats and implementation processes (Kiss, 2022).

Currently, there are no complete solutions to eliminate vendor lock-in. Facility managers should be aware of the risks and strive to minimise vendor lock-in (Kastner *et al.*, 2005). Mitigation strategies include gathering information about vendor standards and developing an exit strategy that considers potential difficulties and costs of switching vendors (Opara-Martins *et al.*, 2016). Another mitigation is choosing an "open" system that allows repairing, modifying and extending without the original manufacturer. However, this demands a higher degree of technological knowledge and may increase hardware and software engineering costs while reducing life cycle costs (Kastner *et al.*, 2005).

4.4 Reliability

BACS depends on the collected data communicated through communication protocols (Gunes *et al.*, 2015). If there are reliability issues with the components collecting data or with the (implementation of the) communicating protocol, it can compromise the safe and secure operation of BACS (Abdulmunem and Kharchenko, 2017; British Standards Institution, 2018; Pašek and Sojková, 2019). Reliability issues can arise from operational/physical failures, manufacturer (physical) failures and/or software design failures.

Both wireless and bus system communication protocols in BACS can experience reliability issues. Bus system communication may suffer from disruptions caused by devices with noise suppression defects or devices injecting noise, e.g. light dimmers (Elsts, 2016), leading to data communication delays. Wireless communication protocols, like Zigbee, are less expensive and time-consuming to implement in existing buildings compared with bus systems, making them more scalable and flexible (Mary Reena *et al.*, 2015). However, wireless systems may face challenges with battery life, limited bandwidth when many devices are connected and network disruptions, particularly when using IEEE.802.15.4 standard (Elsts, 2016; Mary Reena *et al.*, 2015).

Reliability of new hardware components and software that have not yet been implemented poses a challenge because of a lack of operational profile information (actual usage). However, methods such as system engineers' intuition, component behaviour simulations and executions logs of similar components can be used to estimate the operational profile (Quatrini *et al.*, 2020).

To enhance the reliability of wireless communication protocols, prioritising data from sensors in highly occupied rooms and ensuring timely communication of occupancy changes to controllers and actuators can be effective (Mary Reena *et al.*, 2015). In addition, making sensor data accessible to multiple BACS components allows for shared use, such as using anti-intrusion sensors for HVAC control, reducing the need for additional sensors and improving reaction time. A possibility to extend the battery life is to combine a wireless communication protocol with a bus system, offering the benefits of both systems (Schrom *et al.*, 2011).

4.5 Occupant behaviour

Occupant behaviour, defined by the interaction between humans and building, impacts energy consumption and comfort (Balvedi *et al.*, 2018). With the advent of BACS, manual control of the indoor environment was replaced by centralised automation, thus improving energy efficiency. However, early BACS applications relied on occupancy assumptions rather than real-time data for defining setpoints (Klein *et al.*, 2012). Personal control of the indoor environment and the system's response to irregularities were also overlooked. Subsequent developments aimed to increase occupant control and satisfaction of the indoor environment by constantly informing the facility managers (Park *et al.*, 2019; Ramsauer *et al.*, 2022). However, this approach had drawbacks on energy performance due to limited awareness of user behaviour (Pellegrino *et al.*, 2016), discomfort among some occupants and increased workload for facility managers who adjust setpoints based on subjective feedback. Implementing occupancy control in BACS introduces complexity (Ramsauer *et al.*, 2022).

One solution to enhance local occupancy control in BACS is to integrate occupants' interactions directly into BACS. This involves collecting data from indoor sensors such as illuminance, temperature, humidity and adjusting actuators based on predefined environmental standards. Next, the occupant interactions (turning the light switches, manually lowering or raising the blinds) with the building are monitored as feedback to optimise data settings (Park *et al.*, 2019). However, this solution may overlook the interconnection in different BACS applications, like the influence of blinds on lighting and HVAC (Park *et al.*, 2019). Ramsauer *et el.* (2022) proposed a direct feedback implementation approach (HumBAS tool, described in Section 3.4), where feedback is requested, pseudonymised and connected to specific building locations. The collected feedback is then exchanged with a controller through a protocol, enabling the controller to send commands to actuators, while sensors control parameters changes. Both solutions are still in the experimental phase, lacking standardised evaluation and comparison across different case studies (Park *et al.*, 2019; Ramsauer *et al.*, 2022).

4.6 Security

Originally, security and safety were not prioritised when designing BACS in the 1970s and 1980s as they operated autonomously. However, with the development of communication protocols and internet connectivity, BACS became vulnerable to physical or cyberattacks (Graveto *et al.*, 2022; Li *et al.*, 2023).

Components such as sensors and actuators, which are directly linked to control platforms and data management, can be tampered with due to physical accessibility. Remote attacks, including manipulating indoor environments, compromising system functionality and leaking personal information are possible because of open protocols and the Internet Protocol (Graveto *et al.*, 2022; Li *et al.*, 2023). BACS are overall vulnerable to signal corruption, delaying and blocking (Li *et al.*, 2023).

Each level of BACS faces specific risks. The management level is vulnerable to password attacks, malicious codes and database manipulation. At the automation level, controllers are vulnerable to remote and local attacks, e.g. malware injection (Raveendran and Tabet Aoul, 2021), network overload through fake traffic or snooping attacks for unauthorised data access data. The field level is prone to electromagnetic attacks that can reverse signals in the

BACS network or hijack wireless connections. Threats such as fake data releases or battery draining through physical connections are also possible (Li *et al.*, 2023).

Building owners are increasingly aware of the threats and safety concerns for their buildings and its occupants. The interconnected nature of smart buildings has led to notable security breaches, like the 2016 cyberattack through internet of things (IoT) devices that temporarily disabled services such as Twitter, Spotify and PayPal [1]. Collaborative efforts between the information technology (IT) and Operation Technology (OT) industries are essential to develop and implement cybersecurity strategies (King and Perry, 2017).

Mitigation strategies include implementing detection systems on all layers of BACS using rule-based, data-driven and visualisation-based detection methods. Rule-based detection compares network traffic with defined protocol rules to detect and generate alarms for potential attacks. Data-driven detection uses real and simulated data sets to detect attacks. Visualisation-based detection identifies anomalies in messages from a BACnet-based network. Other approaches are to strengthen BACS protocols to narrow the surface for possible attacks and use network firewalls and traffic normalisation to defend against malicious programs, unauthorised access and network overload attacks (Li *et al.*, 2023).

5. Discussion and future research

In this section, the core findings from this extensive literature review will be discussed. This review aimed at clarifying the opportunities and challenges BACS can be for FM and identifying best practices for the field. A total of 285 papers were studied, based on which four opportunities were identified and several challenges were found. An overview of the key findings is given in Table 1.

From the literature, it is clear that the opportunities for FM arising from BACS implementation in (office) buildings are very interesting. Especially the ability of BACS to collect large amounts of data that can be used as input for strategic decision-making for both

Themes	Key findings
Opportunities	BACS can improve strategic decision-making for facility management through data-driven planning and optimisation
	Predictive, proactive and reactive maintenance are facilitated through BACS, increasing system reliability
	BACS can actively improve a building's sustainability by optimising its energy use and service life extension of systems
	BACS can help facility managers balance comfort needs of occupants with energy optimisation, improving overall efficiency
Challenges	As technology keeps progressing, obsolescence is also an important risk for BACS systems
	Interoperability is important for integrating different BACS within one building, as this is necessary to obtain the highest level of energy efficiency. Facility managers should develop interoperability strategies before implementing BACS solutions
	Vendor-lock remains a risk for BACS, as proprietary systems can come with high maintenance or replacement costs
	Occupant behaviour and control of BACS can intersect directly with the goal of BACS implementation, leading to efficiency losses and higher FM workload
	Cybersecurity of BACS has become more important due to the increased use of IoT-based components and internet connectivity of systems

Source: Created by authors

Table 1. Key findings about the opportunities and challenges of BACS for FM from the literature review

maintenance and sustainability efforts is promising. The implementation of BACS allows for further digitisation of building management and improves the usability of other digital applications such as digital twins and artificial intelligence (AI) models (Hakimi *et al.*, 2023). However, the increased use of big data in FM also comes with its own challenges, as this also demands a changing skill set of the facility manager towards more IT-oriented expertise and a higher dependency or reliance on internal IT supporting services or specialised consultancy firms (Palleschi and Villa, 2021).

The introduction of BACS into buildings brings along several technological risks, which can all be traced back to one phenomenon: the introduction of technological systems with shorter life cycles than the building they are implemented in. As a BACS life cycle is generally considered to be around 20–25 years, and buildings are generally expected to have a useful life of more than 60 years, a BACS is expected to undergo several product cycles before the building reaches its end of life (Dwaikat and Ali, 2018).

As in many technological developments, BACS manufacturers are starting to step away from their proprietary systems and are moving towards more prevalent open protocols such as KNX and BACnet. This evolution towards open protocols will positively influence both the risk of interoperability, vendor lock-in and obsolescence, as it increases the flexibility and adaptability of BACS at a relatively low cost. (Andriamamonjy, 2018). Also in the domain of security, parallels can be identified with other technological applications: the increased interconnectedness of systems and buildings with the internet has made them vulnerable to cyber-attacks. The use of the aforementioned open protocols, although having positive effects on technological risks, makes BAC systems vulnerable to intrusions from the outside (Graveto *et al.*, 2023; Siebel, 2017). This should be kept in mind, and appropriate provisions for the cost of securing these systems should be made during the initial planning phase.

6. Conclusion

This paper investigates the expanding link between FM and BACS through a review of various research papers. To the best of our knowledge, this is the first literature review to give an overview of the opportunities and challenges of BACS applications in buildings.

Many studies described the opportunities of BACS for FM, such as support with strategic decision-making by collecting and comparing real-time data and historical data. Other opportunities are preventing defects through predictive maintenance and ensuring more energy efficiency in office buildings due to the interaction of different applications (blinds, HVAC and lighting). A last opportunity is the positive influence of BACS on the comfort level while maintaining energy efficiency.

However, BACS also have drawbacks that limit their potential for facility managers. Obsolescence of BACS could increase costs, but an obsolescence management plan and a DRP can aid future cost planning. Other risks, interoperability and vendor lock-in, can be mitigated with gateways, OSI models and strategic planning of requirements of BACS to prevent unnecessary investments. Gathering vendor information helps prevent vendor lock-in. The impact of occupants' behaviour on BACS and on energy efficiency are beyond the direct control of facility managers, but implementing advanced feedback systems can improve comfort levels and build trust among occupants. BACS security risks are significant, but facility managers and building owners are becoming more aware. Research has been conducted on detecting and protecting strategies for BACS security.

This study highlights the potential of BACS for facility managers and identifies risks and subsequent mitigation strategies for said risks. However, these mitigation strategies generally come with a cost, putting pressure on the return on investment of BACS that is already difficult to estimate. Further research should thus be aimed at understanding the impact of these challenges on the total life cycle costs of BACS. By embracing the challenges into a more accurate life cycle cost analysis (LCCA) of BACS, it would be possible for facility managers to make more informed and sustainable investments in BACS implementations.

Note

1. https://arstechnica.com/information-technology/2016/10/inside-the-machine-uprising-how-cameras-dvrs-took-down-parts-of-the-internet/accessed on March 24, 2023.

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Corresponding author
Sophie van Roosmale can be contacted at: Sophie.vanRoosmale@uantwerpen.be