Journal of Building Engineering 97 (2024) 110943

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Building automation and control systems for office buildings: Technical insights for effective facility management - A literature review

S. van Roosmale [a,*], P. Hellinckx [b], J. Meysman [a], S. Verbeke [a,c,d], A. Audenaert [a]

[a] *Energy and Materials in Infrastructure and Buildings, University of Antwerp, Faculty of Applied Engineering, Groenenborgerlaan 171, 2020, Antwerp, Belgium*
[b] *Modelling4Sustainability (M4S), University of Antwerp, Faculty of Applied Engineering, Groenenborgerlaan 171, 2020, Antwerp, Belgium*
[c] *Vlaamse Instelling voor Technologisch Onderzoek (VITO), Boeretang 200, 2400, Mol, Belgium*
[d] *EnergyVille, Thor Park 8310, 3600, Genk, Belgium*

ARTICLE INFO

Keywords:
Building automation and control systems (BACS)
Facility management (FM)
Fundamental structure
Communication protocols
Security risks

ABSTRACT

This paper provides an overview of the benefits of Building Automation and Control Systems (BACS) for facility managers of office buildings and delves into the fundamental structure of BACS. Facility managers are increasingly tasked with growing demands for sustainability, energy efficiency, and comfort and convenience for occupants in buildings. BACS offers technological advancements to assist facility managers with these tasks. BACS replace manual interactions with building technical systems, such as lighting and climate control, with automated actions, leading to a more optimised control. By collecting real-time data, BACS support facility managers in making strategic decisions based on the condition of the building and its technical systems. Moreover, BACS can identify potential defects or malfunctions through fault detection and diagnosis techniques, enabling facility managers to implement predictive maintenance. Additionally,. However, the implementation of BACS presents challenges, as facility managers require specific knowledge to plan and operate these systems effectively. This paper explains specific knowledge regarding the structure of BACS, such as the three-level model, topologies, communication protocols and the relation between BACS and other digital applications. Despite the benefits offered by BACS, the study acknowledges the increased security risks associated with physical and cyber-attacks. Strategies to detect and defend against potential attacks are discussed, emphasizing the importance of addressing vulnerabilities in protocols, testing on real cases, regularly updating passwords and systems, and improving defence approaches. This research highlights the potential of BACS for facility managers while emphasizing the need for future studies on BACS's impact.

1. Introduction

Facility Management (FM) has increasingly become integral to the management strategy of companies and the care for their real estate assets from the 1980s and onwards [1,2]. Initially, the tasks of a facility manager typically included planning various services such as cleaning, security, catering, green care and the maintenance of systems like the HVAC (Heating Ventilation and Air Conditioning) and lighting. Facility managers are responsible for the correct implementation of all these services, enabling the organisation

* Corresponding author.
E-mail address: Sophie.vanRoosmale@uantwerpen.be (S. van Roosmale).

https://doi.org/10.1016/j.jobe.2024.110943
Received 23 November 2023; Received in revised form 27 September 2024; Accepted 1 October 2024
Available online 2 October 2024

within in the facility to focus on its core business activities [3,4]. Over the years, the role of facility managers has expanded due to the growing demand for sustainability and improved energy performance of buildings [5]. Additionally, the demand for user control over parameters such as like temperature, lighting and shading in office buildings has increased [6].

FM increasingly extends beyond its conventional technical responsibilities, playing a crucial role in optimizing space management in alignment with occupants needs and the core operations of an organization. Furthermore, FM also has a significant influence on the sustainability of a building, which is a primary focus of this paper. In this capacity, FM substantially impacts operating expenses, energy consumption, and the levels of comfort, safety and convenience within the facility [6–9]. FM adheres to the operational strategy of a company to ensure sustainability, productivity and efficiency. Therefore a close collaboration between the facility manager and the top management of a company is essential. A notable trend in the operational strategy of companies is the scaling of the position of the company in a global context. Since FM is a ‘follow strategy’, this trend also reflects on FM in a growing and globally competitive environment [10].

Other important trends in FM, according to the FM-*trend rapport 2021* of Belfa (Belgian Facility Association) [11], are the challenges related to implementation and integration of novel technologiessuch as tBuilding Automation and Control Systems (BACS), smart devices, technical building and Artificial Intelligence (AI).

According to the European sector federation EU.BAC, "*BACS refers to the products that monitor and automatically adjust the energy using technologies in our homes and buildings to deliver a comfortable environment while optimizing the energy use.*" In Standard EN 16484 – “Building automation and control systems”, BACS is defined as *system comprising all products and engineering services (including interlocks), monitoring, optimization for operation, human intervention, and management to achieve energy-efficient, economical, and safe operation of building services* [12]. Several other definitions are in vogue, e.g. proposed by manufactures, standards or various scholars. In European Commission documents, the following definition is used: ‘<*building automation and control system* > *means a system comprising all products, software and engineering services that can* support *energy efficient, economical and safe operation of technical building systems through automatic controls and by facilitating the manual management of those technical building systems’* [13,14]. In this definition, ‘*technical building system’* (TBS) means ‘*technical equipment of a building or building unit for space heating, space cooling, ventilation, domestic hot water, built-in lighting, building automation and control, on-site renewable energy generation and energy storage, or a combination thereof, including those systems using energy from renewable sources*’. Various scholars and industry actors widen the scope of BACS to also include services without important impacts on the energy performance of a building, such as access control, fire or burglar detection, parking lot management, etc. BACS can use real-time and historical sensor data to adjust actuators, like HVAC valves or light dimmers, to meet the setpoints implemented by facility managers or requested by users. Setpoints are the state which need to be reached by the system, for example a specific temperature is reached by the heating system.

The term Building Automation System (BAS) is often used interchangeably with BACS, although others restrict this term to the field level, i.e. hardware such as sensors, wires and actuators [15,16]. In this case, this complemented with a ‘Building Management System’ (BMS), which encompasses the higher-level software and interfaces that aggregate data from the BAS, analyze it, and implement control strategies and possibly perform related services such as providing information dashboards. Others treat BACS and BMS as synonyms, including standard EN ISO 52120–1:2021 – ‘*Energy performance of buildings: contribution of BACS and building management*’ which states that ‘*BACS* is also referred to as BMS’ [16,17].

Other terms often used in conjunction with BACS are EMS or BEMS – referring to (Building) Energy Management System, or EMCS (Energy Management and Control System) [18]. These terms emphasize that these systems focus on energy flows by monitoring and analysing the energy consumption, harvesting and storage. Contrary to more generic BACS, EMS/BEMS/EMCS systems will likely exclude operation of control of TBS such as lights, ventilation rates, etc.

From the above, it is clear that despite some standardisation efforts there is still an apparent fluidity and overlap in terminology within the industry. This overlap can lead to confusion, particularly when different stakeholders—such as engineers, facility managers, and regulatory bodies—use these terms with varying scopes and implications.

Increasingly, BACS also play a role in the integration of the building and its technical building systems with the energy system it is connected to. Smarter control of energy demand (e.g. by shifting heating loads to off-peak hours), local energy storage and management of distributed renewable energy resources such as photovoltaic solar allow for more optimised buildings and energy grids, thus resulting in energy savings, cost savings or carbon emission reductions [19].

Given the increased complexity of buildings, their technical building systems and the intricacy of optimizing the control of both buildings and connected energy grids under implicit uncertainty (e.g. with regard to renewable energy availability subject to local weather conditions). novel control strategies have emerged. Instead of convential rule-based control, new concepts such as Model Predictive control (MPC) and Artificial Intelligence (AI) for BACS have been proposed; thus allowing software and hardware to monitor the building environment and autonomously take action to enhance the performance of the building related to comfort levels, energy efficiency and safety [20]. BACS in combination with AI have various benefits as they can assist facility managers with improving comfort of occupants, maintenance strategies and an increased level of sustainability of the facility [21,22].

The comfort of occupants can be improved with BACS by reaching a high Indoor Environmental Quality (IEQ) through the appropriate selection of setpoints and subsequent control of HVAC, lighting and blinds. The thermal comfort and Indoor Air Quality (IAQ) are influenced by the HVAC and the visual comfort is influenced by the intensity of the lights and the position of the blinds [22,24]. Minimizing occupant disturbance by BACS holds significant importance for the comfort level of occupants. The concept is not centred around frequent adjustments of setpoints by BACS, but rather focuses on the system learning from occupants' feedback about the most suitable BACS behaviour for various future situations [25].

Maintenance strategies can be enhanced by BACS, as it enables proactive maintenance [5]. These maintenance strategies aim to predict, detect and correct future defects or faults and their underlying cause, based on historic data, statistical methods and fault detection and diagnosis techniques, for example a broken light sensor [26–28]. This in contrast with reactive maintenance where defects are being solved after they have occurred and led to damage [29]. In case of proactive maintenance, the fault detection and diagnosis system notifies the facility manager through BACS of the timing of this possible defect and the cause, so the facility manager is able to timely repair or replace the defect. The goals of proactive maintenance are to save cost, improve sustainability by extending an assets' service life, preventing unnecessary component replacement, finding the cause of the defect or reducing machine downtime [5,6,30]. Furthermore, AI can serve as an additional layer in supporting FM with proactive maintenance, as AI can be self-learning and it also learns from the behaviour of occupants and facility managers regarding faults [22].

BACS can assist with realising sustainable buildings by improving the energy efficiency, reducing greenhouse gas emissions and by extending the life cycle of the building and installations. Energy usage can be decreased by integrating different BACS systems, such as automated blinds to reduce the need for HVAC cooling or heating. Lowry (2016) gives an overview of energy reductions in lighting realised by BACS in offices, varying between 6 and 88 %, but Lowry claims that the actual reduction strongly depends on the size and type of office building [31]. However, if BACS is combined with AI it is also able to propose energy optimization projects and assign vendors based on their performance to reduce costs and energy usage [32]. Additionally, the durability of the components of BACS can also be prolonged with BACS itself, by implementing predictive maintenance as mentioned before. This can improve the maintenance efficiency and increase the durability of BACS components [6,33,34].

Facility managers consider the challenges of implementing and integrating developments, like BACS and smart installations, to be crucial to make data-driven strategies for FM and the organization in the facility. The facility managers exploit these technologies to gain insights into their expenses and assets while also utilizing the technologies to provide support in their managerial reporting and the efficient organization of service desks [11]. A 30 % reduction in energy use can be obtained when BACS is correctly implemented, however, only 9 % of the world's energy is controlled with BACS because only 15 % of the buildings use the technology of BACS [35]. This indicates that while BACS can significantly aid facility managers in energy conservation, its full potential remains untapped.

Given the anticipated benefits, BACS are increasingly being incorporated into policy frameworks. The European Commission included provisions on BACS integration in the revisions of the European Energy Performance of Buildings Directive (EPDB) of 2018 and 2024 [13,14]. Earlier versions of the EPBD primarily focussed on energy efficiency of building envelopes and technical systems. However, the newer iterations mandate that existing non-residential buildings be equipped with BACS systems, provided that such systems are technically and economically feasible. The requirements stipulate that by the end of 2024, buildings with a rated HVAC output exceeding 290 kW must be equipped with BACS, and by the end of 2029, this requirement extends to buildings with a rated output exceeding 70 kW. The EPBD also outlines the minimal capabilities required for BACS installations, such as continuous monitoring, benchmarking the building's energy efficiency, and '*informing the person responsible for the facilities or technical building management about opportunities for energy efficiency improvement*'. All European Union member states are tasked with transposing these articles of the EPBD into national legislation.

While facility managers are increasingly recognizing the potential benefits of BACS and novel policies can even explicitly require this for specific building types, concerns related to these technologies, such as issues with interoperability and security risks, are on the rise [11]. Interoperability refers to the ability of systems to interact through structured information exchange [23]. Issues with interoperability are caused by different vendors which al have created their own line of building automation products with the corresponding way or structure of communication between the components [36]. Concerns for security risks arise due to the way BACS is created. Originally, BACS were created to operate autonomously without outside connections and therefore less thought was put in the security of BACS. However, with the recent developments in connectivity such as protocols, internet and IoT, BACS became vulnerable to physical and cyber-attacks [37,38]. Moreover, there is a lack of comprehensive understanding of the operational and maintenance implications of BACS, such as the way BACS is structured or the investment costs compared to the Return on Investment (ROI) of BACS [23,39].

A better understanding of BACS by facility managers could lead to an increased implementation of BACS and an improvement of the strategic FM [40]. This article will delve further into the significance of FM trends based on a literature review. However, before delving into this, an overview of the transition/evolution from a simple to a cognitive building and a definition of BACS is given in Chapter 3 and 3.1. This information is essential to understand the reason why smart buildings and BACS pave the way for the transformation of traditional FM into strategic FM. Furthermore, Chapter 3.2. elaborates on the potential advantages of strategic FM in making enhanced, data-driven decisions, including those related to investments, maintenance and functionality of the facility.

Subsequently, this article will clarify different technical and technological challenges of BACS, including issues with interoperability and security risks, by explaining the architecture of BACS in Chapter 4. This information is crucial to comprehend how these challenges have emerged as potential hurdles to the integration of BACS within the context of strategic FM. The explanation of the architecture BACS will start by delving into the hardware and software components of BACS, followed by an exploration of the three-level structure of these components and their network topology. Furthermore, the communication protocols, which are being used by the components of BACS to collaborate, are explained and lastly the connection between BACS and the digital world is examined.

Chapter 5 will explore the security risks in greater detail. By investigating the origins of security risks related to the connection with the digital world. Then it will focus on the various potential threats the present, such as cyber-attacks and vandalism. In the last part of this chapter a few recent solutions and mitigations to these security risks will be addressed.

2. Methodology

A qualitative systematic literature review was performed to collect information about the definition of BACS and how it can support a facility manager. The research strategy consists of defining search terms, defining the scope and selecting different data sources to identify candidate articles. First, the search terms were a combination of Facility Management and Building Automation Control Systems. However, this did not provide sufficient results, as BACS is a very broad umbrella term. BACS consists of products, software and engineering services for monitoring and optimizing the operation of a facility [41]. There are seven categories in BACS: heating control, cooling control, ventilation and air-conditioning control, lighting control, blinds control, domestic hot water supply control and technical home and building management [41]. We focus in this paper more on BACS in office buildings and therefore used the relevant categories as search terms in combination with the search term facility management. These terms were smart lights, smart blinds, smart HVAC, Intelligent Building and their synonyms, like 'Building Automation and Control Systems', 'Building Control Systems', 'Building Automation Systems', 'Building Management Systems', 'Smart lighting systems', 'Smart HVAC systems, 'Smart Blinds systems', and so on. The used databases are Web of Science, Google Scholar and Jstor. Publications earlier than 2010 are excluded as after this date, major evolutions have taken place in the field of BACS and earlier work may no longer be relevant or representative.

The relevance of the collected papers was ensured by the title, keywords and abstract to define the subject. An additional 121 papers were added using the snowballing technique [42]. The search resulted in 95 relevant findings. The literature process is summarized in Fig. 1.

3. BACS and facility management: a brief overview

BACS are a network or combination of all the software, hardware and services to control and monitor various building functions, such as HVAC, lighting, blinds, security, fire alarms, etc. BACS are also often linked to Building Management Systems (BMS). They play a crucial role in the optimization of the building performances in terms of energy usage, cost efficiency, comfort levels and safety. BACS are able to enhance the energy efficiency by collecting real-time data about occupancy and physical parameters (like temperature and light intensity) to adjust temperature settings, turn lights on or off, close or open blinds and they improve the energy usage by interconnecting different building functions. The cost efficiency can be increased by improving maintenance strategies based on historical data and real-time data logging. In addition, BACS can create alarms in case of faults and defects in building functions to improve the safety and comfort of occupants [41].

3.1. *The evolution of a simple to a cognitive building*

The term BACS is often combined with terms such as smart or intelligent building. The terms smart buildings and intelligent buildings are used interchangeably in the literature but there are clear differences between the two terms [43]. According to Buckman, Mayfield and Beck [44], there are gradations in the level of smartness of a building. Starting with a 'primitive' building, consisting of a building with a basic construction without any form of control or interaction between the occupants and the building. The second

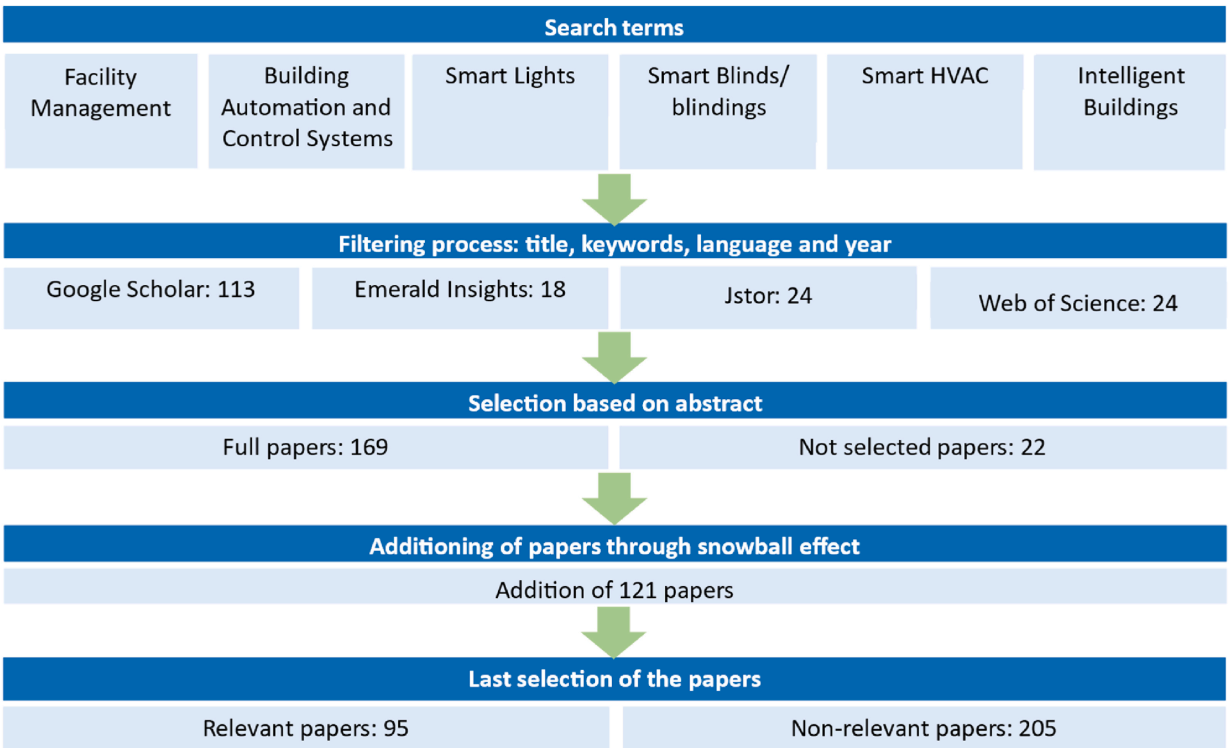

Fig. 1. Literature process of the selection of papers about Building Automation and Control Systems. This process resulted in a total of 95 papers.

level is a 'simple' building, where manually controlled techniques are implemented. An 'automated' building has central controls or controls via timers. In an 'intelligent' building, systems are automatically controlled and sensors in the building respond to users in real time. Finally, a 'smart' building goes even further, collecting data of how and when a building is used with sensors and cameras and it uses this to derive trends and make predictions of future behaviour while keeping energy efficiency, security and comfort in mind [24,44]. Krödel and Martin even add another gradation to the levels of Buckman et al., they call it a ‘cognitive’ building, in which the building is able to learn and implement a control algorithm instead of a programmed or predefined logic [45]. So, BACS is linked to different levels, the automated, intelligent, smart and cognitive building.

3.2. Strategic facility management with BACS and BIM

Facility managers play a critical role in formulating strategic plans and decisions that not only support the seamless operation of a building or facility, but also extend its designed lifespan by preventing sudden breakdowns resulting from malfunctions or defects [46]. On one hand, these strategic decisions relate to maintaining the relevance of the building in the longer term. On the other hand, they relate to optimizing facility's operational costs by making the right investment decisions [4]. Notably, strategic decisions made during the design phase, such as choices for materials and construction, have the greatest impact on a building's operational expenses, because the operational phase is the longest compared to the other phases in the total life cycle of the building. Hence, the involvement of facility managers during the design phase holds the potential to make a significant difference for the investor in terms of a building's life cycle cost and also for the comfort level of future occupants [47]. However in practice, facility managers are rarely involved in the design phase [48]. Therefore, it is important to look at the possibilities and opportunities of BACS on strategic decisions during the operational phase, which are explained in the next paragraphs.

BACS are able to support facility managers in making these strategic (investment) decisions to preserve the relevance and functionality of buildings in the longer term, by collecting data such as temperature, daylight, airflow and -quality [40,49]. This collected data is combined with project information, historical data, condition monitoring analysis and information about the weather. This results in a large quantity of data, also called the ‘big data phenomena’ [22]. A way to manage and analyze this data is by using AI big-data analytic tools implemented in BACS. This allows facility managers to make data-based, tailor-made decisions to realize cost efficiency in the operation of a building, such as changing setpoints based on selected priorities and creating efficient maintenance strategies to avoid unnecessary maintenance, [4,22,23]. The term Artificial Intelligence was first described in the 1950s as the capability of a machine to imitate human intelligence, but the description developed into machines which are able to make advanced decisions based on gained knowledge and recognizing of patterns [50]. In simulations conducted on a university building in Austria by Mayer (2017), the implementation of AI in BACS for data analysis demonstrated the potential to reduce HVAC cooling hours by 17 %, resulting in a significant annual cost reduction of 14 % [40]. In the experiments of Wei (2018), the combination of co-scheduling and model predictive control to improve the energy efficiency of HVAC in buildings and the charging of electrical vehicles, resulted in a reduction of 7.4 % in total energy cost and a 25.4 % reduction in peak demand [51].

Another way the digitisation could enhance facility management is with the implementation of Building Information Modelling (BIM). BIM is a three dimensional digital and virtual representation of the physical characteristics of the facility, such as the materials and the construction. BIM's are often created and used during the construction phase of a building to support the engineer(s), architect(s), building owner(s), construction manager and subcontractors to share knowledge between the design team and the construction team and to estimate costs based on construction planning. However, BIM models can also be useful during the operational and maintenance phase of the building to support the facility manager with data visualisation and accessibility [20,47]. In BIM various information can be combined, such as system's operating data, environmental parameters, costs, condition of materials/constructions, project documents, data sheets, contracts, manuals, maintenance reports, and so on. This BIM model forms a complete picture of the facility's current as well as past conditions, which facility managers could use for creating a streamlined maintenance plan for the whole operational life of the building's components. A Digital Twin (DT) can be created based on the BIM model, this is a virtual 3D replica of the physical facility, which is continuously updated so it performs in the same way as the physical building. The DT can be used for simulations of what-if scenarios for maintenance and operational changes [6].

4. Fundamental structure of BACS

BACS, independent of the application, consists of hardware, software and services [12]. The hardware exists of field devices (such as actuators and sensors), controllers, cabling, communications and computing devices. Sensors collect real-time information about physical parameters (relative humidity lux, temperature, etc) in the form of signals and send these signals to the controllers (e.g. control and computing devices) [52]. The control devices (often referred to as Direct Digital Control – DDC) controls if the signals about physical parameters match with the setpoints and if there is a deviation then the DDC process these signals into a commands based on logic and setpoints and send the command to adjust the actuators. The setpoints for physical parameters are selected by the facility manager in a software system or they are calculated through the intelligence of the Building Management System to reach a specific goal (a specific level of comfort at a selected maximum energy usage). The actuators react to the demand by activating or deactivating devices such as the lighting, thermostats, valves in the HVAC or the motor on the blinds. The sensors and actuators are connected (cabling) to I/O ports of hardware modules to send and receive electric signals [12]. The communication between the devices is based on the control logic (communications). The commands can be scheduled as a one-time event or as a recurring event, depending on the goal of the command. A command can also be sent when a specific scenario occurs, these scenarios can be static or dynamic. A static scenario means that the state of devices is not changed once they are set. A dynamic scenario describes how the systems needs to react when the surroundings change, for example dimming the lighting when a higher intensity of daylight is measured [23].

4.1. Three-level model

Kastner et al. proposed a three-level model to make the control between different subsystems transparent and less complex [53,54]. The three levels are the field level, the automation level and the management level, see Fig. 2. The model is based on clear communication between these three levels in the horizontal as well as the vertical way [55–57].

The field level is the first layer where the interaction between the field devices and the real world happens. A few examples of field devices are sensors, controllers and actuators. The real-time data from the situation in the office – such as temperature, movement, lux, etc - is collected and passed through the next layer, the automation level. This is called vertical communication [55–57].

In the automation level, the collected data and measurements from the field level are controlled in control loops and then the data is processed into commands for the actuators, these are created automatically based on automation algorithms. Often, information collected by specific sensors is also useful for more than one actuator, for example the outside temperature, this is called horizontal communication. The automation level also sends historical data and trends to the top layer (vertical communication) [55–57].

The top layer is the management level, where the decisions are made based on the logged data and defined through schedules, these decisions also include the automation algorithms. In the management level, there is a visual graphic of the condition of the operational system. In addition, trends are plotted and data is collected for the archive to see the effect of specific changes in the BACS [55–57]. Other functions in the management level are alarms and scheduling. Alarms happens when there is a difference between the monitored datapoints values and the predefined rules on these values. These alarms are a form of notification to the operator to perform action and resolve the problem. Scheduling can be used to set and withdraw specific set points at predefined times (holidays, weekends, and so on) [58].

4.2. Topologies

The different hardware components from BACS are arranged in specific structures or topologies to share information among various devices. These devices are connected in a topology through network nodes in which the name, location and other crucial characteristics of the device are stored. Topologies are used to determine the best placements for each device, so the information goes through the most optimal traffic path [57].

There are different types of topologies, bus, ring, star, tree, mesh and hybrid topology, see Fig. 3. The bus topology consists of a long line to which all the nodes are connected. In the ring topology, the nodes are connected in a closed loop. The data can go in one direction or in some cases the data can be transferred in both directions. In the star topology, there is a central device connected to all the other nodes to collect data from sensors and give commands to actuators. In the tree topology, there is one root node and all other nodes are connected in a hierarchy to this root node. In the mesh topology, all the nodes have more than one connection to other nodes so that multiple paths exist to create efficient transferring of data. Fully meshed means that all the nodes are connected to one

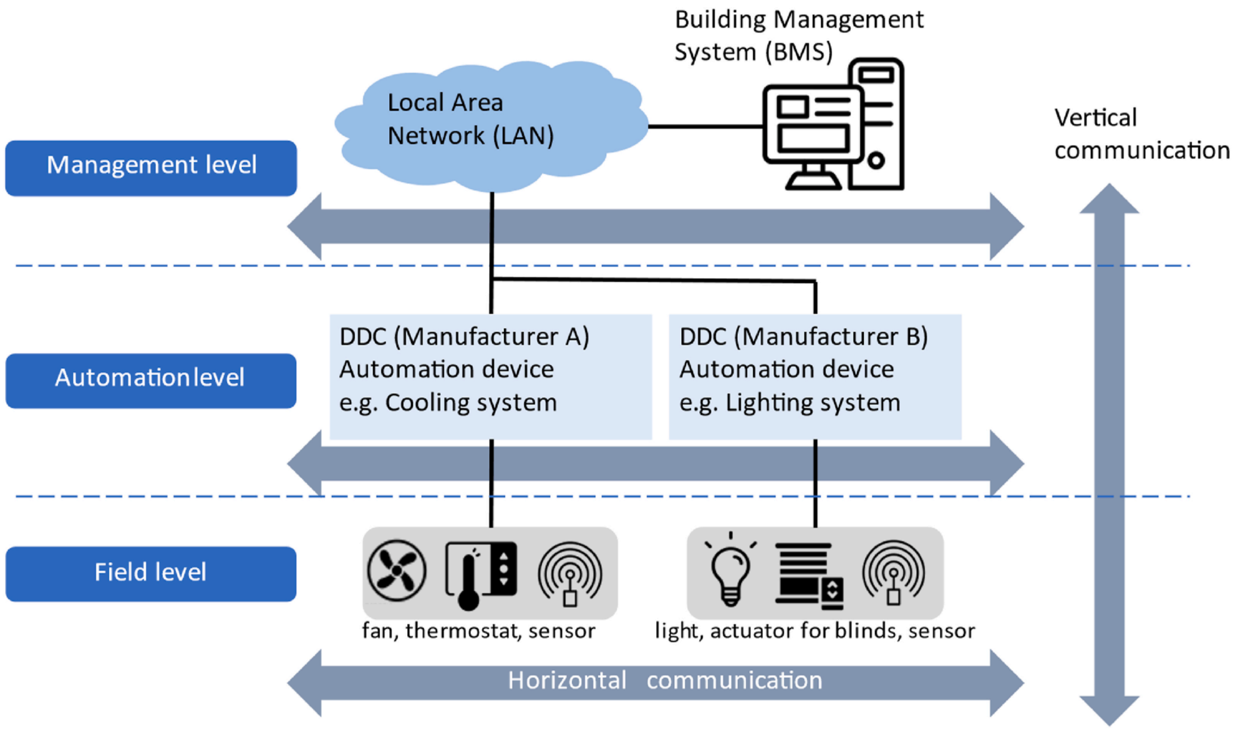

Fig. 2. Three-level model shows the structure of BACS. The devices in the field level collect data and communicate this data to the DDC's in the automation level. The DDC creates the commands for the actuators based on this sensor data and on the setpoints selected in het management level. The management level connects all devices in a LAN, which in turn interfaces with the BMS for decision-making and automated command execution.

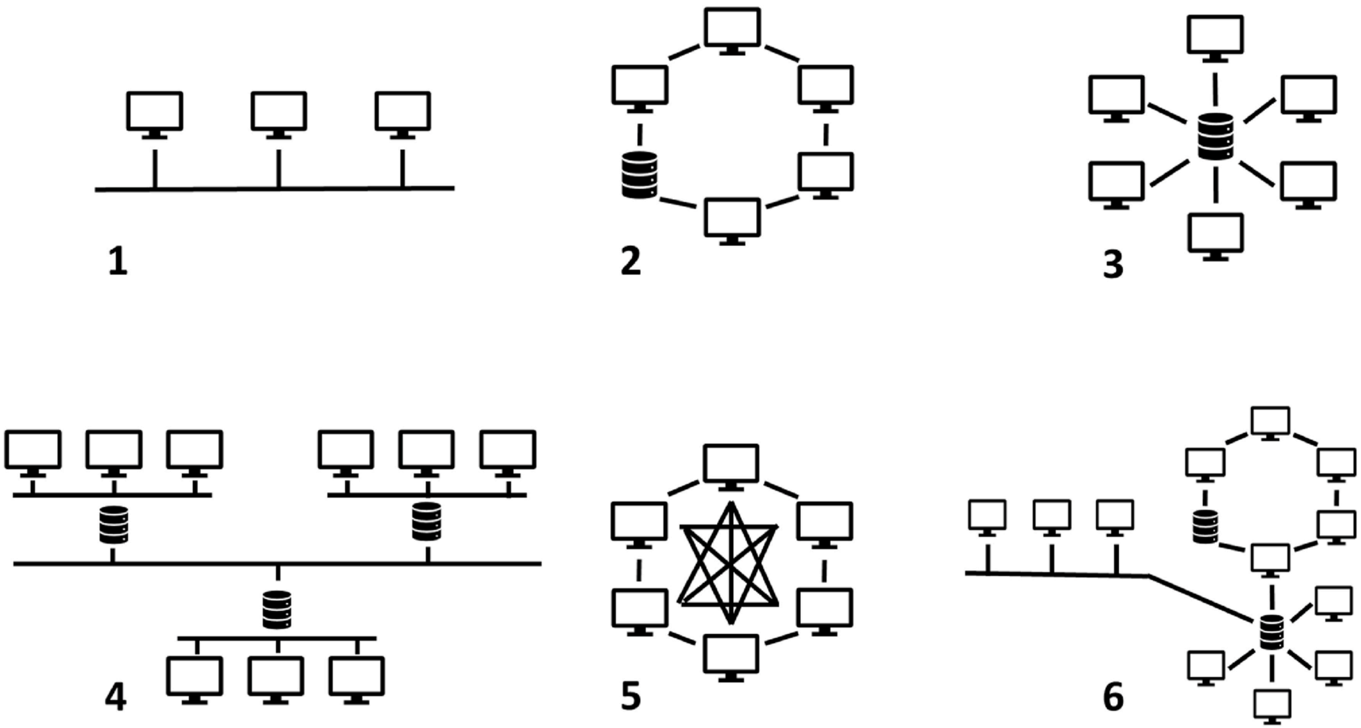

Fig. 3. Different topologies, 1. Bus topology, 2. Ring topology, 3. Star topology, 4. Tree topology, 5. Mesh topology, 6. Hybrid topology.

another to decrease the time of sending data, but more connections also increase the cost. A hybrid topology is a combination of two or more topologies, resulting in more flexibility [57,59].

4.3. Communication protocols

An important issue for BACS implementation is the (lack) of interoperability between software and hardware systems of different suppliers due to lack of standardization. The subsystems like HVAC and lighting can be supplied by a broad range of vendors. When opting for a stand-alone system or proprietary interface or protocols, exchange of sensor values, actuator commands and status information with systems from different soft- and hardware vendors is often prohibited. However, to fully exploit the potential of BACS and choosing the best combination of products for the specific context of the facility, integration of various stand-alone systems is highly advised, requiring exchange of data between various hardware and software systems. A large number of communication protocols have been developed, both using open standards as well as proprietary protocols used by an alliance of manufacturers. A communication protocol is a set of rules that facilitates devices the form and framework of data exchange, proprietary in this case means that the protocol is bound to a specific vendor or entity controlling this intellectual property [12,60]. The first protocols were created for connecting lighting and blind control, because of their interaction in delivering the requested the luminance level [57].

Various vendors intentionally tailored communication protocols to specific situations, preventing the customer from interconnecting various systems from different vendors (also referred to as proprietary protocols). This resulted in a wide variety in communication protocols, vendor lock-in and ensuring customer loyalty to their specific products [12,57,58]. Vendor lock-in refers to the challenges faced by facility managers when transitioning between software and hardware suppliers, due to technologically complex underlying infrastructures and lack of universal or open standards [61].

To enable communication between devices or subsystems from different vendors after all, gateways have been developed. Gateways convert the protocol at the application layer so that it can be used to communicate between different vendor applications [57]. However, the development of gateways is complex because the developer of these gateways must have knowledge of both protocols. Also, it will slow down the process due to the conversion of one protocol to another, which is not an ideal solution. In addition, it is not possible to add a new third-party subsystem into these vendor specific/proprietary protocols because these protocols are not flexible enough to add other subsystems [58].

A solution to the problems of the proprietary protocols and the gateways could be open protocols. These protocols are able to communicate between various soft- and hardware components of different vendors, because they are based on the same communication system, e.g. the seven layers of the standardised ISO/OSI model (Open Systems Inter-connection) [57]. There is a distinction between physical layer protocols and application layer protocols. The physical layer protocols are responsible for the physical transmission of data over a network. They specify the electrical and physical characteristics of the network, including the cable type and signal voltage. A few examples of physical layer protocols are Ethernet, Wi-Fi and Bluetooth. Application layer protocols define the characteristics of the message sent over the physical layer protocol [53].

The devices that communicate with each other in BACS through an open application layer protocol are connected in a fieldbus network or a (wireless) networks. Communication over fieldbuses is often used for communicating between devices in the field level and for communicating between the field level and the automation level, e.g. between field devices like sensors, actuators and controllers (DDC, in the automation level), see Fig. 2. The fieldbus communication is specifically used for sending and receiving of small amounts of data in a short time span over various mediums such as wires, radio waves, Bluetooth, Ethernet and Wi-Fi [57]. Specific decentralized fieldbus system reduces the network traffic, which is required for the timely transmission of real-time data [58]. Communication over network is often used for communicating between the automation level and the management level, see Fig. 2, this communication is for example about automation, trends and alarms. There are larger amounts of data being transferred and they can be communicated over different mediums such as Wi-Fi, Ethernet, Bluetooth, radio waves and wires [57,58].

The choice between wired fieldbus network or wireless networks depends often on the possibilities of implementing the protocol in a specific case. A wired fieldbus open protocol is more secure from the open world compared to a wireless system, though it is more expensive due to the material costs and the installation costs of the wiring [34,62]. Often, the fieldbus systems and the wireless systems will be combined in a hybrid form. The choice of a specific open communication protocol also depends on the speed at which data is transported, this is expressed in two terms, speed and bandwidth. Speed refers to how fast data can be transmitted or processed within a network or system. Bandwidth determines how much data can be transmitted simultaneously within a specific time frame. The terms speed and bandwidth are often used interchangeably. The data about bandwidth and speed, described in the tables below (Tables 1–5), is collected from various papers. However, the speed and bandwidth depend on the type of medium, the size and type of installation, wired/wireless. This makes it difficult to correctly determine the speed and bandwidth of different communication protocols. Further advantages and disadvantages of the most common open application layer protocols will be discussed in the next paragraphs. At the end of chapter 4.3.5. there will be an overview of the advantages and disadvantages of various communication protocols, see Table 6.

4.3.1. Modbus

Modbus is an example of a fieldbus protocol. It can be implemented without a licence from Modbus and therefore it is very popular. Modbus is often implemented in other systems like fire alarms or electricity meters. It is specialized in automatic communication between devices and specific controller-to-controller communication [23]. Modbus uses a simple request/response protocol in which data or an action is requested and the sensors or actuators respond with the collected data or by performing a command [63], this asks for high engineering skills in programming. Modbus is created in 1979 and therefore only 247 devices can be connected at the same time, which can be a problem for large and complex facilities. In addition, a standard to describe data does not exist in Modbus, for ex-

Table 1
Technical aspects of Modbus protocol.

Way of communicating	Used medium	Topology
Simple request/response control [63], Client/server or Master/slave type system, Application layer messaging protocol which provides communication between devices connected at different types of buses or networks [65]	Modbus on TCP/IP over ethernet [66], Two-Wire EIR/TIA-232, EIA-422, EIA/TIA-485-A, Four-Wire TIA/EIA-232-E (short point to point communication, so broadcasting of data is not possible) [65], Fiber, radio, MODBUS PLUS (a high speed token passing network) [66]	Bus topology, tree-bus topology, star topology, mesh topology [67]
Type	**Speed**	**Bandwidth**
Wired/Wireless [66]	To have [68]: 758 bytes/s 329 bytes/s 229 bytes/s 133 bytes/s	This is required [68]: 6064 bps 5164 bps 3664 bps 2128 bps

Table 2
Technical aspects of KNX protocol.

Way of communicating	Used medium	Topology
Functional blocks [57], Through gateways [62], CSMA/CA (Carrier Sense Multiple Access/Collision Avoidence) [57]	Twisted pair (KNX.TP), Power Line (KNX.PL), Radio Frequency (KNX.RF), Ethernet (KNXnet/IP) [57]	Bus topology, star topology, ring topology, (free) tree topology, mixed topology [57,69]
Type	**Speed**	**Bandwidth**
Wired/wireless [62]	9600 bit/s (Twisted Pair) [57] 400 KNX servers: 19200 bit/s [70]	1200 bit/s (KNX.PL) 16.384 kbps (fast KNX.RF) [69]

Table 3
Technical aspects of LonWorks protocol.

Way of communicating	Used medium	Topology
Predictive p-persistent CSMA (a channel access and collision avoidance mechanism) [62].	Twisted pair (most common), Power line, Radio Frequency, Fiber-optics [57], Coaxial cable, Infrared media channels [71]	Free topology (star, ring/loop, linear/bus, mesh and mixed topology for a network of maximum 500m) [62,72]
Type	**Speed**	**Bandwidth**
Wired/wireless [62]	78 kbps (TP/FT-10) 1.25 Mbps (TP/XF-1250) 5.4 kbps (PL-20) [73]	Designed for low bandwidth [74]

Table 4
Technical aspects of BACnet protocol.

Way of communicating	Used medium	Topology
IP, Ethernet, LonTalk, ARCnet, Zigbee, MS/TP [62], BACnet/IP, RS-232 (BACnet Point to Point), RS-485 (with BACnet specific master-slave/token passing LAN technology) [71]	BACnet upper layers are independent from the underlying physical layers [71]	Bus topology, star topology, tree topology [57], mixed topology [62]
Type	**Speed**	**Bandwidth**
Wired/wireless [62]	9.6 Kbps [75] To have [68]: 34000 bytes/s 13600 bytes/s 6800 bytes/s 272 bytes/s	This is required [68]: 272000 bps 108800 bps 54400 bps 2176 bps

Table 5
Technical aspects of Zigbee protocol.

Way of communicating	Used medium	Topology
TCP/UDP [62], CSMA/CA [71], gateway [71]	Forming of a network through one of the 15 radio channels [71]	Star topology, tree topology, mesh topology [78], Cluster-tree topology [79], Blend of star and tree typology, hybrid topology [80]
Type	**Speed**	**Bandwidth**
Wireless [62]	20, 40, 250 kb/s [81]	2.4 GHz (world-wide) 860 MHz (Europe) [81]

Table 6
Overview of advantages and disadvantages of different communication protocols.

Name	Advantages	Disadvantages
Modbus	- Can be implemented without a license [23] - Scope: industrial and HVAC applications [71] - Easy to implement devices with varying performances due to the lightweight structure of Modbus [82] Therefore it is possible to move value-bound information [68] - Low cost communication protocol [74]	- Maximum of 247 devices on one data link [55] - No standard for descriptions of data [55] - Originally there are no security rules implemented [64]
KNX	- Is the only open standard that is able to be implemented with devices from various manufacturers [57] - Maximum of 57,375 devices connected using 16-bit addresses [57] - Possible to modify the parameters of every device [57]	- No automatic access to historical data, event and alarm notification, task scheduling and scenario management [23] - Sensitive to wiretapping [52] - More expensive compared to conventional systems [57]
LonWorks	- Customization of comfort levels and energy efficiency, due to the decentralized architecture of LON technology and the ability to reprogramming instead of rewiring [57] - LonMark Interoperability Association certification guarantees the compatibility of devices from different manufacturers [57] - Only protocol used for data communication in the management layer [57] - Up to 32,385 devices connected [71] - Peer to peer connection [57]	- Na data encryption, implements sender authentication [62] - Has a licensing fee and the highest costs [74]
BACnet	- Tailormade for building applications [57] - Open system, functional and flexible [75] - Scope consists of: HVAC, lighting control, fire control and alarm, security and interfacing utilities to companies [71] - Low cost communication protocol [74] - BACnet is compatible with different physical/data link layer combination (like BACnet over KNX) [54]	- Proprietary objects (required for tailormade option) hinder the interoperability (but BIBB's mitigates these risks) [75] - BACnet is able to interwork with other protocols through mapping. However, there are different ways of mapping which hinders the interoperability [71]
Zigbee	- Data gets encrypted using 128-Advanced Encryption Standard (AES) algorithm with bit key [62] - Very low power consumption (batteries can last up to 2 years) [83,84] - Flexible topology and low complexity [81,84] - Great reliability [71] - Devices can join an existing network in under 30 ms [81] - scope: industrial control and monitoring, sensor networks, building automation, home control and automation, toys and games [81] - Very short time of delay in communication (compared to other devices) [83] - Low cost [83] - Up to 653,356 devices [83]	- Not compatible with consumer electronics such as smartphones or laptops [83] - Susceptible to network interferences, as it uses the 2.6 GHz band which is also used by Wi-Fi [83] - Zigbee has lower transmission rates in comparison with Wi-Fi [83]

ample it is not clear if a temperature value is in Celsius of Fahrenheit [55]. Furthermore, there are no security rules implemented in the protocol, because Modbus was developed to use it without internet [64].

4.3.2. KNX

KNX is a standard which combines three standards, European Home Systems Protocol (EHS), BatiBUS and European Installation Bus (EIB) [62]. It is a fieldbus protocol, implemented on the field layer [52]. It was initially developed with a focus on lighting and blinds control [57]. Each KNX devices is connected and has a clear group address with device parameters. Devices communicate by writing to datapoints (nodes) of other devices and therefore an additional communication device or DDC is not required. KNX is able to connect with various sensors and actuators from different manufacturers, which enables great flexibility [52,57]. A limitation to KNX is that it does not automatically has access to historical data, event and alarm notification, task scheduling and scenario management features. A facility manager is free to implement these functions in the protocol, but it is not a standard option [23]. In addition, data and signals are not encrypted in KNX and therefore they are sensitive to wiretapping, resulting in a large security risk [52]. Also, KNX products are more expensive compared to conventional installations. So, it is more valuable when flexibility is a priority or when various subsystems need to be connected [57].

4.3.3. LonWorks

LonWorks stands for Local Operating Network and is developed by Echelon Corporation. It is another fieldbus protocol and it can be implemented on the Field layer and the Automation layer [52,57]. It was developed to support applications in different domains, like buildings, production lines or transportation. A device is called a node and they have an address, which is necessary for the communication flow. A device or node has a functional profile, which describes the functionality. To exchange information between different devices, a network variable is used. The network variables fall under strict rules described in the LonWorks Standard Network Variables Types, which makes interoperability between LonWorks devices possible. In addition, the compatibility between devices from different vendors is guaranteed with a certification of the LonMark Interoperability Association [57]. An advantage of LonWorks is the ability to connect a DDC to the same bus system as the sensors and actuators, as a form of 'distributed intelligence', so not all control logic is installed in the automation layer [52]. This enables customization of comfort levels and energy efficiency in individual rooms, which is not possible for example with KNX [57]. The functional profiles however, could hinder the interoperability, because not all the functionalities can be foreseen and therefore manufacturers create their own proprietary functions [23].

4.3.4. BACnet

BACnet stands for Building Automation and Control Network and it is created and supported by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers). It is a fieldbus protocol, implemented on the Automation layer and it is based on the Open System Interconnection (OSI) model [52]. The goal of BACnet is to create a solution that fits different types and sizes of Building Automation Systems from different manufacturers or from different generations without the need for licenses [57]. BACnet uses a collection of standard objects to control BACS. An object is a concept that ensures communication and organisation of data between devices in BACS [23,57]. It is a flexible protocol and therefore it is possible for different vendors to create proprietary objects, which makes it a popular protocol among vendors [62]. Despite the opportunities of these proprietary objects, they could also obstruct interoperability to some extent, because other devices or systems (from different vendors) may not be able to communicate and collaborate with these objects. However, ASHRAE developed BACnet Interoperability Building Blocks (BIBBs) to tackle this problem. These BIBBs are clear descriptions of different proprietary objects and how to implement them in BACS. So, a facility manager/engineer/IT specialist is able to integrate these in their BACS and preserve the interoperability [23,75]. Another advantage of BACnet is the possibility to implement varying requirements for different parts of a building, due to remote and decentralized control stations. Additionally, BACnet is most suitable at the Management layer for large and complex buildings and it could be combined with KNX or LonWorks implemented at the Field layer [57].

4.3.5. Zigbee

Zigbee is a wireless standard in which the sensors and actuators are connected through a wireless network. It has several advantages, like the eliminating of wiring costs during installation and therefore reaching more flexibility in the placement of sensors and the expandability of BACS in facilities [76,77]. It is designed with a focus on extreme power efficiency, due to the wireless aspect and it has a long reach, therefore making it suitable for BACS in large facilities [62,77]. Zigbee is based on IEEE 802.15.4 and exists of three layers. The first layer, the Application Support Layer, ensures binding of endpoints, forwarding of messages between bound devices and manages groups. The Zigbee Device layer, the second layer, arranges the management of devices. This means that this layer defines the operating mode of the device (network communicator or endpoint), determines which application services the device provides and it handles the binding requests from other devices. The last layer, the Application Framework, tells what services a device can execute. A specific protocol cluster is used to communicate with other devices, consisting of a predefined message structure. This ensures interoperability between different devices [23]. In addition, it is possible to connect Zigbee with BACnet to combine the advantages of both protocols [77].

4.4. The extended connection between BACS and the digital world

Web-based control network became possible due to the implementation of Wi-Fi in BACS in 2009 and the increased use of smartphones and supporting apps (in 2010). A web-based system is based on a centralized and shared web server or central database [85]. These developments helped to improve the facility manager to monitor the facility remotely from real-time data, with more flexibility and on a larger scale due to great amount of sensors and meters [22,56]. This makes it possible to save costs due to fewer work movements of staff [34,39,86]. Furthermore, adopting to web-based control and the Internet presents the advantage of providing a network for software programs or components to interact and communicate, thus mitigating issues associated with interoperability [85]. The large amounts of sensors helped to improve the observability and to gather more data about the actual state of the facility [22].

Another development that had a large impact on BACS and the way they support the facility managers with building optimization, is the emergence AI from 2016 and the associated techniques of Machine Learning (ML) and Internet of Things (IoT) [5,22,24]. Machine Learning (ML) can be defined as a form of AI in which statistical models are used to give computers the ability to learn with data, without being explicitly programmed to do a specific task [24]. IoT is a network between people (end-users) and inexpensive smart devices equipped with sensors, networking and processing technologies to provide a service, such as historical data logging, logistics and material tracking, document management, monitoring of building components life cycle, collect data on the physical health of BACS [6,47]. Smart devices are connected to form a network of electronic devices that are able to react to real-world situations and make predictions, compared to connected devices that are only able to send and receive data [87]. This enables smart devices to take over the roles of DDC's, as seen in Fig. 3 [58].

The three-level model is expanded with the addition of smart devices connected through IoT in the field level and the implementation of an overarching cloud-based AI platform above BACS, see Fig. 4 [23,45]. A cloud-based AI platform is a large IT infrastructure of the connections between all the devices in BACS, it is remotely accessible and collects larger amounts of data compared to an on-site data storage. Therefore the AI platform is implemented as an overarching layer or cloud above the Building Management System and the whole structure of BACS [45]. The cloud provides data storage and analytics for large amounts of data sets, such as historical data and real-time data on occupancy, IEQ, energy requirements, security and service needs. The cloud-based AI platform leverages these data for anomaly detection, prediction and control [22].

AI can support the facility managers with effective energy management and decision-making through the analysis of large amounts of real-time data collected through all the IoT connected sensors in a building. The AI algorithms evolve due to ML using sensor data to create standards and predictions on the short, medium and long-term levels about occupants' behaviour patterns and occupants' energy usage. These predictions can be used to optimize the building in terms of sustainability and comfort levels [22,24]. An example of this is the AI Chiller from Yu et al., an open IoT cloud-based ML system in which the energy consumption of HVAC is opti-

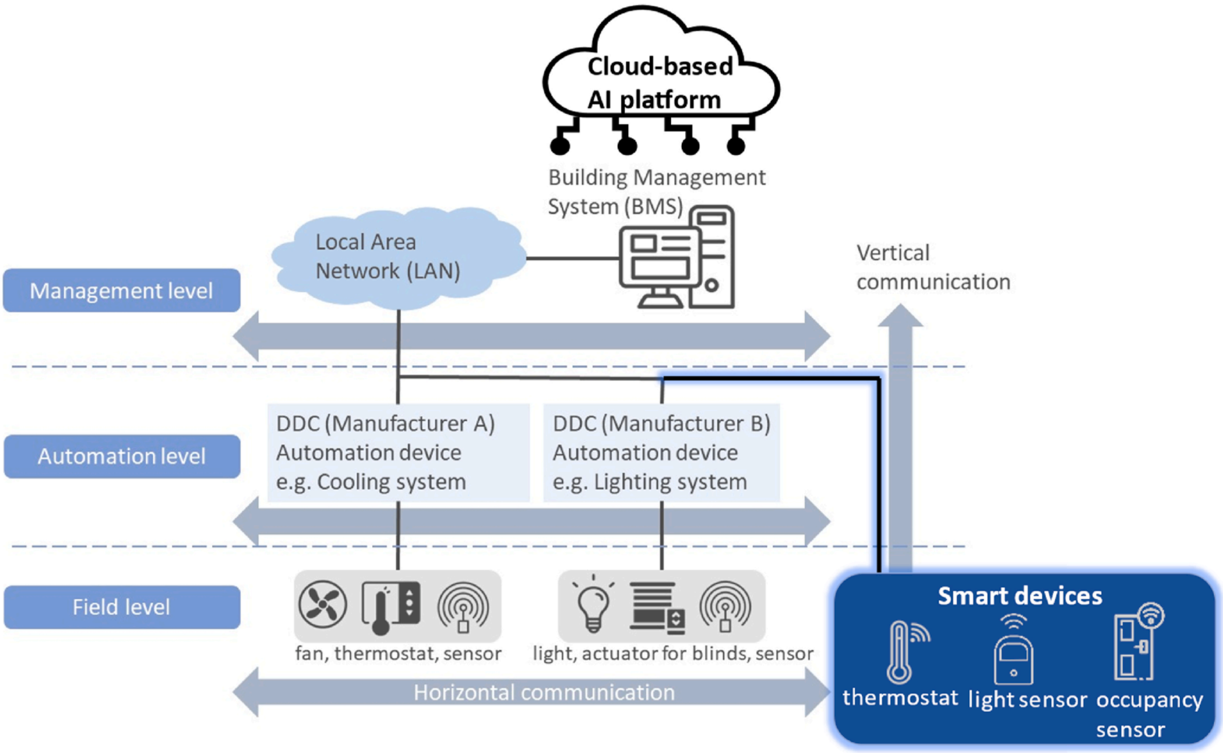

Fig. 4. This figure shows the addition of modern technologies, the cloud-based AI platform, smart devices and IoT (the connection between the smart devices and the automation level) to the three-level model structure of BACS.

mised [22]. Another example is the implementation of an AI ready BACS system in a school in Italy, which enables the optimization of HVAC automatization through AI and ML [88].

Furthermore, AI implemented on BACS is able to support the facility manager with proactive maintenance by detecting faults [6]. Faults are accidental conditions that can result in failures. Failures is a deviation of the required behaviour of the system or component, which may result in unnecessary energy loss and extra costs [22,89]. They can occur in the hardware of BACS, for example in the sensors, controllers or actuators. There are different types of failures, like complete failure, bias, drifting and precision degradation [90]. A *complete failure* happens when for example a sensor has no output or gives a constant value. A *bias failure* refers to a systematic error that results in inaccuracy, for example a device that lacks proper calibration which produces measurements that either overestimate or underestimate the values for each unit. *Drifting* occurs when failures constantly misalign and result in a growing disconnection. *Precision degradation* happens when the precision of a component is not accurate, the measurements are centred around the data but the fault results in an increase of the variability or spread of the measurements [90,91]. Furthermore, failures can also arise in the software of BACS. They are 3 levels of software failures: insignificant failure, significant failure and critical failure. An insignificant failure means the operation of the program is interrupted, but there is no data loss and no requirement for restarting the program. A significant failure occurs when the operation of a program is interrupted and there is loss of (parts of) the data, but restarting of the program is not required. A critical failure happens when the operation is interrupted, data is lost and a restart of the program is required [92]. Components connected with IoT are able to monitor and collect large streams of data that gives information about the condition of the facility and the implemented systems in real time. This data can be used for fault detection and diagnosis by ML algorithms by checking for differences in the parameters and by comparing them with data from normal operation [6,30].

Due to the techniques of AI, IoT and ML, faults can not only be detected but they can also be predicted, resulting in predictive maintenance [6]. Historical, real-time and occupancy data are collected, analysed and compared with environmental conditions and energy consumptions to look for anomalies or small changes in values, like temperature, these may indicate a future failure. By notifying the facility managers to timely check, repair or replace components, a failure or a breakdown in BACS can be avoided [5,6,24]. In addition, AI added to BACS enables the aspect of self-learning, because it learns by registering how the facility managers and users interact with BACS. This has promising perspectives as it supports with determining the cause of faults [22]. However, more research will be needed on BACS in combination with AI in terms of maintenance [24].

In parallel with being an active domain of research and development, integration of AI in BACS is already being adopted in the market. Initial attempts primarily focussed on a restricted set of functions of BACS, e.g. ‘self-learning’ or ‘smart’ thermostats; which adapt control strategies based on user behavior and environmental conditions. These early implementations demonstrated the potential for AI to enhance the efficiency and responsiveness of building systems [19].

As the technology has evolved, AI integration in BACS has expanded to include more sophisticated applications. Through analysing the Unissu global proptech startup database, Zhengzgen et al. listed various companies such as Kapacity.io, BrainBox AI, and Facilio, which deploy AI machine learning to optimize heating and cooling of buildings. In their 2023 review paper of 220 AI companies in the power sector, Franki et al. list 25 companies with main focus area 'Home/Building Energy Management system' and 32 companies focussing on AI for HVAC control [93].

5. Security risks

BACS have always been vulnerable to physical attacks, in the form of vandalism, theft or electric overload leading to incorrect functioning of BACS, because the components of BACS were physical accessible [94]. However, with the recent developments in connectivity such as protocols, internet and IoT, BACS also became vulnerable to cyber-attacks [37,58,95]. Cyber-attacks can be in the form of signal corruption, signal delaying and signal blocking [38]. A few examples of possible risks on the automation and management layer are: leakage of (personal) data, manipulation of databases and setpoints, a Denial of Service attack (DoS), a breakdown of the whole system, malware injection and network overloading [37,38].

Originally, BACS were created to operate without outside connection and therefore less thought was put in the security of BACS. So at the start of these connectivity developments, it was challenging to implement security measures or extensions on to the limited capacity of all the already existing field devices from different vendors [38,58]. However, increasing attention is paid to the threat of cyber and physical attacks on BACS. This results in various mitigation strategies to improve the defences of BACS [37].

A first mitigation is to detect potential attacks, for example by adding specialized devices to field devices for anomaly detection by monitoring and controlling the communication in the field level and searching for subtle changes in the behaviour of control systems of BACS [37]. Another way to detect potential attacks is by implementing ML algorithms on the automation and management level to compare real data with simulated datasets to detect for anomalies [38]. Although, this is more complex than it seems due to data is being influenced by unexpected events such as human action [37]. A next mitigation are defence approaches, these can be implemented on the field level, automation level and management level. At the field level the focus is on privacy protection and device verification. At the automation and management level the mitigations are implemented as BACS protocol hardening, by adding security features to the protocol, using network firewall to block illegal traffic and traffic normalisation is to correct traffic based on rules from the protocol [38].

Despite the attention to the risks and the developed mitigation strategies, there is still room for improvement. Cyber-security experiments should be tested and evaluated on real cases to ensure correct functioning of security measures in BACS in the real world while regarding human interactions. In addition, building owners and facility managers should update their BACS regularly to avoid obsolescence, which increases the risks of attacks. Also, default passwords should be changed immediately and all passwords should be changed frequently. Unused interfaces should be removed and the same counts for unused accounts [38,94].

The challenge of security risks in BACS will probably remain a constant battle, partly because old hardware cannot always be updated, so certain risks remain or cannot be solved. However, building owners, engineers of BACS and facility managers should remain cautious and continue to search for mitigation strategies to address these risks effectively.

6. Conclusion

This paper investigates the most important trends in FM, being (i) the transforming of traditional FM into strategic FM and (ii) the rise of technological development, such as BACS, BIM and AI and its opportunities and consequences for FM. The content of facility managers' jobs is changing due to higher demands of sustainability, energy efficiency and user control in function of comfort levels in buildings. FM is able to support the core operation of an organisation and extend the lifespan of the building and the installations within a building through strategic planning and the implementation of BACS [46]. Thus, FM plays an important role in optimizing space management in alignment with occupants needs and the core operation of an organization.

The various developments through time in BACS, such as the three level model, topologies, open communication protocols and the extended connection through Internet and AI, have facilitated the connection between different subsystems like HVAC and lighting. This connectivity enables them to collaborate effectively, leading to enhanced building conditions, optimised energy usage and reduced operational costs [40,49]. Furthermore, BACS enhanced with AI serves as a powerful data collection and monitoring tool, capable of handling real-time and historical data, occupancy rates, environmental conditions and energy consumption. Through the collection and monitoring of this data, BACS can provide valuable and data-based support to facility management by offering guidance on optimal setpoints creating efficient maintenance strategies to avoid unnecessary maintenance [4,22,23]. This guidance not only enhances the comfort of occupants but also simultaneously lowers energy consumption and reduces costs. Additionally, BACS' capabilities in fault detection and diagnosis and analysis in combination with the large data collection open the door to predictive maintenance, ensuring the continued operation of the buildings systems.

Although the connection through Internet and AI helped improve the efficiency and the user convenience of BACS, it also lead to increased security risks. These attacks can happen at the field, automation and management level of BACS in the form of theft, vandalism, signal corruption, signal delaying and signal blocking. The current mitigation strategies are to implement ways to detect potential attacks and to improve the defence approaches. Despite the attention to the risks and the developed mitigation strategies, there is still room for improvement. Cyber-security experiments should be tested and evaluated on real cases to ensure correct functioning of security measures in BACS in the real world while regarding human interactions.

This study highlights the potential of BACS for facility managers, but more research will be needed on BACS and their effect on FM. Future research should concentrate more on the impact of BACS for FM considering the possible issues of BACS regarding their life cycle, obsolescence, reliability, vendor lock-in and interoperability.

Research funding

This research was funded by the Industrial Research Fund of the University of Antwerp (IOF SBO 44738).

CRediT authorship contribution statement

S. van Roosmale: Writing – original draft, Conceptualization. **P. Hellinckx:** Writing – review & editing. **J. Meysman:** Writing – review & editing. **S. Verbeke:** Writing – review & editing, Supervision. **A. Audenaert:** Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

References

[1] J. Moubray, Reliability-Centered-Maintenance-II, second ed., Biddles Ltd., Guilford and King's Lynn, Oxford, 1997.
[2] F. Becker, Facility management: a cutting-edge field? Property Manag. 8 (2) (Feb. 1990) 108–116, https://doi.org/10.1108/EUM0000000003355.
[3] CEN, "CEN/TC 348 - Facility Management,", 2021.
[4] K.P. Pun, K.L. Tsang, K.L. Choy, V. Tang, H.Y. Lam, A fuzzy-AHP-based decision support system for maintenance strategy selection in facility management, in: *Proceedings Of PICMET'17: Technology Management For Interconnected World*, Hong Kong, 2017.
[5] V. Villa, G. Bruno, K. Aliev, P. Piantanida, A. Corneli, D. Antonelli, Machine learning framework for the sustainable maintenance of building facilities, Sustainability (Switzerland) 14 (2) (Jan. 2022), https://doi.org/10.3390/su14020681.
[6] M. Casini, Advanced facility management, in: Construction 4.0, Elsevier, 2022, pp. 583–605, https://doi.org/10.1016/b978-0-12-821797-9.00003-9.
[7] B. Ton, et al., Primavera: synergising predictive maintenance, Applied Sciences (Switzerland) 10 (23) (Dec. 2020) 1–19, https://doi.org/10.3390/app10238348.
[8] Y. Bouabdallaoui, Z. Lafhaj, P. Yim, L. Ducoulombier, B. Bennadji, Predictive maintenance in building facilities: a machine learning-based approach, Sensors (Switzerland) 21 (4) (Feb. 2021) 1–15, https://doi.org/10.3390/s21041044.
[9] M. Styła, P. Adamkiewicz, T. Cieplak, S. Skowron, A. Dmowski, J. Stokłosa, A smart building resource prediction, navigation and management system supported by radio tomography and computational intelligence, Energies (Basel) 14 (24) (Dec. 2021), https://doi.org/10.3390/en14248260.
[10] CEN, "ISO 41001:2018 Facility Management - Management Systems ,", 2018.
[11] I. Schaeps, J. Weltens, J. Duchamps, K. Schrijvers, FM-trendrapport België 2021. Belfa, 2021.
[12] CEN, "ISO 16484-2:2004 Building Automation and Control Systems (BACS) — Part 2: Hardware,", 2004.
[13] P. Office of the European Union L- and L. Luxembourg, "DIRECTIVE (EU) 2024/1275 of the EUROPEAN PARLIAMENT and of the COUNCIL of 24 April 2024 on the Energy Performance of Buildings (Recast) (Text with EEA Relevance),", 2024 [Online]. Available: http://data.europa.eu/eli/dir/2024/1275/oj.
[14] "DIRECTIVE (EU) 2018/844 of the EUROPEAN PARLIAMENT and of the COUNCIL of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency (Text with EEA Relevance),", 2018.
[15] D. Schachinger, W. Kastner, Semantics for smart control of building automation. Santa Clara: IEEE 25th International Symposium on Industrial Electronics (ISIE) : Proceedings, 2016.
[16] W. Kastner, G. Neugschwandtner, S. Soucek, H.M. Newman, Communication systems for building automation and control, in: Proceedings of the IEEE, Institute of Electrical and Electronics Engineers Inc., 2005, pp. 1178–1203, https://doi.org/10.1109/JPROC.2005.849726.
[17] "ISO 52120-1:2021 Energy Performance of Buildings - Contribution of Building Automation, Controls and Building Management,", 2021.
[18] A.M. Al-Ghaili, H. Kasim, N.M. Al-Hada, B.N. Jorgensen, M. Othman, W. Jihua, Energy Management Systems and Strategies in Buildings Sector: A Scoping Review, Institute of Electrical and Electronics Engineers Inc, 2021, https://doi.org/10.1109/ACCESS.2021.3075485.
[19] J.L. Hernández, I. de Miguel, F. Vélez, A. Vasallo, Challenges and Opportunities in European Smart Buildings Energy Management: A Critical Review, Elsevier Ltd., Jul. 01, 2024, https://doi.org/10.1016/j.rser.2024.114472.
[20] D. Adio-Moses, O.S. Asaolu, Artificial intelligence for sustainable development of intelligent buildings smart cities strategy and sustainable development goals: a literature survey, in: Emerging Trends in Construction Organizational Practices and Project Management Knowledge Area, 2016 Cape Town. https://www.researchgate.net/publication/299437528.
[21] CEN, EN 15323-1:2017 Energy Performance of Buildings - Energy Performance of Buildings - Part 1: Impact of Building Automation, Controls and Building Management, 2017.
[22] Y. Himeur, et al., AI-big data analytics for building automation and management systems: a survey, actual challenges and future perspectives, Artif. Intell. Rev. (Jun. 2022), https://doi.org/10.1007/s10462-022-10286-2.
[23] P. Domingues, P. Carreira, R. Vieira, W. Kastner, Building Automation Systems: Concepts and Technology Review, Elsevier B.V., Mar. 01, 2016, https://doi.org/10.1016/j.csi.2015.11.005.
[24] R. Panchalingam, K.C. Chan, A State-Of-The-Art Review on Artificial Intelligence for Smart Buildings, Taylor and Francis Ltd, 2021, https://doi.org/10.1080/17508975.2019.1613219.
[25] D. Ramsauer, M. Dorfmann, H. Tellioğlu, W. Kastner, Human perception and building automation systems, Energies (Basel) 15 (5) (Mar. 2022), https://doi.org/10.3390/en15051745.
[26] M.V. Shcherbakov, A.V. Glotov, S.V. Cheremisinov, Chapter: proactive and predictive maintenance of cyber-physical systems studies in systems, decision and control 259 cyber-physical systems: advances in design & modelling, in: J. Kacprzyk, A.G. Kravets, M.V. Shcherbakov, A.A. Bolshakov (Eds.), Studies in Systems, Decision and Control Cyber-Physical Systems: Advances in Design & Modelling, vol. 259, Springer Nature Switzerland, Cham, 2019, pp. 263–278 [Online]. Available: http://www.springer.com/series/13304.
[27] H. Fox, A.C. Pillai, D. Friedrich, M. Collu, T. Dawood, L. Johanning, A Review of Predictive and Prescriptive Offshore Wind Farm Operation and Maintenance, MDPI, Jan. 01, 2022, https://doi.org/10.3390/en15020504.
[28] Q. Wang, S. Bu, Z. He, Achieving predictive and proactive maintenance for high-speed railway power equipment with LSTM-RNN, IEEE Trans. Ind. Inf. 16 (10) (Oct. 2020) 6509–6517, https://doi.org/10.1109/TII.2020.2966033.
[29] British Standards Institution, BS EN 13306:2017, BSI Standards Limited, 2018.
[30] S. Lazarova-Molnar, H.R. Shaker, N. Mohamed, B.N. Jorgensen, Fault detection and diagnosis for smart buildings: state of the art, trends and challenges, in: 2016

3rd MEC International Conference on Big Data and Smart City, ICBDSC 2016, Institute of Electrical and Electronics Engineers Inc., Apr. 2016, pp. 344–350, https://doi.org/10.1109/ICBDSC.2016.7460392.
[31] G. Lowry, Energy Saving Claims for Lighting Controls in Commercial Buildings, Elsevier Ltd., Dec. 01, 2016, https://doi.org/10.1016/j.enbuild.2016.10.003.
[32] M. Ewert, D.P. Brodowicz, P. Pospieszny, Artificial Intelligence and machines : a curse or blessing for corporate real estate? Corp. R. Estate J. 7 (4) (2018) 337–351.
[33] G. Osma, L. Amado, R. Villamizar, G. Ordoñez, Building automation systems as tool to improve the resilience from energy behavior approach, in: Procedia Engineering, Elsevier Ltd, 2015, pp. 861–868, https://doi.org/10.1016/j.proeng.2015.08.524.
[34] T. O'Grady, H.Y. Chong, G.M. Morrison, A Systematic Review and Meta-Analysis of Building Automation Systems, Elsevier Ltd, May 15, 2021, https://doi.org/10.1016/j.buildenv.2021.107770.
[35] M. Uzair, A. Bakr Al Siddiq, S. Arabia, S. Yacoub Al-Kafrawi, K. Manaf Al-Janadi, and I. Abdulrahman Al-Bulushi, "A Low-Cost IoT Based Buildings Management System (BMS) Using Arduino Mega 2560 and Raspberry Pi 4 for Smart Monitoring and Automation 219 Original Scientific Paper.".
[36] B. Declercq, et al., "Interoperabiliteit, compatibiliteit en openheid binnen een Smart Building,", 2021.
[37] V. Graveto, T. Cruz, P. Simöes, Security of building automation and control systems: survey and future research directions, Comput. Secur. 112 (Jan) (2022), https://doi.org/10.1016/j.cose.2021.102527.
[38] G. Li, et al., A critical review of cyber-physical security for building automation systems, Annu. Rev. Control (Mar. 2023), https://doi.org/10.1016/j.arcontrol.2023.02.004.
[39] G. Mehedintu, R.C. Bere, C.I. Silvestru, V.-C. Icociu, Web-based architecture for building management systems, Inf. Econ. 22 (3) (2018) 86–96 https://doi.org/10.12948/issn14531305/22.3.2018.08, Sep. 2018.
[40] B. Mayer, M. Killian, M. Kozek, Hierarchical model predictive control for sustainable building automation, Sustainability (Switzerland) 9 (2) (2017), https://doi.org/10.3390/su9020264.
[41] "EN 52120-1 energy performance of buildings - contribution of building automation. Controls and Building Management - Part 1: General Framework and Procedures,", Bureau voor normalisatie, 2022.
[42] C. Wohlin, Guidelines for snowballing in systematic literature studies and a replication in software engineering, in: ACM International Conference Proceeding Series, Association for Computing Machinery, 2014, https://doi.org/10.1145/2601248.2601268.
[43] A. Ghaffarianhoseini, et al., Intelligent or Smart Cities and Buildings: a Critical Exposition and a Way Forward, Taylor and Francis Ltd, Apr. 03, 2018, https://doi.org/10.1080/17508975.2017.1394810.
[44] A.H. Buckman, M. Mayfield, S.B.M. Beck, What is a smart building? Smart and Sustain. Built Environ. 3 (2) (Sep. 2014) 92–109, https://doi.org/10.1108/SASBE-01-2014-0003.
[45] M. Krödel, G. Martin, "Artificial Intelligence in the Field of Building Automation,", 2010.
[46] CEN, "CEN ISO/TR 41013:2021 Facility Management - Scope, Key Concepts and Benefits,", 2021.
[47] V. Villa, B. Naticchia, G. Bruno, K. Aliev, P. Piantanida, D. Antonelli, Iot open-source architecture for the maintenance of building facilities, Applied Sciences (Switzerland) 11 (12) (Jun. 2021), https://doi.org/10.3390/app11125374.
[48] J. Pašek, V. Sojková, Facility management of smart buildings, Int. Rev. App. Sci. Eng. 9 (2) (2019) 181–187, https://doi.org/10.1556/1848.2018.9.2.15.
[49] R. Yang, L. Wang, Multi-objective optimization for decision-making of energy and comfort management in building automation and control, Sustain. Cities Soc. 2 (1) (Feb. 2012) 1–7, https://doi.org/10.1016/j.scs.2011.09.001.
[50] A.A. Al-Saedi, V. Boeva, E. Casalicchio, P. Exner, Context-Aware Edge-Based AI Models for Wireless Sensor Networks—An Overview, MDPI, Aug. 01, 2022, https://doi.org/10.3390/s22155544.
[51] T. Wei, X. Chen, X. Li, Q. Zhu, Model-based and data-driven approaches for building automation and control, in: IEEE/ACM International Conference on Computer-Aided Design, Digest of Technical Papers, ICCAD, Institute of Electrical and Electronics Engineers Inc., Nov. 2018, https://doi.org/10.1145/3240765.3243485.
[52] T. Mundt, P. Wickboldt, Security in building automation systems - a first analysis, in: 2016 International Conference on Cyber Security and Protection of Digital Services, Cyber Security 2016, Institute of Electrical and Electronics Engineers Inc., Jun, 2016, https://doi.org/10.1109/CyberSecPODS.2016.7502336.
[53] W. Kastner, G. Neugschwandtner, S. Soucek, H.M. Newman, Communication systems for building automation and control, in: Proceedings of the IEEE, Institute of Electrical and Electronics Engineers Inc., 2005, pp. 1178–1203, https://doi.org/10.1109/JPROC.2005.849726.
[54] W. Granzer, W. Kastner, "BACnet over KNX,", 2007.
[55] W. Kastner, G. Neugschwandtner, S. Soucek, H.M. Newman, Communication systems for building automation and control, in: Proceedings of the IEEE, Institute of Electrical and Electronics Engineers Inc., 2005, pp. 1178–1203, https://doi.org/10.1109/JPROC.2005.849726.
[56] N. Aste, M. Manfren, G. Marenzi, Building Automation and Control Systems and Performance Optimization: A Framework for Analysis, Elsevier Ltd., 2017, https://doi.org/10.1016/j.rser.2016.10.072.
[57] H. Merz, T. Hansemann, C. Hübner, Signals and Communication Technology Building Automation Communication Systems with EIB/KNX, LON and BACnet, second ed., Springer International Publishing AG, 2018 https://doi.org/10.1007/978-3-319-73223-7, Second Edition.
[58] T. Sauter, S. Soucek, W. Kastner, D. Dietrich, The evolution of factory and building automation, IEEE Industr. .Electron. Magazine 5 (3) (Sep. 2011) 35–48, https://doi.org/10.1109/MIE.2011.942175.
[59] O.G. Aju, "A Survey of ZigBee Wireless Sensor Network Technology: Topology, Applications and Challenges General Terms,", 2015.
[60] EN ISO 16484-5:2022 Building Automation and Control Systems (BACS) - Part 5: Data Communication Protocol, 2022.
[61] R.R. De Oliveira, R.M. Martins, A. Da Silva Simao, Impact of the vendor lock-in problem on testing as a service (TaaS), in: Proceedings - 2017 IEEE International Conference on Cloud Engineering, IC2E 2017, Institute of Electrical and Electronics Engineers Inc., May 2017, pp. 190–196 10.1109/IC2E.2017.30.
[62] K. Lohia, Y. Jain, C. Patel, N. Doshi, Open communication protocols for building automation systems, in: Procedia Computer Science, Elsevier B.V., 2019, pp. 723–727, https://doi.org/10.1016/j.procs.2019.11.020.
[63] S. Suhanto, F. Faizah, K. Kustori, Designing a building automation system with open protocol communication and intelligent electronic devices, in: Journal of Physics: Conference Series, Institute of Physics Publishing, Nov. 2019, https://doi.org/10.1088/1742-6596/1381/1/012006.
[64] M.U. Ali, M. Akhtar, H. Durad, Industrial control and building automation system penetrating testing using Modbus TCP testbed, VFAST Transact. Software Eng. 10 (3) (2022) 3742.
[65] Modbusorg, "MODBUS over serial line specification and implementation guide V1.02." [Online]. Available: http://www.modbus.org/.
[66] MODBUS application protocol specification V1.1b3 Modbus [Online]. Available: http://www.modbus.org, 2012.
[67] G.B.M. Guarese, F.G. Sieben, T. Webber, M.R. Dillenburg, C. Marcon, Exploiting Modbus protocol in wired and wireless multilevel communication architecture, in: Brazilian Symposium on Computing System Engineering, SBESC, 2012, pp. 13–18, https://doi.org/10.1109/SBESC.2012.12.
[68] "Niklas Weckström INTEGRATION of A MICROGRID EN-ERGY MANAGEMENT SYSTEM IN A BUILDING MANAGEMENT SYSTEM,", 2022.
[69] KNX BASICS Smart home and building solutions. Global. Secure. Connected. KNX.ORG.".
[70] Technical Committee ISO/TC 205 Building environment design, "ISO 22510 Open Data Communication in Building Automation, Controls and Building Management — Home and Building Electronic Systems — KNXnet/IP Communication,", 2019 *ISO 22510:2019*.
[71] Olivier Hersent, David Boswarthick, Omar Elloumi, The Internet of Things : Key Applications and Protocols, Wiley, 2012.
[72] "LonWorks Fundamentals A Guide to a Basic Understanding of the LonTalk Protocol,", 2003.
[73] *Introduction To the LONWORKS ® System*, 1.0, Echelon Corporation, Palo Alto, 1999.
[74] A. Jeevanandham, C. Srinivasan, S. Balavignesh, Internet of Things in the implementation of a smart city, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, Mar. 2021 012119, https://doi.org/10.1088/1757-899x/1084/1/012119.
[75] D.M. Schwenk, S.J. Briggs, D.M. Underwood, J. Bush, Development of an Open Building Automation System Specification Based on ANSI/ASHRAE 135-2004, BACnet ® Communications Protocol) A Technical Assessment, 2007.
[76] F. Xia, X. Kong, Z. Xu, Cyber-physical control over wireless sensor and actuator networks with packet loss, in: S. Mazumder (Ed.), Wireless Networking Based Control, Springer, New York, 2010, pp. 85–102, https://doi.org/10.1007/978-1-4419-7393-1_4.

[77] W. Guo, W.M. Healy, M. Zhou, ZigBee-Wireless Mesh Networks for building automation and control, in: 2010 International Conference on Networking, Sensing and Control, ICNSC 2010, 2010, pp. 731–736, https://doi.org/10.1109/ICNSC.2010.5461566.
[78] H. Zemrane, Y. Baddi, A. Hasbi, Performance study of IoT based protocols ZigBee and WiFi, in: Sita'18, 2018 10.475/123_4 New York.
[79] J.S. Lee, Y.M. Wang, Experimental evaluation of ZigBee-based wireless networks in indoor environments, J. Eng. 2013 (2013), https://doi.org/10.1155/2013/286367.
[80] P. Dymora, M. Mazurek, K. Smalara, Modeling and fault tolerance analysis of zigbee protocol in IoT networks, Energies (Basel) 14 (24) (Dec. 2021), https://doi.org/10.3390/en14248264.
[81] C. Peng, K. Qian, Development and application of a ZigBee-based building energy monitoring and control system, Sci. World J. 2014 (2014), https://doi.org/10.1155/2014/528410.
[82] Modbusorg, MODBUS Messaging on TCP/IP Implementation Guide V1, 0b Modbus Organization, 2006 [Online]. Available: http://www.Modbus.org.
[83] V.K. V, A. V Tatachar, S. Kondur, V.Y. C, K.Y. C, Zigbee, it's applications and comparison with other short range network technologies, Int. J. Eng. Res. Technol. 10 (6) (2021) [Online]. Available: www.ijert.org.
[84] T.D.P. Mendes, R. Godina, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, Smart home communication technologies and applications: wireless protocol assessment for home area network resources, Energies (Basel) 8 (7) (2015) 7279–7311, https://doi.org/10.3390/en8077279.
[85] W. Shen, et al., Systems integration and collaboration in architecture, engineering, construction, and facilities management: a review, Adv. Eng. Inf. 24 (2) (Apr. 2010) 196–207, https://doi.org/10.1016/j.aei.2009.09.001.
[86] S.C.M. Hui, Latest trends in building automation and control systems [Online]. Available: www.ddc-online.org, 2007.
[87] K.S. Cetin, Z. O'Neill, Smart Meters and Smart Devices in Buildings: a Review of Recent Progress and Influence on Electricity Use and Peak Demand, Springer Nature, Mar. 01, 2017, https://doi.org/10.1007/s40518-017-0063-7.
[88] M. Magri, F. Padovan, F. Fabris, S. Michelin, Implementation of an AI ready BACS system in treviso school with DCV (demand control ventilation), in: E3S Web of Conferences, EDP Sciences, Mar. 2022, https://doi.org/10.1051/e3sconf/202234302003.
[89] M. Hamill, K. Goseva-Popstojanova, Common trends in software fault and failure data, IEEE Trans. Software Eng. 35 (4) (2009) 484–496, https://doi.org/10.1109/TSE.2009.3.
[90] H. Hou, H. Ji, Detection of sensor precision degradation by monitoring second-order statistics, in: IFAC-PapersOnLine, Elsevier B.V., 2020, pp. 11872–11877, https://doi.org/10.1016/j.ifacol.2020.12.701.
[91] Y. Chen, L. Lan, Fault detection, diagnosis and data recovery for a real building heating/cooling billing system, Energy Convers. Manag. 51 (5) (May 2010) 1015–1024, https://doi.org/10.1016/j.enconman.2009.12.004.
[92] T. Hovorushchenko, "Criteria and Rules for Classification of Software Failures and Vulnerabilities.".
[93] V. Franki, D. Majnarić, A. Višković, A Comprehensive Review of Artificial Intelligence (AI) Companies in the Power Sector, MDPI, Feb. 01, 2023, https://doi.org/10.3390/en16031077.
[94] P. Ciholas, A. Lennie, P. Sadigova, J.M. Such, The security of smart buildings: a systematic literature review, http://arxiv.org/abs/1901.05837, Jan. 2019.
[95] S. van Roosmale, A. Audenaert, J. Meysman, Understanding the opportunities and challenges of Building Automation and Control Systems to support facility management, J. Facilities 42 (7/8) (Apr. 2024) 677–693.