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Recent Innovations, Challenges, and Future Directions in Building Management Systems: A Comprehensive Review

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ABSTRACT

Recent progress in intelligent technologies, in particular, the use of the Internet of Things (IoT), machine learning, and data-driven control concept takes the Building Management Systems (BMS) out of a fixed rule-based and regression framework and towards the concept of intelligent, adaptive, and real-time monitoring, prediction, and optimization. The presented paper presents the synthesizing review of the studies on BMS given over the period of 2010- 2024, including the latest developments, main challenges, and the way the studies advance toward the new research directions within the most important areas of Heating Ventilation and Air Conditioning (HVAC), lighting, and security. The sources were chosen based on automation, energy control and digital revolution in construction areas. The results show that despite the fact that BMS technologies play a crucial role in improving energy efficiency and comfort of the occupants, some of the problems reported to exist such as difficult integration, high costs of deployment, and vulnerability to cyber-attacks hinder widespread use. The future research can be conducted in the area of standardized communication protocols, secure and interoperative architecture, predictive maintenance based on digital twin, and AI-driven adaptive control to realize resilient and human-centered intelligent building systems.

1. INTRODUCTION

Building infrastructure deserves special attention as it involves efficient operation of offices concerning their energy usage, occupant comfort, and safety, and (BMS) is a key element in the modern building. Buildings consume a significant portion of energy in the world and they constitute nearly 40 percent of all energy used in the U.S and nearly 33 percent globally meaning that they need to optimize their activities and adopt environmentally friendly solutions [1-3].

BMS supports the systematic data acquiring, analyzing, and making the decision process [4, 5], this process has been proven to improve energy efficiency and provide environmental comfort and responsiveness for occupants. Automation of BMS is used to manage major operations in buildings, like Heating and Ventilation Air Conditioning (HVAC), lighting, and security, thereby enhancing energy savings and the level of comfort for occupants [6]. The ability to base interoperability on standardized communication protocols such as the Modbus Transfer Control Protocol / Internet Protocol (TCP/IP) and the Message Queue Telemetry Transport (MQTT) enable the building harmonious and automated systems with a wide range of tools, and efficient communication networks are present [7, 8].

BMS has not yet been able to eliminate buildings as energy waste and source of carbon emissions. Indicatively, air conditioning systems used in the office setting could take up 61–88% of electricity consumption [1].

Without a Building Management System (BMS) offering good management, it would be extremely hard to reconfigure these systems in order to accurately balance energy consumption and occupant requirements [9]. Elevated operational costs, increased carbon emissions and aggravated carbon footprints are the consequences.

At the same time, the use of digital systems has grown dramatically, thereby posing significant cybersecurity concerns [10], requiring sophisticated protective measures and highly resilient architectural designs [11] to prevent the data manipulation and system compromise.

BMS are being revolutionized by the contemporary advancements in technology, most notably their integration with IoT devices [12].

Though previous reviews addressed particular concepts related to BMS, which include individual component (HVAC, lighting) or communication standards fail to provide an integrative perspective on recent innovations and research trends.

The purpose of the review is to offer such a perspective, through the systemic synthesis of BMS-related studies published in 2010-24, in which the paper indicates:

1- BMS: IoT, AI, and cloud integration and technological innovation.

2- Interoperability, cybersecurity, and cost barriers are factors that restrict the extensive implementation.

3- The future trends and innovation towards formulating resilient, energy-efficient and human-focused smart buildings.

By doing so, this review offers a novel, unified understanding of the current state of BMS research, setting the foundation for future academic and industrial progress.

A salient feature of BMS is its potential to reduce energy consumption by up to 50% through the integration of advanced sensing, control, and management technologies [13-37]. Globally, buildings account for approximately 33% of total primary energy use and nearly 40% in the United States, with HVAC systems alone responsible for up to 88% of electricity consumption in monitored office spaces [30]. Furthermore, the global BMS market is projected to reach nearly $10 billion USD by 2025, highlighting the growing attention toward sustainable and adaptive energy management solutions [38-54].

As mentioned in the abstract section, it will be rather easy to follow these rules as long as you just replace the "content" here without modifying the "form".

Table 1. Important statistics that support the significance of BMS

Category	Statistic	Details	Source
Global Energy Consumption	Buildings consume a substantial portion of global primary energy.	Buildings account for ~40% of primary energy use in the US and ~33% globally.	Nature Scientific Data [31]
Energy Savings Potential	Existing technologies, including BMS, can significantly reduce building energy use.	Technologies like energy efficiency measures, advanced sensors, and controls, hold the potential to cut building energy consumption by up to 50%.	Nature Scientific Data
HVAC Energy Share	HVAC systems contribute significantly to overall building electricity consumption.	HVAC operations can account for 61-88% of the electricity used in monitored office spaces.	Nature Scientific Data
BMS Market Growth (Projected)	The BMS market is projected for considerable growth in the coming years.	Studies Show that projected is around $10 billion USD by 2025, with a CAGR of 8.5% in this range.	Markets and Markets: Building Management System Market Worth $9.9 Billion by 2025

Key highlights from the Table 1 include:

○ **Global Energy Consumption:** Buildings represent a considerable fraction of worldwide energy demand, underscoring the need for optimization strategies.

○ **Energy Savings Potential:** BMS has a large potential of saving energy in the built environment.

○ **HVAC Energy Share:** A large section of electrical load in a building can be attributed to the operations of heating, ventilating, and air conditioning.

○ **BMS Market Growth (Projected):** The industry in which the BMS operates believes that it will grow thriving in the near future.

2. CHALLENGES AND LIMITATIONS

There are great barriers that will lie ahead of BMS implementation. It is required that crucial areas are taken into account, and summarized studies reflected in Table 2 represent them. The development of numerous technologies and systems is a constant problem. BMS entail alluding to the incorporation of HVAC, lighting, security solutions, sensors, and the operation of systems. A lack of incompatibility may lead to interoperability, data, and exchanges, as well as inefficient performance. As the example, the integration of Modbus / RTU and Modbus / TCP gave some challenges [38-54]. In BMS with the deployment of the IoT, this is a particularly severe problem when it comes to securing data and associated privacy concerns. The data on the users and performance must be secured against malicious security and intruders. Such issues are echoed in several researches (Table 2), where a 2024 article focuses on Modbus TCP/IP privacy implication [15]. And unless there is a strong system of security (encryption, multi-factor authentication, network segmenting, regular updating, vulnerability testing) a sufficient protection cannot occur. Integration of BMS at construction comes with an initial cost particularly when it comes to old buildings or projects that have a small budget. The use of BMS usually requires expenses on high hardware, software, installation, training, and maintenance. The viability will rely on the cost-benefit analysis, including the possible benefits (energy saving, increased efficiency, comfort to the user) and the costs. Successful rollout of BMS is an ultimate challenge in terms of user engagement. The result of insufficient knowledge of the benefits of using system or using the system can lead to the unwillingness of the user to use the system, resistance and poor effectiveness of the system. To optimize the use of BMS, it is necessary to provide users with design and implementation, training and support, and receive feedback. The systematic analysis of available literature on energy management in buildings by Table 2 provides a summary of methodologies, devices, environments, benefits, and weaknesses of the research needed to define trends, strengths, limitations, and suggest research directions.

Table 2. Systematic analysis of energy management research in buildings

Ref.	Methodology Used	Devices Used	Environment	Advantages	Limitations and Key Challenges
[1]	Pricing policy and PLC-based management for shared backup energy systems	Programmable Logic Controller (PLC), Local Area Network interface, Backup generators/energy	Multi-apartment buildings (Gaza context)	Efficient management/protection of backup source, fair energy distribution, enhanced resident satisfaction (real-	Small-scale testing (4 apartments) constrained and did not allow their validation in practice, and future improvements in PV integration were necessary.

		source, PV inverter (future plan)		time monitoring), easily expandable (up to 24 apts).	
[34]	Review and application of AI/ML algorithms for thermal comfort prediction	AI/ML algorithms (e.g., neural networks), IoT devices (data collection), Indoor condition data (temp, humidity)	Building control systems / Energy efficiency	More accurate thermal comfort prediction than traditional models (PMV/PPD), enhances energy efficiency while maintaining comfort, utilizes IoT data.	The main constraints are the absence of field validation and huge cost of development, which are complicated by the interdisciplinary cooperation issues and the need of quality IoT data.
[41]	Smart controller using Fuzzy Logic Control (FLC) and Artificial Neural Networks (ANN) for energy efficiency	FLC, ANN, MATLAB Simulation Model (thermal house), Renewable energy sources (solar), Energy storage system	Buildings (HVAC management)	Effective energy reduction (FLC/ANN), accurate forecasting (ANN, 2% deviation), energy cost reduction (storage/off-peak use), increased renewable use, smart control.	Its performance depends on the possibility to model simulation and to tune filter the FLC/ANN algorithm correctly with some further difficulties in integrating it with the current systems.
[49]	Dual-layer monitoring network using Modbus RTU and Modbus/TCP protocols	Modbus/RTU, Modbus/TCP protocols, Network infrastructure (two layers)	Multi-equipment environments (factories, buildings)	Improved monitoring/control efficiency vs traditional systems, convenient control of small groups while monitoring large numbers, versatile applications.	Limitations revolve around the fact that it is complicated to deal with the Dual-layer network, may contain bottlenecks in case of improper implementation, and the nature of Modbus protocols is that they are vulnerable to security threats.
[12]	Integrated intelligent BMS merging model-based control and machine learning	Embedded sensors (thermal, visual, auditory, etc.), Real-time management system, Machine learning algorithms, Model-based control components	Smart building control	Adapts to real-time conditions, optimizes multiple comfort levels, minimizes energy use, handles uncertainties via ML, meets user comfort/safety needs.	Sensitivity of ML algorithms to different levels of comfort parameter complicates the choice of model-based control, which has significant sensor data requirements and prompts the necessity to ensure that the ML algorithms are properly tuned.
[18]	Automated auditing and continuous commissioning software development	Building Management System (BMS), ObepME Tool (energy performance monitoring), Integrated monitoring/control tech (meters, sensors), Automation systems	New and existing buildings	Expected energy efficiency increase (up to 35%), projected operational cost reduction (~25%), supports emission reduction, ensures sustained performance, aids EU goals.	Implementation and integration of software is the key to success, and the projected savings will rely on the peculiarities of the building and will have to be checked in practice.
[51]	Performance Investigation of Building Energy Management System Based on Data-Driven Approach	(Implicitly, general BMS components and data)	(General BMS context, relates to user interfaces)	(Implicitly, enabling user control and enhancing responsiveness)	Data-driven methods have intrinsic issues particularly in terms of quality of data, complexity of models and interpretation of results.
[35]	Evaluation of deep learning algorithms for indoor temperature prediction (Digital Twin context)	ML algorithms (Extra Trees, Random Forest), DL algorithms (MLP, LSTM, CNN), Feature selection techniques, HVAC system data	HVAC Systems / Digital Twins	DL outperforms tree-based models (MLP best: 0.16°C RMSE), high accuracy (0.10-0.13°C MAE), identifies best look back window (60min), reliable for real-time use.	Key limitations include difficulties in predicting abrupt temperature changes (transitions, system start/stop) and increased errors during seasonal transitions, compounded by significant training data needs.
[37]	Review of technologies and trends in smart facility management	Building Information Modeling (BIM), Internet of Things (IoT), Digital Twin (DT), Artificial Intelligence (AI), Block chain	Smart facility management	Highlights growing research interest, identifies BIM as dominant tech, shows potential for enhanced operations/decision-making, outlines future research needs.	Enormous entry prices and substantial integration issues (especially with BIM/IoT), as well as a lack of more pragmatic test cases and overall benefit analysis, are hindrances to Faces.
[42]	Visual anomaly detection using thermal cameras and ML	Thermal cameras, ML algorithms (Facebook Prophet mentioned for data processing)	Building management (security, energy)	High accuracy in detecting unusual events, low error rates vs deep learning, efficient data processing (Prophet), performs well outdoors/challenging environments.	The quality of thermal cameras, as well as cost, dependability is determined; the efficiency of data condensation methods should also be compared against deep learning, as compared to the former, which should be expounded upon as well.

[7]	Digital Twin (DT) model development for an electric car using Vehicle-in-the-Loop (ViL) simulation	Digital Twin (DT), Vehicle-in-the-Loop (ViL) simulation, LabVIEW (software), SG Telemetry Viewer (software), Modbus TCP/IP, Torque/Speed sensors	Electric Car Performance Analysis	Enhances performance analysis (sharp turns, high speed), increases energy efficiency/motor performance (objective), uses real-world data, real-time analysis via cloud.	Issues such as dealing with differences between simulation and real-world data (that affects the accuracy of simulation), and the necessity of fine-tuning performance checks to factor in variability in the real world (random incident and variety of operating conditions) are problems.
[15]	Multi-layered security architecture for Modbus TCP in SCADA systems	Firewalls, Intrusion Detection Systems (IDS), Network Traffic Analysis (NTA), Load Balancer, Elliptic Curve Cryptography (ECC), Python software	Edge Intelligent Devices / SCADA systems	Significantly reduces unauthorized access/malicious attacks, improves reliability/availability (load balancing), continuous monitoring.	The testing, which is local to a subnet, is limited, and therefore needs to be extended to broader scalability testing; specific cases of attack (e.g. compromising a Master/key theft) are not covered, and the performance characteristics of the security architecture are yet to be investigated in wider deployment.
[3]	Penetration testing of ICS/BAS using Modbus TCP	Modbus TCP protocol, Ettercap tool (MITM), fuzzing (fuzz testing), Kali Linux OS, EasyIO-FS-32 Controller, HVAC system components	Industrial Control Systems (ICS) / Building Automation Systems (BAS)	Highlights Modbus TCP vulnerabilities (lack of auth/encryption), demonstrates MITM/ARP spoofing attacks, shows impact of data manipulation, reveals fuzzing weaknesses.	The evaluation had been restricted to a particular installed environment/testbed, and the results of fuzzing were technologically specific, which essentially underscores the natural vulnerability of the Modbus protocols to security issues (e.g., no authentication/encryption).
[46]	Simulator design for real-time electrical parameter monitoring	Power Tag device, Concentrator, PC with HMI software, Zigbee, Modbus TCP/IP, Eco structure Commission Software	Electrical Design Laboratory	Real-time monitoring/recording, facilitates energy management, detects imbalances, relatively balanced voltage observed in tests.	The threats are that it might have problems in wireless connection (e.g. Zigbee retries) and depend on certain vendor software (Eco structure) that can restrict interoperability.
[16]	Hybrid deep learning models for multi-timescale energy prediction	Deep Learning Models (LSTM, CNN, GRU, BiLSTM), Hybrid Models (CNN-LSTM, etc.), Performance Metrics (MSE, RMSE, MAE)	Smart Buildings	Improves prediction accuracy (esp. CNN-LSTM for minute/hour), handles multiple time resolutions, captures complex patterns.	The effect of performance implications on daily predictions (because of reduced data amounts) on long-term prediction performance is worsened by large training data requirements and high computation demands.
[36]	Review of smart buildings and EMS technologies for energy efficiency	Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Real-time Data Analytics, Automated EMS	Buildings	The possibilities of up to 30% energy savings, better energy management (predictive maintenance, adaptive control), and comfort of the occupants.	Its massive adoption is impaired by expensive initial expenses, substantial cyber security issues, and already established regulatory obstacles.
[6]	ML (Reinforcement Learning) for adaptive HVAC control in BMS	Actor-critic algorithm of reinforcement learning (RL) activities, Deep neural networks, stochastic gradient descent, Penalty-based reward, Heat exchanger data.	(BMS) / HVAC control	Effectively determines optimal positioning of the valve, improved performance/flexibility compared to the old procedures, has the potential to optimize in the real world.	The major issues are data noise of real-world sensors, the complexity of implementation of an efficient reward function, and the need of data preprocessing and substantial real-world testing, among others.

Table 2 indicates a variety of researches that illustrate the overall tendency of Smart Building Management Systems (SBMS), as it will need a tremendous change in the paradigm of control and the introduction of Artificial Intelligence (AI), Machine Learning (ML), and digital simulation to maximize energy use, thermo-indoor comfort, and smart surveillance. The challenges that are common in all these systems are complexity in integration of varied components, the requirements of good and complete data, high implementation expenses and the issue of field validation.

The statistics also demonstrate a trend of technology advancement, whereby small scale- Experimental solutions have been replaced by fully operational, adaptability systems that continue to depend on predictive analytics and multi-layered intelligent systems largely.

3. LITERATURE REVIEW

Development and deployment of BMS are important to solve the energy consumption, environmental sustainability, develop smart, adaptive built environments. This review of the literature reviews some of the most important innovations and research impetus in BMS technology. To be understood, this analysis is categorized using the underlying technology (e.g. IoT, AI algorithms), the target application sector and the main goal (e.g. energy efficiency, security). As shown in Figure 1, AI and Big Data analytics frameworks create a taxonomy that includes learning models, applications, platforms, challenges, and future directions that constitute the structure by which to consider individual studies and evaluate current research on BMS research.

The following extensive taxonomy of AI and Big Data analytics models applied in BMS can be presented in Figure 1, in which the diagram demonstrates AI methods in the categories of supervised, unsupervised, semi-supervised, and reinforcement learning, also explaining some of the most popular algorithms and models that may be implemented within those categories. The models of learning are incorporated into AI-Big Data learning pipelines that interact with computing systems, the environment where buildings are built, and applications.

The taxonomy also emphasizes the existing challenges, case studies as well as possible future directions as a structured overview to inform the further classification into eight areas of BMS research.

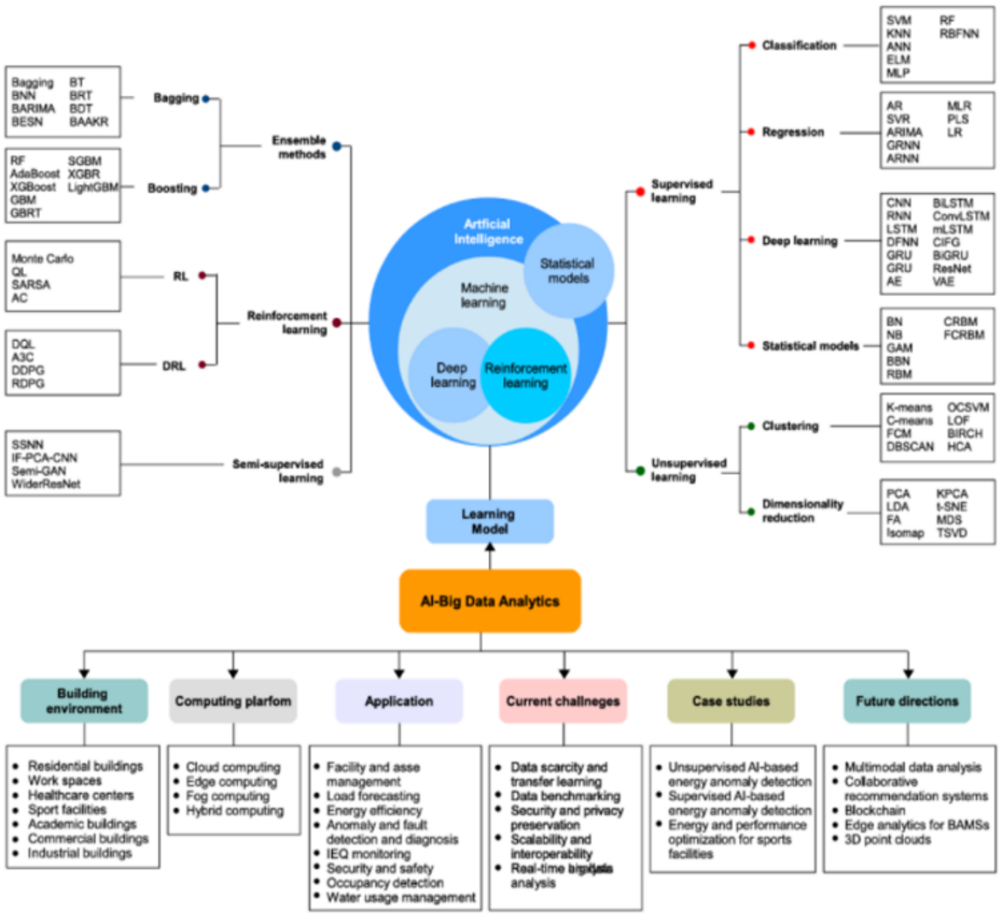

Figure 1. A taxonomy of artificial intelligence and big data analytics frameworks for BMS

3.1 Foundational systems: IoT, monitoring, control, and protocols

The basic monitoring and control platforms are based on the existing and new IoT technology, sensors, and communications standards. As compared to one another it is indicated that:

Hardware-based monitoring: Modbus TCP/IP and PowerTag sensor-based hardware-centric real-time electrical monitoring proved to be accurate in managing energy and detection of imbalance [46]. The low-cost energy monitoring device that was made with Arduino and PLC allowed the users to trace appliances that demand high power and efficiency in their use [28]. The everything was automated using microcontroller based systems in form of gates, lights, door locks, and alarms, thereby enhancing efficiency, security and comfort [4]. Elderly or disabled user friendly systems were systems that were optimised to have an accurate control of the flow of AC and water and thus improved the safety and comfort of the system [10].

Network and protocol implementations A two-layer (RTU + TCP) Modbus network with enhanced monitoring efficiency was developed [49]. Wi-Fi based Smart meters that utilized the IEEE 1888 (TCP/IP) eased the process of tracking energy [27]. The increased energy conservation was provided by the use of WSN with Zigbee modules [33]. Fuzzy logic control through IoT was able to control the speed of AC motors and light in smart prototypes of BMS [4].

Comparative knowledge: Modbus-related systems have a high level of interoperability, whereas WSN/Zigbee is versatile and expensive to implement. IoT-fuzzy systems are decent in adaptive control but have to be highly calibrated.

3.2 AI and ML applications

The field of AI/ML applications is interested in the prediction, optimization, and detection of anomalies in BMS.

Prediction and forecasting: ANN models are capable of accurate prediction of the outdoor temperature [41]. The CNN-LSTM hybrid models have been found to be more effective than the conventional models in multi-timescale energy prediction [16]. MLP models were found to be better in predictions of indoor temperature compared to tree-based models [35]. This improved the accuracy of short-term load prediction using LSTM with Multi-Behavior Bottleneck Features [8]. AlexNet based transfer learning facilitated CCTV based human counting at high accuracy [40].

Optimization and control: Fuzzy Logic Control (FLC) offers an easy-to-use HVAC control [41]. A model-free reinforcement learning (actor-critic) is an optimization of the valve positions [6]. MAS-driven decentralized BMS is effective in coordinating both the demand-side and supply-side management, and makes significant energy savings [29]. The integration of deep learning and Named Data Networking (NDN) improves the forwarding of data and control of HVACs [5].

Anomaly/fault detection: Visual anomaly detection by thermo camera is faster/flexible than deep learning [42]. MQTT cloud and ML/AI are used to detect waveforms anomalies [20]. Fuzzy-ADLD allows detection of the anomaly at a quick pace with a linguistic explanation [48]. Multi-stage Boolean Identification and ML identify cyber-attacks against electrical faults [44].

Relative understanding: Deep learning and hybrid ANN models are strong and efficient in forecasting, MAS and reinforcement learning are better at control flexibility, and the fuzzy based systems give human interpretation. Selection is based on the availability of sensors, real time needs and computation constraints.

3.3 System design, integration and advanced frameworks

Some integration solutions and architectures are described in studies:

Architectures and platforms: BRICKS rule-based system that has the option of energy forecasting and DR [30]. The BuildCOM software performs, with systematic auditing, which allows saving energy. The simultaneous integration of EMS, which entails the combination of IoT, Edge/Cloud, Big Data, AI, and Bloc kchain can result in energy reduction to as much as 50 per cent [31]. VLC-based and multi-agent simulation-based human-aware BMS enhances the occupant tracking [32].

Microgrid and backup integration:Various intelligent control schemes have been considered.A SCADA-based energy management system will integrate solar and battery storage to reduce dependence on the grid by 27 percent of the operational costs in large scale microgrids [33], and a PLC-controlled pricing scheme will be more efficient in shared backup systems [7].

Comparative understanding: Systematic control is provided by centralized platforms, scaling can be increased with MAS, and occupant-conscious insight can be raised due to VLC combination. Some of the constraints are the complexity of integrating the data and reliance on the sensors.

3.4 Data management, modeling and visualization

Visualization of data and proper structuring is a vital attribute of BMS performance:

BIM and data mapping: BEM variables in the raw BMS database using DBSCAN and X-gram were text mined automatically to process high accuracy large BEM variables [37].

Dataset maintenance: Brick schema high-resolution 3-year LBNL Building 59 dataset is in high resolution allowing it to be reproducibly analysed [38].

Inference: Data-driven methods will improve the prediction models and decision-making processes, however it requires fullness of the data and calibration of sensors.

3.5 Security and resilience

Security of BMS is vital to eliminate cyber threats:

Vulnerability assessment: MITM attacks reflected the vulnerability of Modbus TCP [8].

Security architectures: Firewall, IDS, ECC, and NTA as multi-level security architectures will help to minimize un authorized access [6].

The third point that can be made is that protocol-based vulnerabilities are one of the greatest shortcomings; layered security architecture is more resilient, yet introduces more system complexity.

3.6 Demand side management, energy flexibility and shared resources

Demand Response (DR): DR decreased the peak power (AC) by 43.79 percent using software [9]. Light and AC reduction (SCADA-based) of office buildings were coordinated [10].

Demand elasticity modeling: Q-learning enabled demand learning and predictions in the models of the IoT energy meters [11, 12].

Shared systems: PLC controlled optimum backup energy management pricing [7].

Knowledge: Predictive DR and demand management with MAS yields more flexibility on energy, and in order to be efficient, controlling demand in real-time is extremely vital.

3.7 Emerging technologies: Digital twins and advanced communication

Digital twins MLP deep learning works well with real-time twin HVAC systems as it creates an indoor temperature prediction that is an accurate one [35]. Digital twin frameworks of electric cars comprised ViL simulation, LabView, Modbus, sensors and cloud networking [16].

VLC: LEDVLC allowed tracking the occupants in great detail with multi-agent simulations [32].

Intelligence: VLC is better location-based control, whereas digital twins give real time operational insights. These include computational load and sensor fidelity.

3.8 Evaluation, trends and human factors

There are some systems of evaluation: the Wuli-Shili-Renli (WSRI) system that proved effective in evaluating EMPs [13].

Trend analysis and bibliometrics: BEMS research trends an alternative, PV, IoT and IoE; BIM, IoT, and Digital Twins dominate the existing research [14, 15].

User views: UTAUT2 questionnaires reveal Intelligent Operations and Safety as the essential SBMS attributes; the preliminary adoption through involvement of stakeholders via Living Labs enhances their use at an early stage [17, 18].

Informing point: Practical usability and adoption with the help of integrating human factors, technological innovations are complemented.

4. RESEARCH GAP

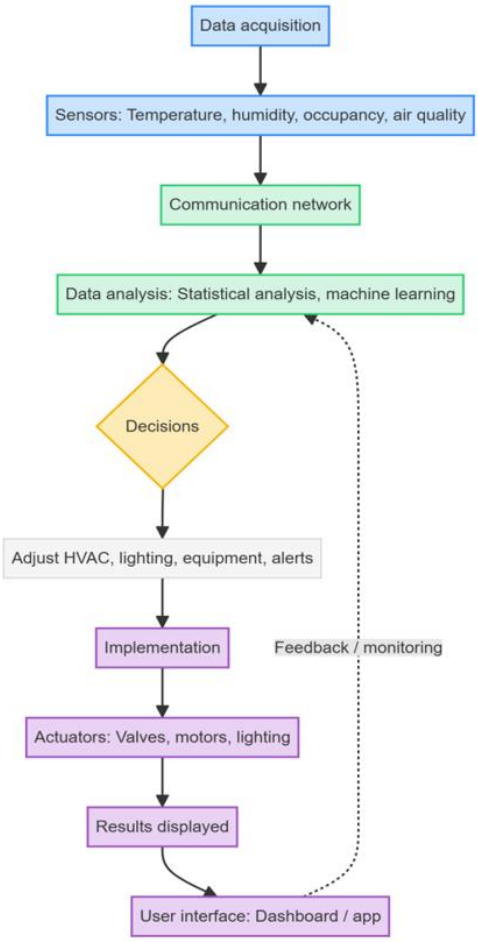

Figure 2. Data, signals, and instruction flow in BMS

Despite the significant progress, BMS makes, there are critical knowledge gaps, and this fact limits the deeper insight into BMS functions and does not allow developing more effective and sustainable plans [12].Figure 2, the "Data Flow in (BMS)," illustrates the system's fundamental operational cycle, commencing with data acquisition from sensors, proceeding through analysis (via statistical methods and machine learning) and decision-making, culminating in actuator-driven implementation, and completing the loop via the user interface and the crucial feedback mechanism. Among these gaps we have a lack of knowledge regarding the effects of the BMS on the psychosocial well-being. The existing research frequently does not pay enough attention to the delicate research of the impact of specific aspects of BMS on human psychosocial comfort; e.g., the impact of light control on circadian and vitality or the impact of indoor air quality on concentration and cognitive power are under-researched or largely unknown [12]. This inadequate knowledge will hinder the realization of BMS objectives in both energy saving and comfort of the occupants.

Moreover, there exists absence of theoretical and practical framework of integrating emerging technologies. Although the idea to implement AI and ML into BMS is gaining more and more popularity, profound theoretical and practical schemas remain absent [6, 15]. Such a lack makes it impossible to take full advantage of the potential of such innovations to enhance the performance of BMS and limits the capability to integrate AI and ML into the existing BMS hierarchy without issues and to eliminate the actual intelligent building management system development. Lastly, poor exposure to cyber security and privacy is not properly alleviated [15]. With the modern age of growing dependence on the connected world, it is essential to deal with cyber security emergency and privacy concerns. These critical areas need strong countermeasures that will maintain interdependent system integrity and protect personal data. Notwithstanding, the current work does not provide any systemic treatments to these weaknesses and one of the gravest risks is that it is not followed by all-encompassing protection mechanisms [15].

5. RESULTS AND DISCUSSION

An overview of the literature under review reveals that the building management technologies have been transformed significantly due to the introduction of novel technologies that combine IoT, machine learning, and sophisticated sensor networks. This development facilitates operational effectiveness of HVAC, lighting and security systems and energy conservation based on DSM and renewable incorporation. Automation through BMS is one of the pieces of the comfort of occupants because it allows them to be responsive and data-driven.

In spite of these factors, there still are some issues. The initial cost of installations to be made is big due to the necessity of special equipment and sensors, as well as qualified experts. Increased integration between systems poses a challenge, because the technologies used are heterogeneous, vendors expose their systems using proprietary platforms, and the universal communication protocols are lacking, which also results in vendor lock-in. All of these issues are complex, which leads to costs, absence of standardization increases the struggle of integrating various elements, and all of this affects the reliability of a system and its usability.

Addressing these impediments requires a multifaceted approach. Standardization of protocols and interoperable platforms can reduce integration barriers. Cyber security must be proactive and resilient, incorporating adaptive security frameworks. Leveraging predictive analytics and machine learning can optimize energy performance and system responsiveness. Additionally, human-centric design ensures that automation enhances occupant comfort while maintaining efficiency. Collectively, overcoming cost, complexity, standardization, and security challenges is essential to realize the full potential of intelligent BMS and to advance sustainable, adaptive, and efficient building operations.

6. CONCLUSIONS

Based on the systematic analysis of the included literature, approximately 50–60% of studies employ AI and ML techniques. These approaches are favored for their ability to predict, optimize, and detect faults through analysis of complex building data, thereby enhancing operational efficiency and occupant comfort. However, they are constrained by high data requirements, computational costs, and implementation complexity.

Around 25–35% of studies focus on IoT integration and communication protocols, which are essential for real-time data acquisition and remote control. While foundational for efficient operations, this reliance introduces challenges in data security, interoperability, and the initial costs associated with deploying sensor networks.

Yet, smaller growing segment, approximately 10–15%, explores advanced simulation methods such as Digital Twins and multi-agent optimization systems. These approaches enable in-depth performance analysis and adaptive control, though they are often limited by model validation complexity and higher development overhead.

Simpler rule-based or hardware-centric systems remain relevant for basic applications due to their lower cost and ease of deployment, but they lack adaptability to dynamic building conditions. AI/ML approaches address this limitation but introduce new challenges related to data dependency and operational complexity.

The evolution of BMS is strongly driven by AI/ML and IoT technologies, offering transformative potential for sustainable, adaptive, and efficient building operations. To fully realize this potential, persistent method-specific challenges must be addressed. Future research should prioritize the development of standardized, secure, interoperable, cost-effective, and human-centric solutions, enabling BMS to achieve high performance while remaining accessible, resilient, and user-focused.

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