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Performance and energy optimization of building automation and management systems: Towards smart sustainable carbon-neutral sports facilities

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ABSTRACT

Sports facilities (SFs) consume massive energy given their unique demand profiles and operation requirements. Intelligent and effective solutions are necessary to tackle the matter of facilities' sustainability and efficiency. Promoting efficient and environmentally sustainable SFs is pivotal towards environmentally friendly and socially resilient cities. There is a lack of systematic literature review focused on the progress in SFs operation, sustainability, and energy optimization. To the best of the authors' knowledge, this research presents the first review article addressing the research gap in building operation management and optimization for SFs compared to other types of buildings and SFs located in hot climatic zones compared to cold ones. The topic's significance is highlighted with emphasis on the climatic zone and the characteristics of SFs. A comprehensive review and in-depth discussion of existing solutions are presented. Limited studies covered the management and optimization of SFs for the past five years compared to residential and commercial buildings, and 71% of them were for facilities located in cold regions. About 45% of the surveyed works targeted swimming pools since they are the most popular SFs' type with the highest energy consumption per usable area. 39% of the reviewed studies employed simulation-based approaches to investigate the subject, 26% used artificial intelligence and machine learning, and 35% utilized optimization algorithms and other standard approaches. The limitations of those works and the prospects in energy and operation optimization of SFs are presented. The latter includes deploying evolving typologies such as deep learning, developing modular solutions that can be integrated into existing technologies, and deploying renewable energy systems for sustainable facilities. Finally, the active role of SFs in energy markets is discussed.

1. Introduction

The world is witnessing significant growth in energy consumption driven by the increased world population, economic growth, and modernization and technological development. In 2017, fossil fuels generated more than half of the electricity worldwide, comprising 64.5% of the global electricity generation among other cleaner sources [1]. These plants are economical and reliable for providing electricity over long periods. However, it aggravated the controversial dilemma of global warming as large amounts of CO_2 are released, driving climate change and the consequent environmental concerns [2].

According to the international energy agency (IEA), the buildings sector accounts for more than one-third of the total energy consumption worldwide and nearly 40% of the total direct and indirect CO_2 emissions [3]. In 2019, the highest level of CO_2 emissions due to electricity use and air conditioning systems in buildings was recorded [4]. It can be due to the growing energy demand for heating and cooling with the current extreme weather events. The primary energy consumers in buildings are heating, ventilation, and air conditioning (HVAC) systems with about 40% of the total building energy; lighting systems with 11%; major utilities and appliances such as domestic water heating, refrigerators, freezers, and others, comprising 18%, and the remaining is accounted for consumption in miscellaneous areas such as internal equipment and electronics [5] (Fig. 1).

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Nomenclature

AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
ANN	Artificial Neural Network
BAMS	Building Automation and Management System
BIM	Building Information Modeling
BPNN	Back-Propagation Neural Network
CCTV	Closed-Circuit Television
CFD	Computational Fluid Dynamics
CO2	Carbon Dioxide
CO	Carbon Monoxide
DHW	Domestic Hot Water
DL	Deep Learning
DRL	Deep Reinforcement Learning
EIA	U.S Energy Information Administration
EV	Electric Vehicle
GA	Genetic Optimization
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IoT	Internet of Things
ML	Machine Learning
MOO	Multi-Objective Optimization
NN	Neural Network
OPT	Optimization Algorithms
P2P	Peer-to-Peer
PID	Proportional Derivative Integral
PSO	Particle Swarm Optimization
PV	Photo-Voltaic
RES	Renewable Energy System
RL	Reinforcement Learning
SF	Sports Facility
SM	Simulation
SVM	Support Vector Machine
WS – BA	Weighted Sum Bat Algorithm
XAI	Explainable AI

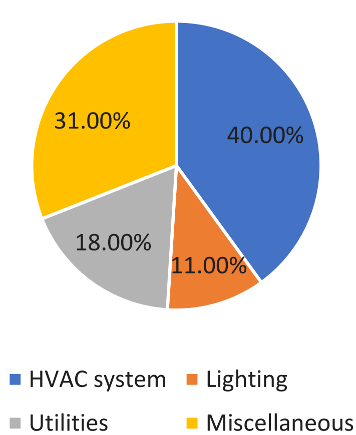


Fig. 1. Breakdown of energy consumption in the buildings sector [5].

The U.S energy information administration (EIA) revealed that the buildings' electricity share of the total energy consumption will nearly double between 2018 and 2050 [6]. The increase in the total buildings' electricity consumption for the past decade was the highest in Asia with a total increase of 40%. Africa came second with 19%, then South and North Americas with 12% and 4% increase, respectively, and the total electricity increase was the least in Europe with only 0.6%.

Energy optimization and operation management of buildings have been handled extensively for common building types as covered in the following review papers: in [7] for computational intelligence techniques for HVAC systems, in [8] for improving the energy performance of residential buildings, in [9] for the different strategies for HVAC energy saving, in [10] for HVAC scheduling techniques for efficient and effective building' operations, in [11] for modeling techniques used in building HVAC control systems, in [12] for residential net-zero energy buildings, and in [13] for energy saving in HVAC systems of underground metro stations.

Additionally, the efficient and effective management of buildings' operation in terms of other aspects is equally important such as occupants' thermal comfort and well-being (i.e., [14–16]), and services' qualities and sustainability (i.e., [17,18]). Ultimately, all aspects (i.e., energy use, users' content and health, sustainability) of buildings' operations are correlated and are to be jointly managed to achieve a decent trade-off. For instance, the authors in [19] covered – among other points – the role of the users' interaction in achieving energy-efficient operation and a thermally comfortable environment in buildings.

1.1. Sports facilities versus other types of buildings

The Architecture, Engineering, and Construction (AEC) sector is highly wasteful and inefficient in energy use. Sports facilities (SFs), being notable buildings, consume a massive amount of energy. They are characterized by special energy and water demand profiles, unique use schedules with steady low usages during the off-season and rapidly high usages during sports events, unique comfort and ventilation requirements given the high occupancy levels and the intensive type and level of activities involved, and encompassing various spaces with different sizes, characteristics, and requirements. That is, the facility's services/systems are operated more heavily. Hence, they consume more energy to meet the requirements of the users' comfort, health, and safety and the requirements of the sporting event/activity (e.g., lighting, broadcasting, water heating). A brief comparison between the different types of buildings is presented in Table 1.

1.2. Energy consumption and sport tourism in the middle east

Buildings' electricity use in the Middle East – characterized by its hot arid climate – has increased by about 29% between 2010 and 2018, specifically by 35% in the Gulf region. In addition, the region has witnessed a rise in sports tourism initiatives as the number of secured mega sporting events has increased in the past few years, such as the 2021 FIFA Arab World Cup, 2022 FIFA World Cup, and 2030 Asian Games. The number of SFs in Qatar, for example, has increased by 25% between 2011 and 2016, with most of them being football stadiums [20].

It will impact the energy supply and demand in the region since SFs are known for their high energy demand profile. Studies revealed that sports and recreation buildings are responsible for around 10% of the annual energy consumption in Europe, and they represent about 8% of the building stock in some countries and regions [21]. Moreover, the energy used in a single 90-minute football match is sufficient to operate a residential building for a whole year [22].

1.3. Motivation and aim

Optimizing the operation and electricity use in SFs is substantial given the global increased energy use, specifically for SFs located in regions with high dependency on fossil oil for its generation. More informed and adapted interventions have become crucial to cope with the emerging societal challenges around safety and sustainability in SFs. Unlike other buildings, research works in SFs energy, performance and operation management and optimization are scarce [27]. Therefore, the goals of this survey paper are:

Table 1
A comparison between the different types of buildings.

Building type	BAMS type	Use	Characteristics	Example
Residential	Simple system for basic requirements for inhabitants' well-being and comfort	Dwelling	Limited user flows, light operations, and causal equipment/appliances.	Houses
Commercial	Inclusive system for closed-circuit television (CCTV) surveillance, lighting, air ventilation and conditioning	Commerce	Year-round operation, frequent peak periods, frequent and considerable users flow	Shopping malls, office buildings
Industrial	Sophisticated system for centralized automation and management	Industries	Involve limited and consistent users flow, energy-intensive and delicate machinery and processes associated with health, social, and environmental risks	Factories, power stations
Sports	Advanced system for extensive lighting, air conditioning, broadcasting, and surveillance and security	Sporting events and activities	High seasonal usage patterns, high users flow, encompass various space types, require specific visual conditions and broadcasting requirements	Stadiums, sports centers

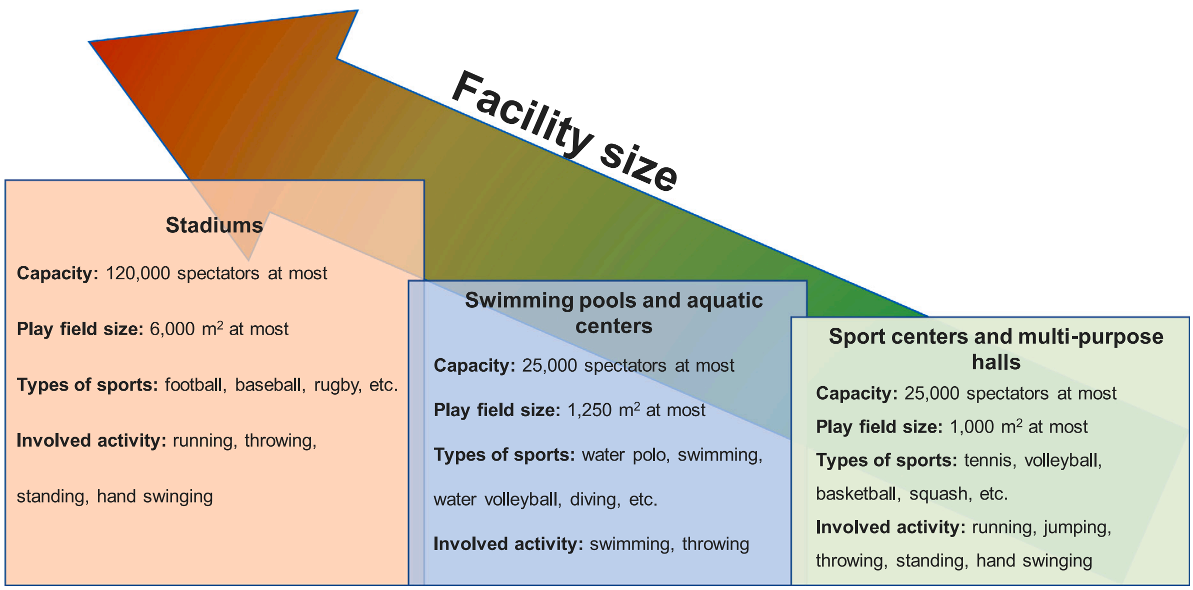


Fig. 2. Overview of the various typologies of SFs [23–26].

- addressing the research gap regarding energy and operation management and optimization for SFs compared to other types of buildings,
- addressing the importance and significance of energy management and optimization of SFs in general and for those located in hot climate regions in particular,
- presenting a comprehensive review on existing solutions for SFs energy and operation management and optimization,
- identifying the limitations and constraints in addition to the research prospects and improvements in energy efficiency and operation optimization of SFs.

The main contributions of this paper are:

- presenting a comprehensive survey of studies targeting the management and optimization of SFs mainly for their energy consumption and the performance of their building automation and management system (BAMSs). A generic taxonomy is defined to classify them based on the type of the SF, the approach used, and the objective of the study.
- presenting an analysis and an in-depth discussion about the surveyed works to emphasize the importance of the management and optimization of sports-related buildings in the context of their types and geographic locations, and highlighting the state-of-the-art works' shortcomings and limitations in same context.
- presenting the current trends and future research directions towards improving the operation, efficiency, reliability, and sustainability of SFs revolving around deploying innovative and advanced techniques for their operation management and optimization, and modular and scalable solutions with simple and adequate integration requirements with the existing technologies.

The remaining of the paper is organized as follows. In Section 2, the characteristics of SFs are presented. Then, the research methodology is presented in Section 3. In Section 4, the conducted literature review is provided, while Section 5 presents the discussion and the statistical analysis of the complied survey. Finally, prospects and conclusions are presented in Sections 6 and 7.

2. Typologies and characteristics of sports facilities

SFs have distinctive energy demand profiles compared to other types of buildings. The energy demand depends on several factors such as the type of sports activity, the operating time of the facility, the season of the year, and the geographical location of the facility [28]. It manifests the complexity of the required interventions and reforms in SFs and their management systems to address the safety, efficiency, and sustainability concerns. This section presents the popular SFs and the main elements of their BAMSs.

2.1. Types of sports facilities

Fig. 2 demonstrates the various typologies of the SFs characterized by their size, capacity, and types of sporting activities. Further descriptions are presented in the subsequent sections.

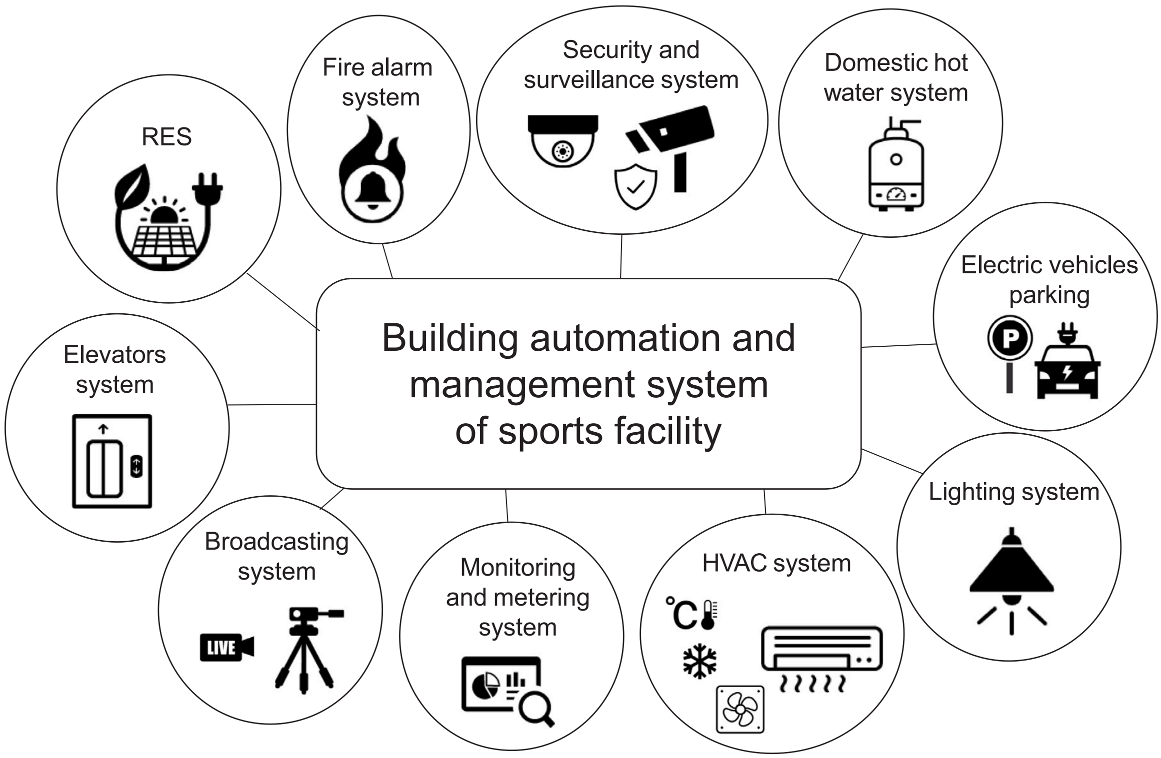


Fig. 3. Overview of a typical BAMS of SFs.

2.1.1. Stadiums

Stadiums are considered one of the most sophisticated buildings worldwide as they take up numerous and vast spaces and require extremely high energy for operation. Therefore, adopting suitability measures and strategies in the design and operations of stadiums is imperative towards improving their prosperity and efficiency. Stadiums' energy usage is substantial even though they are infrequently operated [29]. They have extensive lighting requirements, air conditioning, broadcasting, etc. The three primary spaces in stadiums are the playing field, the concourses, and the supplementary spaces such as the offices, toilets, etc. In the absence of outdoor air conditioning, lighting and broadcasting systems are the most significant contributors to total energy consumption.

2.1.2. Swimming pools

Aquatic centers are the second most popular type of SFs, which host different water events, including races, diving, and water polo. They encompass several spaces such as changing rooms, toilets and shower rooms, offices, and others. Under nominal operation, it is estimated that their energy consumption constitutes 55% for air conditioning and ventilation, 33% for pool water heating, 9% for lighting system and electrical equipment, and 3% for the DHW system [30]. The energy demand is higher for outdoor swimming pools in the winter season due to the increased water heating requirement.

2.1.3. Sport centers

This type of SFs includes indoor and outdoor tennis courts, squash courts, indoor football halls, volleyball courts, basketball courts, training halls, sports arenas, gymnasiums, sports cultural centers, etc. Similarly, they have special air conditioning and lighting requirements, but their energy demand is comparatively lower than stadiums and swimming pools, given their user flow and type of sporting activity. According to [28], typical sports courts use 68% for air conditioning and ventilation, 30% for lighting and electrical equipment, and 2% for domestic hot water systems.

2.2. Building automation and management systems (BAMS) of sports facilities

A typical BAMS of a SF is demonstrated in Fig. 3. This configuration may vary for different SFs based on their size, location, involved activities, etc. Additionally, each component directly or indirectly contributes to the overall efficiency, sustainability, operability, and incurred expenses of the facility.

2.2.1. Heating, ventilation, and air conditioning (HVAC) system

The HVAC system is responsible for conditioning the space and controlling the air quality to maintain users' thermal comfort, safety, health, and productivity. The air conditioning requirements of SFs are delicate as they encompass large spaces of different types such as offices, changing rooms, indoor and outdoor training areas, etc. Adequate temperature and air quality control are essential for the comfort, health, and performance of athletes in particular as well as for other users and spectators. Moreover, the energy usage should be optimum as the HVAC system is known to be the most energy consumer in buildings [5].

2.2.2. Lighting system

SFs require special considerations in the design and control of the lighting system as SFs involve delicate and various activities in large spaces, with high ceilings, open areas, and/or vast glazed areas. Therefore, adequate space's light quality and a comfortable environment should be ensured for athletes and users with minimum energy usage. In addition, the lighting requirements for the various activities that can be performed in the space should be met [31].

2.2.3. Domestic hot water (DHW) system

A DHW system provides human end-use hot water to fixtures in toilets' taps, showers, and other user appliances demanding hot water. It typically consists of boilers, water storage tanks, control systems, and water pumping and piping systems [32].

2.2.4. Renewable energy system (RES)

A RES aims to partially supply the facility with clean energy, which may consist of a storage battery system, solar electrical system, and others. It helps reduce the reliance on non-renewable resources such as fossil fuels for electricity generation and improves facility sustainability [33].

2.2.5. Electric vehicles (EVs) parking

As the popularity of EVs continues to grow, their parking/charging stations are installed in new and existing infrastructures, among which are SFs. Although the link between the EVs market and sports may not be immediately apparent, greening stadiums is a growing trend in the sports world [34]. Towards supporting the transition to EVs and promoting cleaner transport options, EVs parking in SFs has many benefits because SFs involve a considerable number of people gathered to attend a live event for a sustained period. Administering the necessary infrastructure for EVs' users among the sports fans provides them a place to park and the ability to charge their car while at the event. Nevertheless, facilities' managers must heed the grid capacity for energy management of the EVs charging stations and the other facilities' services.

2.2.6. Broadcasting system

Mega sporting events are hosted in SFs, involving prolonged press and broadcasting activities. The broadcasting system includes much electrical equipment such as control systems, conventional cameras and robotic systems, transmitters and receivers, broadcasting and production systems, and others [35].

2.2.7. Fire alarm system

Fire safety is essential in SFs since they occasionally handle large numbers of users in extended venues and spaces. It involves the consideration of users' health and safety, and the facility sustainability and restoration costs. It may include mechanisms promoting the following: fire prevention for fire-hazardous areas such as kitchen areas and spaces involving extensive electrical and heat source equipment, evacuation management for conducting prompt and effective evacuation implementation, and fire extinction system for prompt and effective elimination of the fire cause [36].

2.2.8. Security and surveillance system

The security and surveillance system in SFs is imperative because this involves a considerable number of users and great publicity and exposure. It helps defer and mitigate any irreversible jeopardy to the users, sporting event management, or the facility [37,38].

2.2.9. Others

Additional systems/services may be used in SFs, such as grass irrigation systems, grass heating systems, battery systems, backup electricity generators, fuel tanks, elevators systems, and motorized curtains/windows control systems. The architecture of SFs' BAMSs depends on the sophistication level and the operational requirements.

3. Research methodology

The methodology shown in Fig. 4 was followed to ensure a well-founded literature review. The research questions were defined with precise scope in alignment with the research objective. The objective is to address the research gap and significance of operation management and optimization for SFs and identify the considerations, limitations, and research prospects in energy efficiency and operation optimization of SFs. The scope of the review was defined as follows:

- The effective solutions and techniques that can be developed to tackle the matter of SFs sustainability and efficiency employing the different optimization techniques,
- The consideration of the distinctive features of SFs (e.g., energy demand, use profiles) given their geographical location, activity type, and operating time.

The review was based on searching academic electronic databases for peer-reviewed journal articles and conference publications about SFs energy and operation optimization spanning several decades. The major challenge was capturing and including the relevant research publications given the limited conducted studies. The following academic search engines were used: Mendeley (www.mendeley.com/search), ScienceDirect (www.sciencedirect.com), Scopus (www.scopus.com/home), and Google Scholar (scholar.google.com). The literature search was carried out using relevant keywords with the appropriate utilization of logical operators, which are: (1) the type of SF (e.g., stadium, swimming pool), (2) the components of the building management system (e.g., HVAC system, lighting system), (3) the application objective (e.g., control, thermal comfort, management), (4) climate zone (i.e., hot climate, cold climate), and (5) other keywords such as optimization, saving, efficiency.

The electronic databases were scanned based on the selected keywords by publications' titles, keywords lists, and abstracts with no timed constraints. The initial screening of the publications was conducted by skimming through the abstracts and conclusions to determine the relevance of the study to the research objective. Publications selection was made according to the research scope. Only studies concerning the development, implementation, or investigation of solutions for the sustainability and efficiency of SFs' operation were considered. Non-relevant studies to the scope of the review were removed to maintain a reliable focus. The majority of the search results were relevant for the following reasons: the scope of the review is strict and precise, and studies about SFs' management and optimization are limited and recently evolving.

Based on the filtered publications, a taxonomy aligned with the research scope was devised to administer the structure of the compiled literature review. The relevant publications were analyzed in-depth by going over their conducted method and experiments and the results and discussion section to inspect their approaches and findings towards addressing the underlying research objective of the presented literature review. Data extraction was conducted by inspecting the objective of each study in the filtered publications, the proposed approach to achieve the objective, and the reported outcomes, limitations, and potential improvements. Brief schematic and descriptive detailing of the approaches followed were provided, and critical and comparative analyses were conducted. Finally, tabulated and graphical data representations were used to summarize and interpret the results, and the conclusions and recommendations were presented accordingly.

4. Literature review

This section presents the conducted literature review based on the taxonomy shown in Fig. 5. The main aspects are SFs' types due to their distinctions, utilized approaches, and the objective of the works. The research studies' objective towards the management and optimization of the operation and performance of SFs is categorized as follows:

1. Implementations for performance improvement, by investigating and applying energy-saving implementations, and enhancing and optimizing the provided service,
2. The development of advanced designs of the BAMS's sub-systems for improved performance and operation,
3. The development and utilization of estimation and predictions models that can assist in enhancing the operation and performance of the BAMSs,
4. The development of effective BAMSs' control schemes that tend to outperform the conventional/existing ones,

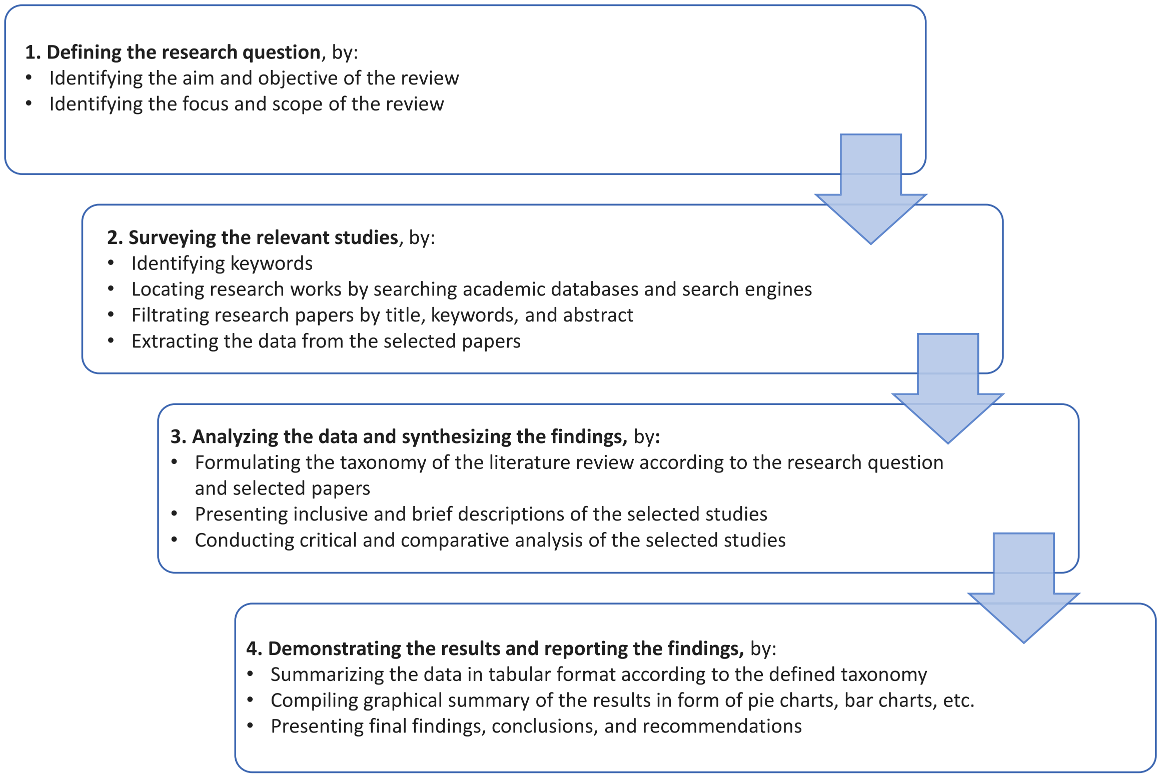


Fig. 4. Research methodology for the presented literature review.

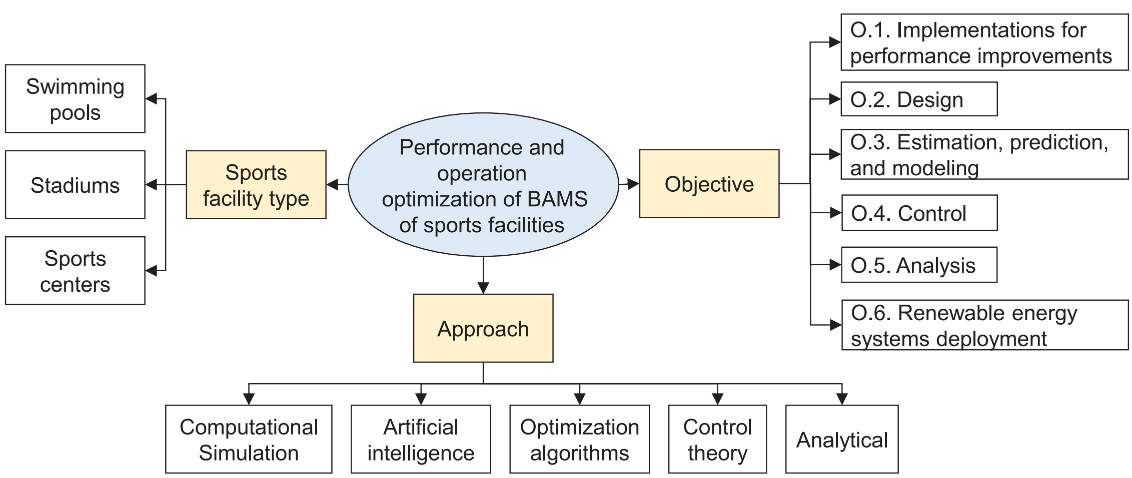


Fig. 5. Taxonomy of the presented literature review regarding optimization of SFs' operation and performance.

5. Analysis by carrying out detailed examinations of aspects related to the system function and operation such as efficiency, reliability, effectiveness, influential parameters, etc.,
6. Deployment of RESs by investigating the adaptability and feasibility of implementing supplementary clean energy generation sources to improve the efficiency and sustainability of the facility.

That is, the research about managing and optimizing the operation of SFs' BAMSs towards efficient and sustainable facility covers both or either of the following tasks: (i) facility's planning (e.g., design, layout, configuration), and (ii) facility's operation (e.g., control). It relates to both the BAMS as a tool and the sub-systems/services monitored/regulated by the BAMS towards improved automation and management of the facility in terms of efficiency, sustainability, and other performance aspects. For instance, items 2 and 6 from the list above are planning-orientated for services handled by the BAMS. Item 4 is associated with the BAMSs' configuration, while items 1, 3, and 5 can be for the facility's planning and/or operation.

The following subsections present a hierarchical survey of the current research works based on the taxonomy in Fig. 5, starting with the approach used, the type of the SF, and finally, the work objective. Tables 2–5 provide a summary of the review for the different approaches deployed (i.e., simulation (SM), optimization algorithms (OPT), artificial intelligence (AI), others) based on the work objective (O.1, …, O.6), facility type (i.e., swimming pool, stadium, sports center), tool/algorithm used, climate conditions of the SF (i.e., cold, warm, hot), and the publication year.

Table 2
Summary of existing works utilizing simulation (SM)-based optimization for performance management of the BAMS of SFs.

Ref	Objective	Obj. description	Facility	Approach	Climate	Task	Year
[39]	O.3	Energy modeling	Sports center	SM - Energy Plus	Cold	Planning and operation	2015
[40]	O.6	Solar and geothermal systems deployment	Stadium	SM - Design Builder	Cold	Planning	2018
[41]	O.1	Energy saving implementations	Swimming pool	SM - TRNSYS	Cold	Operation	2020
[42]	O.1	Energy saving implementations	Swimming pool	SM - TRNSYS	Cold	Operation	2021
[43]	O.1	Energy saving implementations	Swimming pool	SM - Energy Len	Cold	Operation	2010
[44]	O.5	Thermal load analysis	Swimming pool	SM - N/G[a]	Cold	Operation	2017
[45]	O.1	Energy saving implementations	Swimming pool	SM - TRNSYS	Cold	Planning	2018
[28,30]	O.1	Energy saving implementations	swimming pool	SM - DOE-2	Cold	Planning	1998
[46]	O.1	Energy saving implementations	Swimming pool	SM - IDA ICE	Cold	Operation	2021
[47]	O.1	Energy saving implementations	Sports center	SM - STELLA	Cold	Planning	2016
[48]	O.1	Energy saving implementations	Swimming pool	SM - EPS-r	Cold	Operation	2016
[49]	O.6	Geothermal system deployment	Swimming pool	SM - TRNSYS	Cold	Planning	2018
[50]	O.1	Ventilation system optimization	Swimming pool	SM - ANSYS Fluent 17.2	Cold	Planning	2018
[51]	O.4	Management system control	Swimming pool	SM - TRNSYS	Cold	Operation	2019
[52]	O.3	Energy modeling	Swimming pool	SM - TRNSYS	Cold	Planning and operation	2020
[53]	O.6	Solar-combi system deployment	Swimming pool	SM - N/G[a]	Cold and hot	Planning	2020
[54]	O.1	Energy saving implementations	Sports center	SM - TRNSYS	Cold and hot	Planning and operation	2019
[55]	O.6	Solar collectors deployment	Swimming pool	SM - TRNSYS	Warm	Planning	2019
[56]	O.6	Solar and wind systems deployment	Stadium	SM - HOMER	Warm	Planning	2016
[57]	O.2	Stadium roof design	Stadium	SM - AIRPAK	Warm	Planning	2020
[58]	O.5	Thermal comfort analysis	Sports center	SM - IES	Warm	Operation	2013
[59]	O.5	Lighting system analysis	Sports center	SM - DIALux	Warm	Planning	2019
[60]	O.5	SM - Thermal comfort analysis	Stadium	SM - OpenFOAM	Hot	Operation	2021
[61]	O.3	SM - Energy modeling	Sports center	SM - LABVIEW	Hot	Planning	2008

[a]N/G: Not given.

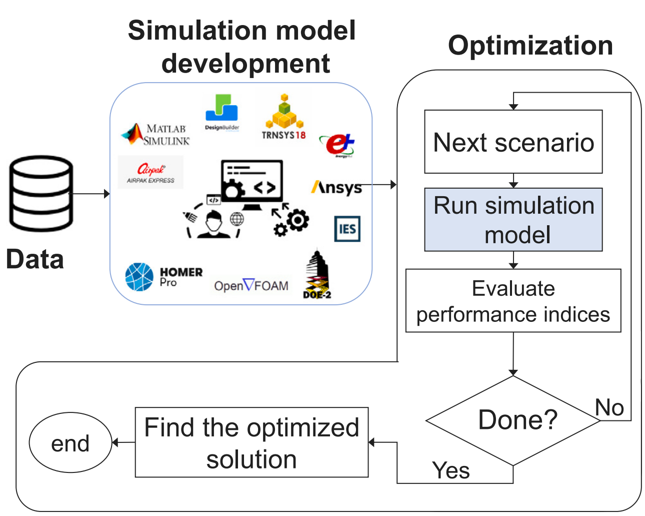


Fig. 6. Overview of the workflow of simulation-based optimization.

4.1. Computational simulation

Simulation-based optimization is an iterative improvement process using numerical simulation for finding optimal solutions for the problem under study, as demonstrated in Fig. 6. Computer-based simulations are conducted iteratively by evaluating one scenario at a time to provide information about the system's behavior. Each scenario represents a selection of a set of the system's variables undergoing optimization. At each iteration, the process moves closer to the optimum solution [39]. Several software tools are used for simulation-based optimization, such as Design Builder, Energy Plus, MATLAB/Simulink, TRNSYS, DOE-2, and others. The following subsections cover the existing works of simulation-based optimization of SFs summarized in Table 2.

4.1.1. Stadiums

O.2. Design of a retractable roof: Retractable roofs in a stadium were assessed in [57] using computational fluid dynamics (CFD) simulation to investigate the energy-saving potentials considering the external weather conditions.

O.5. Analysis of thermal comfort: In [60], a CFD analysis of the thermal comfort of fans and athletes was presented on a stadium with a centralized HVAC system given the variations in the ambient conditions and the duty cycle of the HVAC system. Steady-state mathematical models were employed to demonstrate the thermal process.

O.6. RESs deployment: The use of RESs for electricity generation was investigated in [56] towards reducing operational and maintenance costs via computational simulation. The optimal configurations of RESs were mainly organized by photo-voltaic (PV) arrays, wind turbines, and battery storage units. The potential implementations in a stadium to achieve energy saving by RESs were investigated in [40]. A series of dynamic simulations using Design Builder were conducted to deploy roof PV systems for electricity generation and a geothermal/biomass plant for heating and cooling of the conditioned space.

4.1.2. Swimming pools

O.1. Implementations for performance improvement: A study was presented in [41] to identify the optimal heating system measures that achieve energy savings while maintaining the heating demands of the pool. Computational simulations using TRNSYS were conducted to investigate saving strategies, which achieved 21.2% energy savings. Strategies for microgrid energy management and control were investigated in [42] for energy self-sufficiency and savings in a swimming pool. A TRNSYS model was used to conduct the dynamic simulation. In [43], a range of control strategies and heat insulation measures capable of achieving an energy consumption reduction of about 20% for the Wales National Pool were explored employing Energy Len software. In [48], a simulation-based control optimization approach was presented for the HVAC system of swimming pools using ESP-r simulation tool resulting in 7.4% energy reduction. In [50], CFD simulation was utilized to optimize the efficiency of swimming pools' ventilation systems by investigating different air distribution concepts. However, the study lacked practical validation.

In [28,30], energy conservation was investigated, and practical and cost-efficient solutions were proposed for optimized energy usage and users' comfort using DOE-2 software. The potentials of heat reuse in liquid-cooled data centers in swimming pools were explored in [45] using a TRNSYS. The simulation model was utilized to find the servers' optimal layout to reuse the excess heat for pool water heating. In [46], the energy usage of pool ventilation systems was evaluated by examining the effect of reducing the supply air flow rate on the annual energy consumption.

O.3. Estimation, prediction, and modeling: In [52], a pool thermal energy model that captures the evaporation and other heat losses was presented. The model's validity was tested using practical data, and dynamic simulation was used to demonstrate its usefulness in solving complex thermal situations such as the energy usage of indoor swimming pools.

O.4. Control of management system: In [51], employing TRNSYS simulation, model predictive control was used to implement an early switch-off strategy in indoor swimming pools equipped with hybrid heating systems that consists of solar systems and conventional water boilers to improve the energy efficiency and integration of the solar systems.

O.5. Analysis of thermal load: A thermal design assessment was carried out in [44] for an outdoor swimming pool considering the environmental and climatic changes towards promoting efficient management of the pool. Mathematical modeling and simulation were used to conduct the study.

O.6. RES deployment: In [49], a feasibility study for deploying the geothermal technology for an indoor swimming pool was presented using a TRNSYS model considering the water evaporation heat losses and others from the pool surface. While in [53], a technical and economic feasibility study of using solar-combi systems in swimming pools was demonstrated employing computational simulation. Even though this can be highly conditional on the annual fluctuation and magnitude of the thermal power demand, solar-combi systems were proven to be excellent options capable of securing an annual thermal energy coverage of 50%–55% of the overall demand. In [55], employing a TRNSYS-based model, it was found that the use of solar thermal collectors for outdoor swimming pool heating applications in regions with a warm climate was technically and economically viable. It achieved adequate temperature regulation of the pool and considerable operating cost savings.

4.1.3. Sport centers

O.1. Implementations for performance improvement: In [47], a study was presented on the utilization of waste heat recovery technology in a sports center where a high demand for hot water in showers applies. The proposed approach was cost effective especially when there is sufficiently high-water volume flow. However, further research is required to enable the application of heat recovery technology for facilities with low water volume. A cluster of passive and active measures for energy saving in a SF was presented in [54] that was optimized through the computational simulation using TRNSYS of their annual operation achieving overall energy savings of over 83% annually.

O.3. Estimation, prediction, and modeling: In [39], energy cost models were developed for energy planning of an air-supported indoor sports hall and analyzing the potential energy management schemes to achieve efficient and proper indoor environment regulation. In addition, Energy Plus was used to analyze energy efficiency measures, and it demonstrated a helpful tool for HVAC system sizing and energy planning for similar halls. A LABVIEW-based framework was demonstrated in [61] for power and energy usage estimation in sports centers given the requirements of general lighting, air-conditioning, water, and motive power. However, the generalization of the proposed tool for other facilities was lacking and the validation of the mathematical models used.

O.5. Analysis of thermal comfort: In [58], the thermal comfort and ventilation quality of a naturally-ventilated sports hall was investigated using practical data and computation simulations. The results were analyzed to devise viable strategies for low-cost environment conditioning that maintain adequate thermal comfort levels.

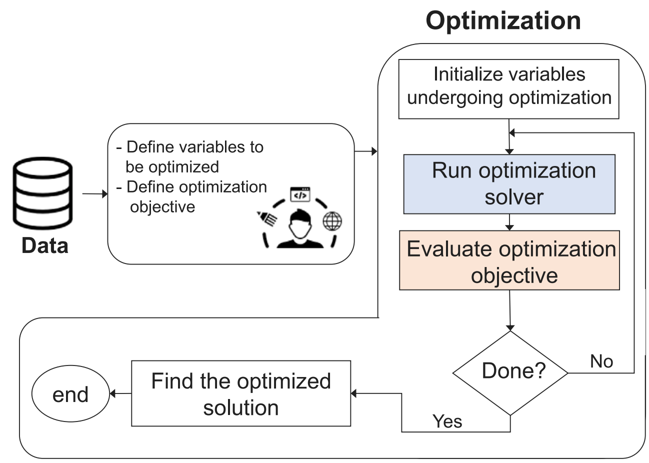


Fig. 7. Overview of the workflow of the use of optimization algorithms.

O.5. Analysis of lighting systems: An analysis of a squash court's lighting system was presented in [59] according to the different levels of play for renovation and refurbishment purposes. The existing lighting system was simulated using DIALux evo, and the power consumption and the light power density of the existing system were analyzed.

4.2. Optimization algorithms

Optimization algorithms such as genetic optimization (GA) particle swarm optimization (PSO) are more advantageous than empirical or simulation-based approaches for their evolutionary parallel search abilities and flexibility in objective function formulation. They result in optimized solutions, with one drawback being the high computational overhead proportional to the problem complexity. They have been used to optimize the design and operation of SFs as presented in the following subsections and summarized in Table 3. Fig. 7 demonstrates the workflow of the process.

4.2.1. Swimming pools

O.1. Implementations for performance improvement: In [67], the PSO algorithm was used for heat pump system design to reduce its life-cycle energy consumption. While in [71], the multi-objective optimization algorithm was applied for optimizing the solar heat pump system given two optimization objectives: minimizing the annual life-cycle cost of the system and maximizing the users' comfort level. TRNSYS and MATLAB were used to assess the energy-savings potential. In addition, outdoor swimming pools' operation during the winter was investigated in [65] by deploying the techno-economic optimization for the pool heating system design. The work aimed to minimize the system's life-cycle cost while ensuring the pool users' thermal comfort. Simulation experiments were conducted using MATLAB and TRNSYS by applying single-objective and double-objective optimizations using GA. The same research group proposed utilizing multi-objective optimization using GA for the same purpose in [66].

4.2.2. Sports centers and stadiums

O.1. Implementations for performance improvement: Building information ing (BIM)-based energy optimization was demonstrated in [69]. The BIM model was utilized to obtain the electricity consumption of the HVAC system, and multi-objective GA was applied to optimize the consumption of a sports center.

O.2. Design of lighting systems: The GA was deployed in [62, 63,72] for optimizing an outdoor football stadium's lighting system design towards saving the lighting system's energy use compared to

Table 3
Summary of existing works utilizing optimization (OPT) algorithms for performance management of the BAMS of SFs.

Ref	Objective	Obj. description	Facility	Approach	Validation tool	Climate	Task	Year
[62]	O.2	Lighting system design	Stadium	OPT - GA	AGI32	Cold	Planning	2014
[63]	O.2	Lighting system design	Stadium	OPT - GA	MATLAB	Cold	Planning	2015
[64]	O.2	Lighting system design	Sports center	OPT - GA	N/G[a]	Cold	Planning	2003
[65]	O.1	Heating system optimization	Swimming pool	OPT - techno-economic - GA	MATLAB and TRNSYS	Cold	Planning	2020
[66]	O.1	Heating system optimization	Swimming pool	OPT - multi-objective - GA	MATLAB and TRNSYS	Cold	Planning	2020
[67]	O.1	Heating system optimization	Swimming pool	OPT - PSO	N/G[a]	Cold	Planning	2008
[68]	O.2	Lighting system design	Sports center	OPT - WS-BA	MATLAB	Cold	Planning	2020
[69]	O.1	Building management optimization	Sports center	OPT - GA	MATLAB	Cold	Operation	2017
[70]	O.2	Design - sensor placement	Stadium	Optimization solver	MATLAB	Cold	Planning	2016
[71]	O.1	Heating system optimization	Swimming pool	OPT - GA	MATALB and TRNSYS	Warm	Planning	2018
[72]	O.2	Lighting system design	Stadium	OPT - GA	MATLAB	N/G[a]	Planning	2014

[a]N/G: Not given.

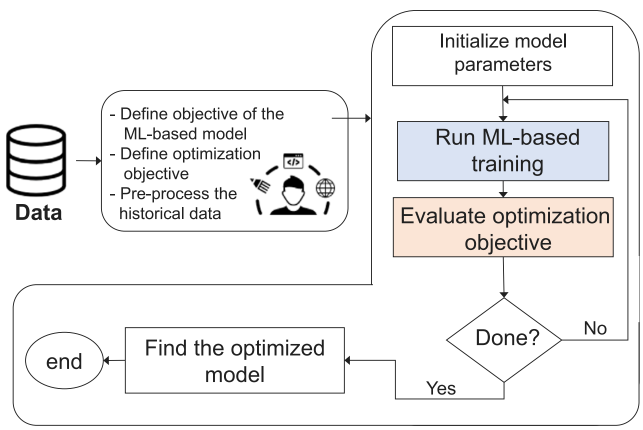


Fig. 8. Overview of the workflow of the development of ML-based models.

the conventional approach. Additionally, GAs were applied for lighting systems' design optimization concerning the illuminance level and uniformity across the space in [64]. They were demonstrated on two case studies: an outdoor tennis court and a football field, and in [68] using weighted sum bat algorithm (WS-BA) to jointly optimize the vertical and horizontal aiming angles for the luminaries in a tennis court.

O.2. Design for sensors placements: An optimization solver was used in [70] to evaluate the measuring performance of sensor placement combinations using a performance index based on statistical features given that accurate measurements of the indoor conditions are crucial for an effective performance of the monitoring and control system of SFs.

4.3. Machine learning and artificial intelligence

AI and machine learning (ML) algorithms such as support vector machine (SVM), neural networks (NNs), regression and statistical analysis, fuzzy logic have been deployed in several applications for the management and optimization of BAMSs. As demonstrated in Fig. 8, they are developed using the historical data of the building under study to achieve a defined objective or perform a particular task. They are data-dependent, and the advancement in the technologies deployed in BAMSs made accessing buildings' data easier. A summary of the existing works utilizing ML and AI for performance optimizing the BAMS of SFs is presented in Table 4.

4.3.1. Stadiums

O.1. Implementations for performance improvement: In [78], using deep belief networks, a study was presented to optimize the control strategies for energy saving. While in [76], energy savings potentials for the grass heating system of a football stadium were evaluated using statistical analysis tools. In [85], energy-savings of 56% during the winter season were achieved in a football stadium's grass heating system after experimenting with a variety of control heuristics using simple statistical methods with NNs used to predict the soil temperature evolution. An active energy management system was proposed in [77] for complete monitoring of the electrical signals of a stadium's BAMS. An ANN-based control system was developed for managing the lighting system and the air conditioners in the outdoor and indoor areas. In [89], K-means clustering algorithm was used to optimize the design of an intelligent BAMS to achieve integration of automation, digitalization, and information management towards overall energy, water, and cost savings.

O.3. Estimation, prediction, and modeling: In [79], a NN-based prediction model for the thermal environment in an ample space was presented for a stadium utilizing the information about the indoor environment and users. It facilitates the control of HVAC systems in stadiums and similar facilities.

O.4. Control of lighting systems: In [90], the application of an intelligent lighting control system was investigated by characterizing the lighting requirements for the different sports events in stadiums. A lighting demand analysis algorithm was proposed employing a gray-scale modulation model and a NN-based lighting control system.

4.3.2. Swimming pools

O.3. Estimation, prediction, and modeling: An ANN was utilized in [80] to predict energy consumption and thermal comfort level towards the management and control of an indoor swimming pool. In [81], an ANN-based framework was used for component sizing optimization using multi-objective optimization (MOO) for a heating system for outdoor swimming pools. In [83], the energy consumption of circulating pumps of residential swimming pools and their impact on the peak load were analyzed. A novel load monitoring and estimation method was proposed using a weighted difference change-point regression model to predict their energy consumption.

In [84], NNs were used to predict the water evaporation rate of an indoor swimming hall. The NN-based model demonstrated a notable capability in handling the complexity of the system model and its associated uncertainties. A hybrid model of the thermal behavior of pools was proposed in [86], considering the regional climatic conditions utilizing thermodynamic models and ANNs. ANNs were utilized to integrate the climatic inputs in the overall thermal model. However, the generalization capability of the proposed approach for different climatic data cannot be guaranteed due to the dependency of the NNs on training data representation.

O.6. Analysis of sustainability assessment: In [82], a holistic sustainability assessment of aquatic centers in cold climates was presented utilizing fuzzy logic. Even though the use of fuzzy logic was proven effective in evaluating the system performance based on experts' assessment, the study lacked substantial efforts to practically implement and evaluate rigorous benchmarking analysis.

Table 4
Summary of existing works utilizing ML and AI for performance management of the BAMS of SFs.

Ref	Objective	Obj. description	Facility	Approach	Validation tool	Climate	Task	Year
[73]	O.4	Management system control	Sports center	AI - NN and GA	Practical experiment	Cold	Operation	2014
[74]	O.3	Energy modeling	Sports center	AI - Regression analysis	Practical data	Cold	Planning and operation	2012
[75]	O.1	System fault diagnosis	Sports center	AI - NN	Practical data	Cold	Operation	2021
[76]	O.1	Energy saving implementations	Stadium	AI - Statistical analysis	Practical data	Cold	Operation	2015
[77]	O.1	Energy saving implementations	Stadium	AI - NN	Experimental setup	Cold	Operation	2016
[78]	O.1	Energy saving implementations	Stadium	AI - Deep Belief Network	Practical experiment	Cold	Operation	2018
[79]	O.3	Thermal process modeling	Stadium	AI - NN	Simulation	Cold	Planning and operation	2018
[80]	O.3	Energy modeling	Swimming pool	AI - NN	Practical data	Cold	Operation	2014
[81]	O.3	Energy modeling	Swimming pool	AI - NN	Practical data	Cold	Planning	2020
[82]	O.5	Analysis of sustainability assessment	Swimming pool	AI - Fuzzy logic	N/G[a]	Cold	Planning	2021
[83]	O.3	Energy modeling	Swimming pool	AI - Regression analysis	Practical data	Cold	Operation	2018
[84]	O.3	Thermal process modeling	Swimming pool	AI - NN	Practical data	Cold	Planning and operation	2014
[85]	O.1	Energy saving implementations	Stadium	AI - Statistical analysis and NNs	Practical data	Cold	Operation	2015
[86]	O.3	Thermal process modeling	Swimming pool	AI - NN	Simulation	Warm	Planning and operation	2013
[87]	O.3	Users flow prediction	Sports center	AI - SVM-BPNNs	Simulation	Warm	Operation	2020
[88]	O.4	Management system control	Sports center	AI - NN	Simulation	Hot	Operation	2021
[89]	O.1	Energy saving implementations	Stadium	AI - K-means clustering	N/G[a]	N/G[a]	Operation	2020
[90]	O.4	Lighting system control	Stadium	AI - NN	N/G[a]	N/G[a]	Planning	2018

[a]N/G: Not given.

4.3.3. Sport centers

O.1. Implementations for performance improvement: In [75], deep learning models for fault diagnosis of SFs management systems were utilized to improve the HVAC system's sustainability and provide preventive maintenance. The study demonstrated a considerable amount of potential to predict failures in the facility's building management system, but with limitations related to data availability and feedback collection.

O.3. Estimation, prediction, and modeling: In [74], a heating energy-demand forecasting model was established based on the building envelope information using regression analysis that facilitates the management and performance evaluation of SFs. In [87], an intelligent sports center management system was developed employing a hybrid model combining SVM with back-propagation NNs (SVM-BPNNs) for predicting the users' flow in the center that was utilized to manage the facility better. The proposed framework demonstrated a fruitful initiative for exploiting the big-data-based strategies and the internet of things (IoT) technologies in the building management system in the facility.

O.4. Control of management systems: In [73], a modular optimization framework was proposed using a HTCondor system. It comprises three interactive modules using simulation-based optimization, GA-based optimization, and ANN-based optimization for optimized control of a SF in terms of energy use and thermal comfort levels. The proposed framework was proven effective and can be extended to other comparable problems. In [88], a NN-based model predictive control system was proposed for temperature setpoint selection to improve the SF's management in terms of energy consumption and indoor thermal comfort levels.

4.4. Others

This section includes other approaches that have been deployed for the management and optimization of SFs employing control theory, analytical methodology, physical and mathematical modeling, etc., as summarized in Table 5.

4.4.1. Stadiums

O.4. Control of lighting systems: In [100], an intelligent lighting control system was developed for a stadium using a proportional derivative integral (PID) incremental control model and the Karatsuba multiplication model. It was implemented using a multi-level fuzzy evaluation model.

O.5. Analysis of energy use: An analytical study was conducted in [94] to determine the energy consumption patterns for the different components of the system utilizing the operational energy data of the HVAC system of a football stadium. The study aimed to provide insights for designers and facility managers towards performance improvements of the stadium operation in the form of load shedding while maintaining the systems' service quality.

O.6. RES deployment: The study in [102] aimed to analyze football stadiums' energy-saving potentials using the wind's kinetic energy. By utilizing wind energy to satisfy the energy requirement for these stadiums, it was estimated that 23.376 tons of CO2 per match could be saved.

4.4.2. Swimming pools

O.1. Implementations for performance improvement: Energy-saving potentials for uncovered domestic swimming pools were investigated in [93] by analyzing the performance of solar collectors under reduced flow rate conditions, and savings of up to 80% of the electrical energy were achieved. The research was carried out using theoretical and experimental analysis on pool solar collectors, and it lacked the application for large-scale pools. In [97], the options for reducing thermal heat needed for swimming pools' temperature regulation towards promoting overall energy savings were investigated. The practical data of existing local facilities were used to carry out the study, and the analysis demonstrated economic and energy savings compensating initial costs of the facilities.

O.3. Prediction, estimation, and modeling: A thermal performance prediction model of outdoor swimming pools was presented in [98] employing physics and thermodynamics laws. The model was validated using practical data. It can be used to predict the swimming pool's water temperature and estimate their heating plant capacity under active use.

O.6. Analysis of energy use: In [99], a study was conducted to investigate the energy performance of aquatic centers utilizing the facility operational data regarding the physical and occupancy characteristics. The study aimed at identifying the interrelationship between the various factors that contribute to the overall energy consumption.

4.4.3. Sport centers

O.1. Implementations for performance improvement: In [96], a comfort-based monitoring approach was developed utilizing the thermal comfort model developed in [95] to provide a tool for facility managers for monitoring and control.

O.3. Prediction, estimation, and modeling: In [92], an approach for forecasting energy consumption was proposed using a hybrid of physical and statistical-based techniques that produced an exploitable model for potential uses. A study for quantitative estimation of the

Table 5
Summary of existing works utilizing other approaches for analysis and optimization of performance management of the BAMS of SFs..

Ref	Objective	Obj. description	Facility	Approach	Validation tool	Climate	Task	Year
[91]	O.4	Air quality control	Sports center	Control theory	Simulation	Cold	Operation	2011
[92]	O.3	Energy modeling	Sports center	Model-based	Simulation	Cold	Planning and operation	2015
[93]	O.1	Energy saving implementations	Swimming pool	Analytical	N/G[a]	Cold	Operation	2012
[94]	O.5	Energy use analysis	Stadium	Analytical	Practical data	Cold	Planning and operation	2015
[95]	O.3	Thermal comfort modeling	Sports center	Analytical	Simulation	Cold	Operation	2014
[96]	O.1	Energy saving implementations	Sports center	Model-based	Simulation	Cold	Planning and operation	2014
[97]	O.1	Energy saving implementations	Swimming pool	Analytical	Practical data	Cold	Operation	2017
[98]	O.3	Thermal process modeling	Swimming pool	Model-based	Practical data	Cold	Planning and operation	2019
[99]	O.5	Energy use analysis	Swimming pool	Analytical	Practical data	Warm	Planning	2014
[100]	O.4	Lighting system control	Stadium	Control theory	Simulation	Warm	Operation	2018
[101]	O.5	Thermal comfort analysis	Sports center	Analytical	Experimental setup	Warm	Planning	2021
[102]	O.6	Wind power system deployment	Stadium	Analytical	Practical data	Hot	Planning	2020

[a]N/G: Not given.

thermal comfort level in sports centers was presented in [95] towards developing comfort-based metering and energy control systems. It included a standard component involving the indoor environment variables and a subjective component to measure the users' thermal environment perception and level of satisfaction.

O.4. Control of air quality: In [91], a dynamic demand-controlled ventilation strategy for CO2 control in a sports center was applied. It demonstrated an overall energy saving of 34% compared to the conventional control strategy.

O.6. Analysis of thermal comfort: In [101], the performance of a naturally ventilated sports hall in the humid season was analyzed with respect to the thermal comfort levels and the indoor air quality, considering the air parameters and air pollutant concentrations of this site as key factors. The users' perspectives about the indoor environment were considered by conducting a questionnaire survey.

5. Trends analysis and discussion

Figs. 9–15 demonstrate the statistics of the complied literature in terms of the climatic conditions of the SF under study, the work objective, the type of the SF, and the followed optimization approach.

On the contrary to residential and commercial buildings, the work conducted for the management and operation of the BAMS of SFs is quite limited and yet recently started to evolve. On Scopus, which is the largest database of peer-reviewed scientific journals, books, and conference proceedings in the fields of science, technology, social sciences, and others, a search using the keyword “energy management of buildings” yielded 2148 journal articles in Energy subject in the past five years. The following was observed: (1) 67% and 36% of the articles were concerned with “residential buildings” and “commercial buildings”, respectively, and (2) less than 1% of them were related to “sports facilities”, “swimming pools” or “stadiums”.

This is intuitive given that commercial and residential buildings comprise most of the buildings stock worldwide. Residential buildings are used for dwelling purposes with low occupancy density and low user flow. Commercial buildings include office buildings, shopping malls, warehouses, retail, etc., which operate all-season according to particular operation and activity schedules and with relatively high occupancy density and user flow. SFs have special operating schedules as they experience extremely high user flow and occupancy density during specific periods. Even though they operate less frequently, they utilize extensive energy given the operation requirements due to the extremely high number of users.

The distribution of the surveyed works based on publication type and date is shown in Fig. 9. We found 66 research works covering performance and energy management and optimization of SFs consisting of 85% journal articles and 15% conference publications, and about 60% were carried out in the past five years. Energy efficiency problematic and environmental impacts of SFs started to gain substantial attention in the past decade due to the increase in the number of sports buildings, the global realization of the buildings sector's energy consumption challenge, and the aggravated climate change dilemma.

5.1. Energy consumption of SFs and the regional context

The energy consumption of facilities located in regions with cold to average weather conditions is due to heating loads in contrast with hot climatic zones where mainly cooling is required. Subject to the technologies utilized, heating is more energy-intensive than cooling. Nevertheless, for cold regions, it is only required for less than six months of the year, while economical air conditioning is sufficient during the rest of it due to the amiable weather conditions.

However, regions characterized by round-the-year hot and humid weather conditions require energy-intensive air conditioning to meet the cooling demand and maintain the air ventilation requirements. Additionally, energy sources and their sustainability are key factors as power plants can be dependent on solar power, hydro power, wind power, fossil fuel, and many others. The geographic region determines the available natural resources and the technological advancement and popularity, and hence their power generation means. For some regions such as the Gulf region, oil and gas are the primary electricity generation sources, while the clean energy plants are still evolving and not fully exploited.

Fig. 10 shows the distribution of the works based on the climate of the facilities' location. Studies about the management and optimization of SFs located in regions characterized by an overall cold weather condition (e.g., Europe) were extensive, comprising about 71% of the research works. This is attributed to: the relative size of countries in the regions, population concentration, and the development-state of the countries. The cold regions mainly include developed countries with high populations, considerable tourists flow, and popular local and international sporting events. While many of the countries in hot climate regions are developing countries or early developed countries with fewer sports attentiveness. The studies about SFs management and optimization in warm and hot regions are lacking. Nevertheless, it has become essential as the region is witnessing a sports evolution era. Therefore, it is fundamental to put the regional context in perspective and study the application of the SFs' BAMS optimization in general and in terms of energy consumption, particularly for facilities demanding extensive cooling and air conditioning due to extreme weather conditions.

5.2. Approaches for the management and optimization of SFs' operation

Fig. 11 shows the research works' distribution based on the method used. The most popular approach was simulation-based optimization, which was used in around 40% of the research works. It is the traditional approach followed by scholars and designers in BAMSs optimization for design phase and it has been generalized for optimization applications of existing constructions where various scenarios of the problem under study can be examined and investigated.

Fig. 12 demonstrates a summary of the research works based on the approach used versus the purpose of the work. Primarily, studies

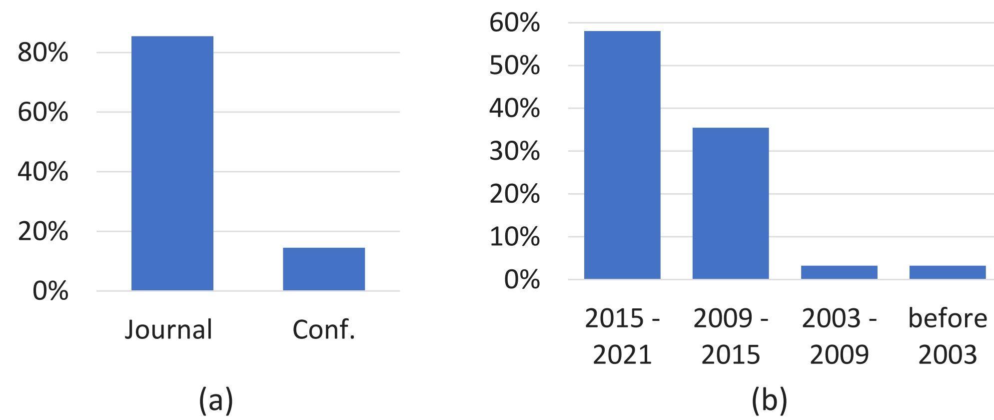


Fig. 9. Distribution of surveyed research works by publication type and year.

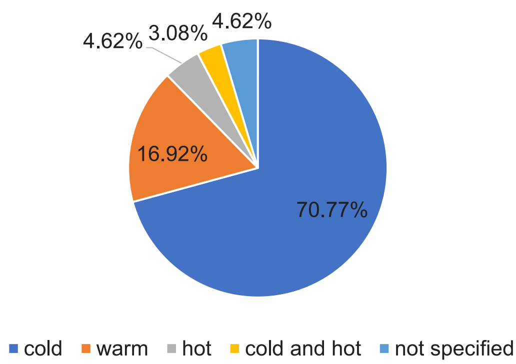


Fig. 10. Disposition of surveyed research works by climate.

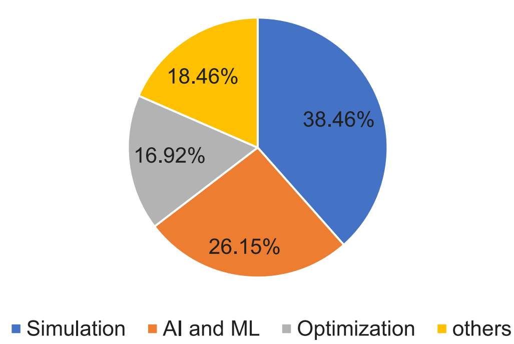


Fig. 11. Disposition of surveyed research works by used method.

consider: (i) planning task aiming to optimize the design, sizing, or layout of the facility or its subsystems/services, (ii) operation task, focusing on optimizing the performance of the facility operation in terms of control, regulation, and management. 50% of works using simulation-based optimization targeted planning such as [40,49,53,55,56] investigating the potential of RESs deployment for reduced energy costs, and [45,50,57,59] for system's layout and design. 40% were for operation tasks as in [42,43,46,48] for optimizing the operation of the facility services for reduced energy use. The investigations were conducted by developing simulation model(s) then performing simulation experiments to conclude solutions' feasibility, optimal design options, or control strategies.

Optimization algorithms were mostly employed for planning, mainly for system's design optimization towards costs reduction, while over 60% of the AI and ML-based studies targeted the optimization of BAMSs' operation, e.g., fault diagnosis [75], control strategies [77], and system's settings [88,89]. Studies using other approaches such as control theory and conventional data analysis covered the tasks of planning and operation evenly (See "Others" in Fig. 12). They are basic and convenient for simple cases, which is exceptional for SFs.

In terms of the objective of the work, Fig. 13 demonstrates a summary for the different approaches. About 44% of the simulation-based optimization-based works were deployed for (O.1) performance improvement implementations of the BAMS of SFs. Computational simulations were conducted to identify optimal design options, practices, measures, or procedures for improved performance and operation in terms of energy consumption (e.g., [41,43,45,48,54]), and ventilation system efficiency (e.g., [50]). 20% and 16% of the works utilizing computational simulation were used for (O.5) conducting analysis related to thermal comfort, energy demand, sustainability, reliability, etc. (e.g., [58,60]), and (O.6) investigating the RESs' deployment (e.g., [49,56]), respectively.

However, this approach is associated with several constraints, which are:

- It requires accurate and reliable models or representations of the component undergoing the optimization. The results and findings are highly influenced by the degree of accuracy and reliability of the models used,
- It is case-specific for the building or component under study. Hence, it has poor flexibility, generalization ability, scalability as models must be developed uniquely for the different problems,
- Proportional to the problem complexity, it is computationally demanding, time-consuming, potentially inefficient, and may result in sub-optimal solutions if the exploration space was not covered sufficiently.

Limited application of computational intelligence techniques for the management and optimization of SFs operation was observed such that optimization algorithms, and ML and AI approaches comprised around 17% and 26% of the surveyed works (Fig. 11), respectively. Optimization algorithms were utilized mainly for design (≈55%), and component sizing optimization (≈45%) (See Fig. 13) as they promote solving for optimized settings or parameters of the evaluated problem given a defined objective. While ML and AI algorithms were primarily deployed for modeling (47%) such as developing prediction and estimation models for energy consumption/demand (e.g.,[74,80]), thermal process (e.g.,[79,84]), etc. Around 35% of the AI and ML-based works were developed for achieving energy savings by optimizing the facility management system.

About 71% of the ML-based approaches employed NNs, which can be attributed to the following reasons: (1) they are data-driven methods that can be developed using historical system data, (2) their ability to model complex functions with high accuracy, and (3) their flexibility and generalization ability in terms of their performance on unseen data. Nevertheless, they require quality and representative training data, and

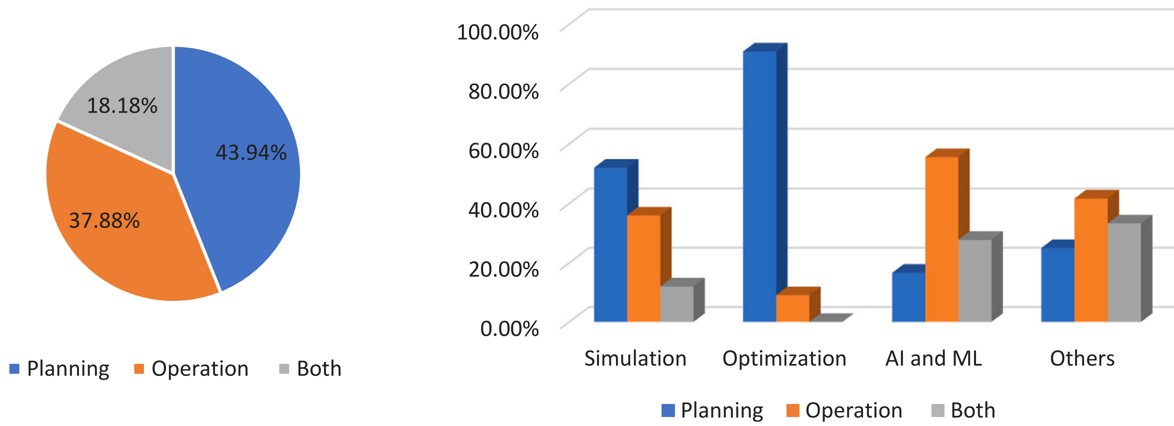
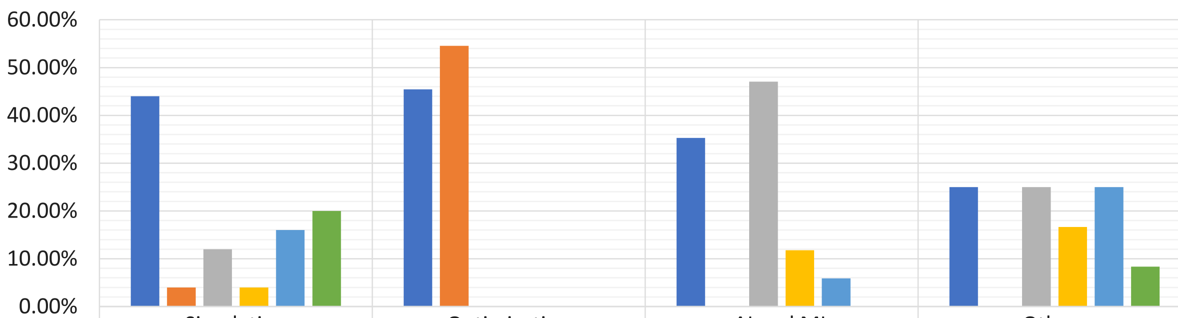


Fig. 12. Summary of surveyed research works based on the task/aspect.



	Simulation	Optimization	AI and ML	Others
O.1	44.00%	45.45%	35.29%	25.00%
O.2	4.00%	54.55%	0.00%	0.00%
O.3	12.00%	0.00%	47.06%	25.00%
O.4	4.00%	0.00%	11.76%	16.67%
O.5	16.00%	0.00%	5.88%	25.00%
O.6	20.00%	0.00%	0.00%	8.33%

Fig. 13. Summary of surveyed research works based on used approach and intended objective.

they can be computationally expensive depending on the complexity of the problem under study.

These approaches are evolving and seem to be more convenient as they tend to be more efficient and yield more optimal results. They have promising potentials for effective application in the AEC sector in light of the advancement of the BAMS technologies. Great prospects have been revealed for the use of the various computational intelligence algorithms for HVAC system optimization and management as presented in [7] and so further studies can be conducted for the application of those approaches in the management of SFs. Additionally, several studies were conducted to investigate the subject by applying control theory and analyzing operational data and representation models. They are basic, require concrete and extensive expert knowledge, and are not scalable. On the other hand, the recently evolving fields of deep learning (DL) (e.g.,[103]) and reinforcement learning (RL) (e.g., [104]) are yet to be explored more thoroughly for applications in BAMSs. Additionally, the applications of explainable AI and blockchain in BAMS of SFs holds great potentials. Further elaboration on these topics is provided in Section 6.

Considering both planning and operation tasks in terms of the management and optimization of SFs is important. More focus on operation-oriented optimization is commendatory as it is more practical and covers both new and existing facilities towards improved performance in terms of efficiency and sustainability. For outdated SFs, planning may be compulsory. Overly, the following characteristics should be considered in the development of management and optimization approaches such that they should be (1) practical, feasible, and easily integrated with the BAMS of existing facilities and new constructions, (2) modular, scalable, and flexible solutions, and (3) comprehensive in terms of achieving energy savings, maintaining adequate service quality in terms of thermal comfort, safety, and health of the facility's users, as well as providing accessible and handy tools for facility and operation managers for online monitoring and management, and offline analysis and screening.

5.3. Objectives of management and optimization and the SF's types

Fig. 14 outlines the objectives of the surveyed works. Most of the studies focused on achieving performance improvements and optimization implementation (O.1) and about 75% of them were conducted for swimming pools. This included implementing energy saving measures and optimizing components of the BAMS (heating system, HVAC system). About 22% of the works targeted establishing prediction and estimation models (O.3) for energy demand, thermal comfort, and thermal process in swimming pools and sports centers that facilitate the development of management and optimization systems. Limited studies were conducted to study the other objectives, which are design, control,

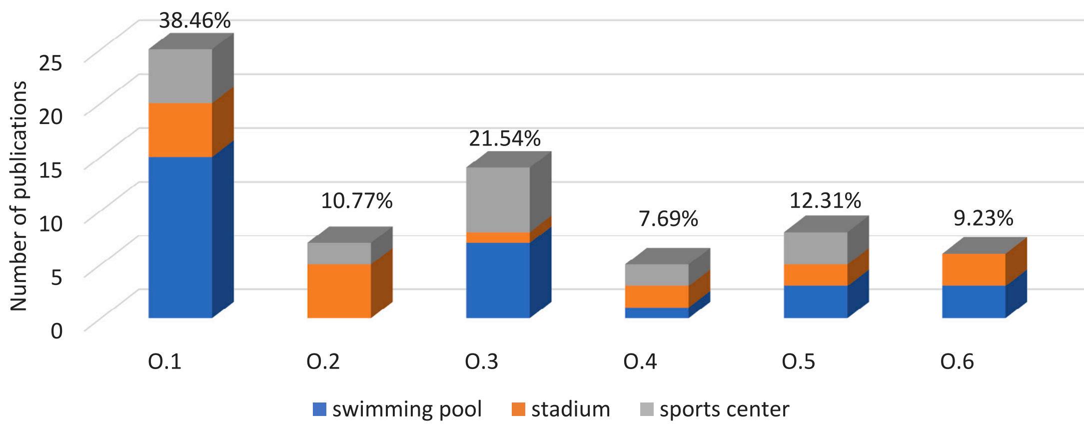


Fig. 14. Overall distribution of surveyed research works based on objective.

analysis, and deployment of RESs with around 10% ±2 works per objective. There is plenty of potential in those areas that is worth exploring especially in terms of utilizing clean, sustainable, and renewable energy generation/dependent systems under the current circumstances.

For the different types of SFs, considerations about their special requirements should be taken as those features determine the specifications and requirements for their management and optimization. Fig. 15(a) presents the distribution of the existing works for the management and optimization of SFs based on their types. Swimming pools are the most popular type with the highest energy consumption per usable area. About half of the works were deployed for swimming pools, mainly in terms their operation's management and optimization (Fig. 15(b)) as they require extensive heating for the pool water temperature regulation to provide adequate thermal comfort conditions for users. For stadiums (Fig. 15(c)), in addition to performance improvements, the focus was achieving optimized design of the lighting systems since sufficient and comfortable levels of illumination for both players and spectators are required. For sports centers (Fig. 15(d)), most of the works covered O.3. Prediction and modeling (≈35%), and O.1. Implementations for performance improvement (≈27%).

6. Future directions

This section presents the future directions regarding the operation of SFs in terms of: (i) the evolving techniques that can be deployed to improve and optimize their operation and performance, and (ii) the potential of SFs' contribution in the energy markets towards tackling their challenges.

6.1. Advanced management techniques

6.1.1. Deep reinforcement learning (DRL)

Utilizing advanced AI approaches can help tackle challenges related to accurate thermal dynamics modeling, spatial and temporal operational constraints for different services, and computational cost and its associated implementation constraints [105]. DRL has the ability to overcome the aforementioned issues. It combines RL and DL, in which RL addresses the issue of computational learning for making accurate decisions by trials and error. For example, when DRL is used to model energy consumption in a specific environment, it continues to learn from the environment, and therefore is able to deal with unpredictable and highly varying power demands [106].

In [107], a DRL-based solution was proposed for optimizing the use of PV for energy production in residential buildings. DRL is attracting significant attention for building indoor comfort's control as discussed in [108]. Additionally, in [109], a DRL model was used to help the building end-users in purchasing more energy at off-peak hours to decrease the energy cost and balance demand and supply. It did not need any prior knowledge about the uncertainty and could appropriately learn the optimum energy management approach using RL.

6.1.2. Explainable AI

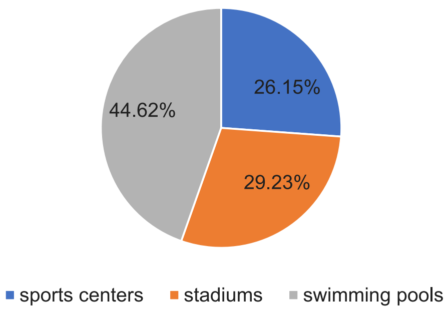
The BAMS technology aims to provide the buildings' managers with control functionalities to manage the indoor conditions, energy consumption, safety and security, etc. Using AI in BAMSs offers the possibility of sustaining comfortable indoor climate, and reducing consumption and cost. However, standard BAMSs are still struggling to satisfy a large public as they lack the full insight and capabilities required for taking advantage of integrated systems [110]. Therefore, it is important to develop advanced BAMSs that help in providing managers with valuable explanations about their BAMSs. It becomes challenging that BAMSs solve the trust issues with their managers/users by using explainable AI (XAI) tools [111,112], which makes the "black-box" ML models used in BAMSs more transparent [113].

Novel BAMSs should be developed, which include improved architectures where existing systems are augmented with an explainable intelligent layer. The latter aims at interpreting the autonomic decisions/values into concepts and identifying causality relations for better explaining the rationale behind the decisions made and the values generated to the managers/end-users [114].

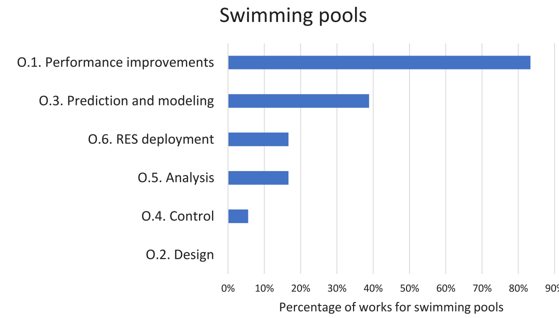
6.1.3. Blockchain

Blockchain is one of the most promising technologies due to its potential applications. It is gaining increasing interest for managing and securing medical platforms [115], IoT operating systems [116], and energy data [117]. It helps improving BAMSs' functionalities by tackling issues related to data security and privacy, and reshaping the energy installations in SFs. Accordingly, blockchain, which is a form of distributed transaction ledger is deployed for tracking and validating changes in BAMSs including access control systems, automation systems, or security/surveillance systems [118,119]. Moreover, BAMSs encompass several IoT sensors and distributed devices connected to a peer-to-peer (P2P) validation network, which are used for tracking end-users occupancy and collect environmental patterns within the facility, and hence enabling the space to be more energy efficient. Considerable privacy concerns emerge due to the large amount of BAMSs' data recorded. Blockchain is suitable for providing security and privacy through implementing secure and private P2P networks.

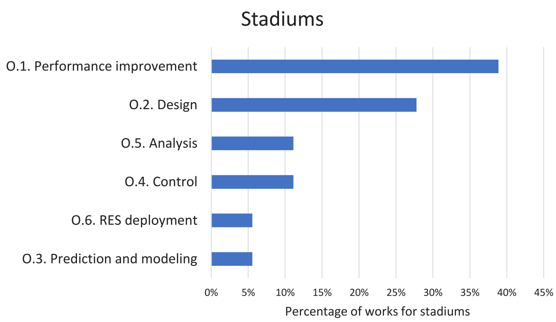
An increasing interest is devoted to developing powerful and reliable blockchain-based BAMSs as in [120] where a novel approach was developed to target the security, privacy, and transparency aspects of IoT sensors. While in [121], a technique that enables to operate a BAMS was developed based on blockchain. It includes (i) the distributed devices to perform the BAMS's automation tasks and generate transaction information; and (ii) a P2P validation network that receives



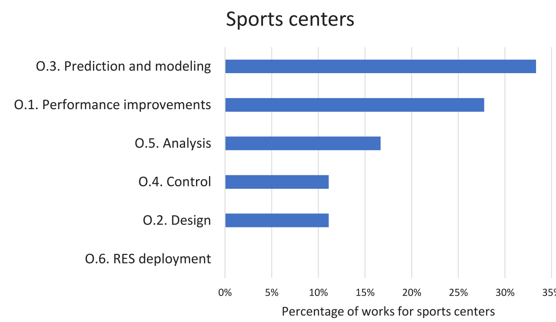
(a) Disposition of surveyed research works by facility type.



(b) Distribution of research works conducted for the optimization of the BAMS in swimming pools by objective.



(c) Distribution of research works conducted for the optimization of the BAMS in stadiums by objective.



(d) Distribution of research works conducted for the optimization of the BAMS in sports centers by objective.

Fig. 15. Summary of the compiled literature review.

transaction information, which is used for generating new ledger inputs for a transaction ledger (based on the transaction information), and distributing the new ledger inputs.

6.1.4. Analytics-driven management software

Strategic planning is crucial to unify SFs' BAMSs, and to deploy big-data-analytics-driven events and management software. Specifically, with increasingly complex buildings and diverse stakeholders, enormous data are collected by BAMSs. Hence, it is essential to design BAMSs incorporating big-data-analytics systems for collecting, organizing, and analyzing data produced by the IoT sensors, and the connected devices and equipment throughout the facility [122]. Moreover, visualization tools are advantageous for providing single-pane-of-glass dashboards. They can be used for offering a clear vision of the operations, and actionable insights occurring through the SFs [123]. Combining big-data-analytics and visualization tools aims at providing new possibilities for greater automation and improving SFs' functions [124].

Using big-data-analytics platforms with ML in BAMSs will help in automating core building operations, and hence optimizing efficiency and performance. Moreover, the continuous mining of historical data and monitoring of current conditions will help in automating the adjustments and adaptations of critical equipment (with reference to different parameters, e.g., the season, air quality, temperature, occupancy patterns, time of the day, etc.) [125,126], detecting and preventing faults [127–129], and predicting energy demand and consumption [130,131], etc. Integrating data analytics, optimization algorithms, and dynamic control theory to harness IoT and edge technologies has been applied towards enhancing SFs' energy management [132].

6.1.5. Behavioral change strategies

Behavioral change strategies were proposed to achieve energy savings in residential and office buildings given that they involve high degree of users' involvement with the building's systems. The arbitrary operation of those systems driven by occupants' preference and requirements can be very inefficient and it attributes to a sizeable variation in building's energy use [133]. SFs, unlike other types of buildings, exhibit an overall regular users' behavior given that the majority of them are spectators restricted to specific areas and with limited interaction with the facility's systems. Moreover, the operation in the large spaces of the facility is controlled centrally, and hence, immune to users' habits or unwanted intervention. However, users behavioral change strategies can be useful when applied to occupants-controlled spaces (e.g., offices) towards minimizing the overall energy consumption, especially during off-season periods where the facilities are less involved with sporting events and likely to exhibit irregular users' behaviors.

Behavioral changes initiatives include (i) eco-feedback, where users are informed of their energy consumption trends leading to increased self-awareness and sense of responsibility, and (ii) social intervention by raising the awareness of the importance and means of energy use reduction [133–135]. A thriving behavioral change strategy is gamification [136], such as the mobile gamification platform proposed in [137] to motivate users in office buildings to adopt energy efficient behaviors whenever possible. It fostered users' awareness and engagement by analyzing context, sending tailor-made messages, and managing peer competition. In [138], a gamification approach was deployed for smart building infrastructures to encourage users to consider personal energy usage by incorporating humans-in-the-loop modeling and creating an interface to allow managers to interact with occupants and potentially prompt energy-efficient behaviors. Additionally, in [139], the authors studied the development of a gamified load management platform that is compatible with BAMSs of residential buildings.

6.2. Sports facilities and energy markets

An interesting aspect is the contribution of SFs in the energy markets. It was studied for residential buildings [140,141] and commercial buildings [142]. The idea is that buildings with smart and green technologies (i.e., RES, EV, etc.) can produce energy and support the energy market. Energy advances, RESs, and progressing building technologies are changing the energy and the building markets, driven mainly by energy and climate dilemma [143].

SFs generally and stadiums in particular have enormous building surface areas, take up vast space, and use advanced BAMSs. Therefore, RESs can be deployed on the facilities' envelops and external spaces, and energy storage systems can be integrated with the main supply grids. This promotes self-sufficiency of SFs and tackles the energy markets' challenges as SFs have large energy demands.

Moreover, the integration of demand response, and renewable-energy generation and storage provides an opportunity to address SFs' active role in energy markets. Even if the capacity of the RESs does not fully meet the demand during events, they help in reducing the electricity demand from the grid. Additionally, they can feed energy into the grid when the facility is not in use [144]. However, the main issue is the added expenses for RESs and energy storage systems installation and maintenance that should be carefully considered by the facilities' managers and owners.

7. Conclusion

SFs have unique characteristics among which are their energy usage profiles and occupancy schedules. Additionally, the regional context determines the sports recognition, technologies used, and energy requirements. Furthermore, SFs' types determine the most operated service(s) and energy consumer(s) in the facility. Considering those distinctions is pivotal to the effectiveness of SFs' management and operation.

Studies on SFs' energy and operation management are scarce, especially for ones located in hot and humid regions. About 44% of the existing works investigated the subject in terms of planning and design, while 38% of them were for operation's optimization and management. Additionally, 39% of the studies employed simulation-based approaches, 26% used AI and ML, 17% utilized optimization algorithms, and 18% used other standard approaches. Even though simulation tools provided basic and disposable solutions to conduct analysis and optimization, other techniques (i.e., optimization and AI-based) that have demonstrated auspicious outcomes in analogous contexts are worth further investigation.

This review called the significance of studies and applications for SFs' energy optimization and operation management, and presented the existing literature, shortcomings, and prospects. The concluding remarks towards improved management of SFs' operation are:

- Further studies should be conducted considering the diverse features of SFs, and the regional context.
- Operation-oriented optimization provides more feasible and functional solutions than planning-oriented.
- Applications of the evolving typologies (i.e., AI, DL) for energy optimization and operation management of SFs should be firmly considered.
- Practical and modular solutions are needed, that can easily be associable with the existing technologies, and maintain acceptable energy consumption and convenient service quality.
- Embracing clean energy sources becomes a must by investigating RESs deployment and initiatives.
- The prospect of the active role of SFs in energy markets to tackle their challenges is worth exploring.

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.

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