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Editorial

Machine Intelligence in Smart Buildings

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Energy efficiency is a key concern in achieving sustainability in modern society. Smart city sustainability depends on the availability of energy-efficient infrastructures and services. Buildings comprise most of the city, and they are responsible for more than two-thirds of global CO_2 emissions and energy use.

The rapid evolution of artificial intelligence (AI) and machine learning (ML) has equipped buildings with an ability to learn. Machine intelligence (MI) has been used to learn patterns of living and behaviors, to thus regulate the use of energies. MI represents a collection or a set of various technologies such as the Internet of Things (IoT), deep learning (DL), deep reinforcement learning (DR), fuzzy logic systems (FLS), digital twins (DW), artificial intelligence (AI), machine learning (ML), and evolutionary algorithms (EA) involving non-linear dynamics, computational intelligence, ideas drawn from physics, physiology, and several other computational frameworks. MI investigates, simulates, and analyzes very complex issues and phenomena in order to solve real-world problems requiring a multidisciplinary approach. MI can be considered as a higher evolution of ML, and a stepping-stone on the roadway to explainable AI (XAI).

This Editorial on "Machine Intelligence in Smart Buildings" includes a collection of ten excellent papers covering different technological aspects of advanced machine intelligence in smart buildings, ranging from intelligent energy predictions based on deep neural networks [1] to occupant predictions based on IoT technologies [2]; from machine learning classifiers for energy efficiency classifications of buildings [3] to building energy management based on digital twin and artificial intelligence approach [4]; from an energy and comfort management optimization approach using evolutionary algorithms [5] to exploring the potentialities of deep reinforcement learning for incentive-based demand response in a cluster of small commercial buildings [6]; from fuzzy control systems for smart energy management in buildings [7] to a systematic review contribution and risk of AI in building smart cities [8]; and finally, unsupervised machine learning for smart building energy inefficiencies through time series [9] and smart electrochromic windows to enhance building energy efficiency and visual comfort [10]. A summary of the content associated with each of the selected papers presented in this Editorial is presented subsequently.

Sadeghi, Sinaki et al. used deep neural networks (DNNs) to forecast heating and cooling loads (HL and CL, respectively) to measure the energy performance of buildings (EPB). The DNNs explored in their study include multi-layer perceptron (MLP) networks, and each of the models studied was developed through extensive testing with a myriad number of layers, process elements, and other data preprocessing techniques. As a result, a DNN was shown to be an improvement for modeling HLs and CLs compared with traditional artificial neural network (ANN) models. To extract knowledge from a trained model, a post-processing technique, called sensitivity analysis (SA), was applied to the model that performed the best with respect to the selected goodness-of-fit metric on an independent set of testing data. There are two forms of SA—local and global methods—although both have the same purpose in terms of determining the significance of independent variables within a model. Local SA assumes that inputs are independent of each other, whereas global SA does not. To further develop the contribution of the research presented within this article, the results of a global SA, called state-based sensitivity analysis (SBSA), were compared with the results obtained from a traditional local technique, called sensitivity analysis about the mean (SAAM). The results of their research demonstrate an improvement over existing conclusions found in the literature, which is of particular interest to decision-makers and designers of building structures.

Floris, Porcu et al. created an Internet on Things (IoT)-based smart building (SB) solution for indoor environment management, exploiting the huge amount of data generated by temperature, humidity, luminosity, and air quality sensors, and performed processing with data analytics and machine learning (ML) techniques to extract useful and interesting insights, which provided the inputs for building optimization in terms of saving energy as well as improving occupants' health and comfort. The proposed solution provided the following main functionalities: monitoring of the room environmental parameters; detection of the number of occupants in the room; a cloud platform where virtual entities collect the data acquired by the sensors and virtual super entities perform data analysis tasks using ML algorithms; and a control dashboard for the management and control of the building. The proposed prototype model tested on 10 days of data and two prediction models were built: a classification model that predicted the number of occupants based on the monitored environmental parameters (average accuracy of 99.5%), and a regression model that predicted the total volatile organic compound (TVOC) values based on the environmental parameters and the number of occupants (Pearson correlation coefficient of 0.939).

An example of how ICT and data science technologies can be applied to evaluate a buildings' energy efficiency is given by Benavente-Peces and Ibadah. They applied ML techniques to classify buildings based on their energy efficiency. Particularly, they focus on single-family buildings in residential areas. In this paper, the capabilities of ML techniques are demonstrated to classify buildings depending on their energy efficiency. Moreover, the authors analyzed and compared the performance of different classifiers. Furthermore, they introduced new parameters which have some impact on the thermal modeling of buildings, especially those concerning the environment where the building is located. They also present insights to ICT and remark on the growing relevance of data acquisition and monitoring of relevant parameters using wireless sensor networks. Additionally, they remarked on the need for an appropriate and reliable dataset to achieve the best results. Finally, they demonstrated that reliable classification is feasible with a few featured parameters.

The potential of digital-twin-based methods and approaches were explored by Agostinelli, Cumo et al. Their research aimed to achieve an intelligent optimization and automation system for the energy management of a residential district using three-dimensional data model integrated with the IoT, artificial intelligence (AI), and ML. The case study focused on Rinascimento III in Rome, an area consisting of 16 eight-floor buildings with 216 apartment units powered by 70% self-renewable energy. The combined use of integrated dynamic analysis algorithms enabled the evaluation of different scenarios of energy efficiency interventions aimed at achieving virtuous energy management of the complex, maintaining the actual internal comfort and climate conditions. Meanwhile, the objective was to plan and deploy a cost-effective information technology (IT) infrastructure able to provide reliable data using the edge-computing paradigm. Therefore, the developed methodology led to evaluation of the effectiveness and the efficiency of integrative systems for renewable energy production from solar energy necessary to raise the threshold of self-produced energy, meeting the near-zero-energy building (nZEB) requirements.

Wahid, Fayaz et al. proposed a hybrid model to maximize energy consumption and user comfort in residential buildings. The proposed model consisted of two widely used optimization algorithms, namely, the firefly algorithm (FA) and genetic algorithm (GA). The hybridization of two optimization approaches resulted in a better optimization process, leading to better performance of the process in terms of minimum power consumption and maximum occupant's comfort. The inputs of the optimization model are illumination, temperature, and air quality from the user, in addition with the external environment. The outputs of the proposed model are the optimized values of illumination, temperature, and air quality, which are, in turn, used in computing the values of user comfort. After the computation of the comfort index, these values enter the fuzzy controllers, which are used to adjust the cooling/heating system, illumination system, and ventilation system according to the occupant's requirement. A user-friendly environment for power consumption minimization and user comfort maximization using data from different sensors, user, processes, power control systems, and various actuators is proposed in this study. The results obtained from the hybrid model were compared with many state-of-the-art optimization algorithms. The results revealed that the proposed approach performed better as compared with the standard optimization techniques.

Deltetto, Coraci et al. explored the economic benefits associated with the implementation of a reinforcement learning (RL) control strategy for participation in an incentive-based demand response (DR) program of a cluster of commercial buildings. For this purpose, optimized rule-based control (RBC) strategies were compared with an RL controller. Moreover, a hybrid control strategy exploiting both RBC and RL is proposed. Results showed that the RL algorithm outperformed the RBC in reducing the total energy cost, but it was less effective in fulfilling DR requirements. DR programs represent an effective approach to optimally manage building energy demand while increasing renewable energy source (RES) integration and grid reliability, helping decarbonization of the electricity sector. To fully exploit such opportunities, buildings are required to become sources of energy flexibility, adapting their energy demand to meet specific grid requirements. However, in most cases, the energy flexibility of a single building is typically too small to be exploited in the flexibility market, highlighting the necessity to perform analysis at a multiple building scale. The hybrid controller achieved reductions in energy consumption and energy costs, by 7% and 4%, respectively, compared with a manually optimized RBC, while fulfilling DR constraints during incentive-based events.

Kontogiannis, Bargiotas, and Daskalopulu present the design and implementation of a fuzzy control system which processed environmental data to recommend minimum energy consumption values for a residential building. This system followed the forward chaining Mamdani approach and used decision tree linearization for rule generation. Additionally, a hybrid feature selector was implemented based on XGBoost and decision tree metrics for feature importance. The proposed structure discovered and generated a small set of fuzzy rules which highlighted the energy consumption behavior of a building based on time-series data of historical operation. The response of the fuzzy system based on sample input data was presented, and evaluation of its performance showed that the rule-based generation was derived with improved accuracy. In addition, an overall smaller set of rules was generated, and the computation was faster compared with the baseline decision tree configuration.

A systematic literature review of 93 articles was conducted by Yigitcanlar, Desouza et al., aiming to provide an insight into how AI can contribute to the development of smarter cities. The results were categorized under the main smart city development dimensions, i.e., economy, society, environment, and governance. The findings of the systematic review containing 93 articles disclose that: (a) AI in the context of smart cities is an emerging field of research and practice; (b) the central focus of the literature is on AI technologies, algorithms, and their current and prospective applications; (c) AI applications in the context of smart cities mainly concentrate on business efficiency, data analytics, education, energy, environmental sustainability, health, land use, security, transport, and urban management areas; (d) there is limited scholarly research investigating the risks of wider AI utilization; and (e) upcoming disruptions of AI in cities and societies have not been adequately examined. Current and potential contributions of AI to the development of smarter cities were outlined to inform scholars of prospective areas for further research.

Talei, Benhaddou et al. identified energy inefficiencies after exploring the cluster results of a single building's HVAC consumption data and building usage data as part of the energy efficiency analysis. Time series analysis and the K-means clustering algorithm were successfully applied to identify new energy saving opportunities in a highly efficient office building located in the Houston area (TX, USA). The paper used 1-year data from a highly efficient Leadership in Energy and Environment Design (LEED)-, Energy Star-, and Net Zero-certified building, showing potential energy savings of 6% when the K-means algorithm was applied. The results showed that clustering is instrumental in helping building managers identify potential additional energy savings.

Cannavale, Ayr et al. reviewed the relevant literature concerning the benefits obtainable in terms of energy consumption and visual comfort, starting from a survey of the main architectures of the devices available today. Electrochromic systems for smart windows make it possible to enhance energy efficiency in the construction sector, in both residential and tertiary buildings. Dynamic modulation of the spectral properties of a glazing, within the visible and infrared ranges of wavelengths allows one to adapt the thermal and optical behavior of a glazing to the everchanging conditions of the environment in which the building is located. This enables appropriate control of the penetration of solar radiation within a building. The consequent advantages are manifold, and are still being explored in the scientific literature. On the one hand, the reduction in energy consumption for summer air conditioning (and artificial lighting) becomes significant, especially in "cooling dominated" climates, reaching high percentages of saving, compared with common transparent windows; on the other hand, continuous adaptation of the optical properties of the glass to changing external conditions makes it possible to set suitable management strategies for smart windows, in order to optimize other conditions to take advantage of daylight within the confined space.

From the perspective of machine intelligence computing applied in smart buildings, these studies endow the corresponding research field with insightful views, methodologies, and techniques, offering alternative ways to effectively improve the energy efficiency, indoor environment, and sustainability of smarter cities.

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