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Editorial

Practical Applications of Model Predictive Control and Other Advanced Control Methods in the Built Environment: An Overview of the Special Issue

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Abstract: This paper summarizes the results of a Special Issue focusing on the practical applications of model predictive control and other advanced control methods in the built environment. This Special Issue contains eleven publications and deals with various topics such as the virtual sensing of indoor air pollutants and prediction models for indoor air temperature and building heating and cooling loads, as well as local and supervisory control strategies. The last three publications tackle the predictive maintenance of chilled water systems. Most of these publications are field demonstrations of advanced control solutions or promising methodologies to facilitate the adoption of such control strategies, and they deal with existing buildings. The Special Issue also contains two review papers that provide a comprehensive overview of practical challenges, opportunities, and solutions to improve building operations. This article concludes with a discussion of the perspectives of advanced controls in the built environment and the increasing importance of data-driven solutions.

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1. Foreword

Many buildings are adopting increasingly complex heating, ventilation, and air conditioning (HVAC) systems to improve their performance and contribute to the decarbonization of the building sector. However, inadequate system controls and suboptimal operation sequences prevent buildings from reaching their full performance potential. Advanced controls are thus required to maximize building performance at low or no capital cost. The field of building operation is undergoing a paradigm shift; buildings are evolving from being passive and reactive, simply responding after a change occurs, to being dynamic and proactive, detecting and correcting inefficiencies, anticipating changes, and adjusting the operation accordingly. The ever-increasing availability of operational data on buildings and the significant advancements in modelling capabilities represent an untapped opportunity to better manage and operate buildings [1].

Advanced control methods such as model-based controls or model predictive controls are widely acknowledged as effective solutions for improving building operation. Despite extensive investigation in the past, widespread adoption has yet to be realized. Existing buildings are inherently imperfect and may present obstacles to the implementation of advanced controls that might not be encountered in simulation studies; these include, among others flaws and inefficiencies in existing controls, a lack of data for critical variables and communication issues with the building automation system or external services [1]. These barriers may significantly affect the development of advanced control strategies and, thus, their deployment in actual buildings. This Special Issue has collected publications that deal with existing buildings and address some of these gaps. It ultimately aims to encourage research and foster the adoption of practical data-driven solutions to improve the operation of existing buildings.

2. The Papers

The Special Issue presents eleven publications tackling various topics related to advanced controls in buildings that are summarized in this section. They have been organized based on the scale of the application, from the sensor level to the supervisory control and predictive maintenance of heating and cooling systems. Figure 1 illustrates the various topics explored in the Special Issue with a word cloud plot based on titles and abstracts.

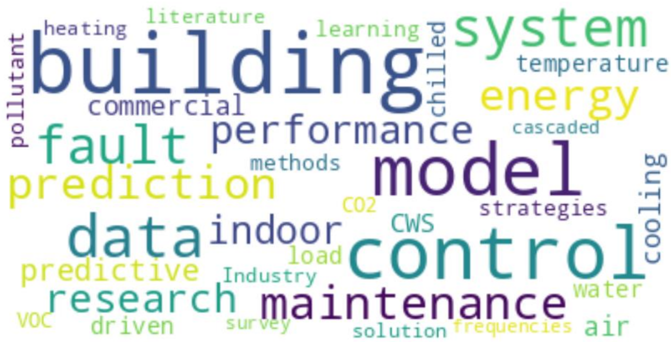

Figure 1. Word cloud plot based on titles and abstracts of research papers published in the Special Issue.

The opening article by Saloux et al. [1] is a perspective paper focusing on current research trends in the field of building operation. The authors explored pressing challenges and identified inefficient local controls, inadequate data availability and quality, communication issues with the building automation system, and the lack of guidelines and standards tailored for controls as critical obstacles to the widespread adoption of advanced controls. According to the authors, cost-effective solutions, successful case studies, and better training and engagement between the industry and research communities could also foster the uptake of advanced controls. They also discussed promising opportunities and highlighted the increasingly important role of modelling for various control applications, as well as the inevitable paradigm shift from building energy efficiency towards decarbonization. Data-driven and data analytics methods (e.g., automated fault detection and diagnosis, predictive maintenance, key performance indicators, virtual sensors and virtual energy meters, thermal and electric energy use breakdown, and automated data labelling), as well as high-performance local controls, occupant-centric controls, and advanced supervisory controls, including predictive control, were identified as promising avenues for improving building performance.

Gabriel and Auer [2] tackled the critical topic of human health and well-being and investigated the virtual sensing of indoor air pollutants using deep learning models. This virtual sensor is an alternative to physical sensors and relies on a long short-term memory (LSTM) neural network model to estimate indoor air pollutant concentrations such as particulate matter (PM), volatile organic compounds (VOCs), and CO_2 concentrations from building automation system data (e.g., temperature, humidity, illumination, noise, motion, and window state), as well as weather conditions and outdoor pollution data. The case study building is a high-rise office building located in Munich (Germany). The authors found that the proposed virtual sensing method is suitable for determining PM and VOCs and is less accurate but still reasonable for estimating CO_2 levels; they also demonstrated the potential for generalization and transfer learning.

Norouzi et al. [3] studied the application of deep learning algorithms to predict indoor air temperatures in educational buildings as part of a broader project toward the development of a digital twin for HVAC systems. They explored five algorithms (extra trees, random forest, multilayer perceptron, LSTM, and convolutional neural networks) along with different sliding windows (i.e., inputs at previous time steps; up to 120 min) and forecast horizons (up to 60 min). They tested their model on seven zones of a university building on the campus of the British Columbia Institute of Technology in Burnaby (British Columbia, Canada). The results showed that deep learning algorithms outperformed tree-based algorithms and can reach an average root mean square error of 0.16 °C.

Irshad et al. [4] developed a novel approach to predict residential building heating and cooling loads in hot arid climates. This approach relies on a shuffled shepherd red deer optimization linked self-systematized intelligent fuzzy reasoning-based neural network. The authors tested their model for the climate of Al-Dhahran (Saudi Arabia) and generated typical heating and cooling load profiles for residential buildings in such climates; for this purpose, they developed a database of 70 buildings with specific characteristics and systems. Simulations showed that the proposed model outperformed conventional methods in terms of various accuracy metrics.

Price et al. [5] presented the implementation of cascaded control architectures for air handling unit chilled water valves at three university campus buildings located at Texas A&M University in College Station (TX, USA). This cascaded control aims to overcome the often-overlooked issue of actuator hunting and targets better tracking and more consistent performance of control loops. This cascaded system only requires one additional line of code to existing control routines in the building automation system and was tested for more than a year in the case study buildings. Field implementation showed 2.2–4.4% energy savings, in addition to reduced operational costs for maintenance and controller retuning.

Morovat et al. [6] investigated model-based control strategies, aiming to unlock the energy flexibility of electrically heated school buildings. These strategies build on data-driven grey-box models to evaluate the optimal duration of building preheating. They were tested in a school building, located near Montreal (QC, Canada), equipped with geothermal heat pumps, hydronic radiant floors, and energy storage systems. The authors tested different resistance–capacitance thermal network models and used the dynamic building energy flexibility index (BEFI) to evaluate the performance. Simulations showed that the energy flexibility can be improved by 40% to 65% during peak demand periods.

Arroyo et al. [7] compared the performance of a model-based predictive control strategy using different types of control-oriented modelling paradigms (white-box, grey-box, and black-box models). The strategy was implemented during a 26-week period in a 6 m^2 test building zone equipped with a thermally active building system (TABS) and located in the Arenberg campus of the KU Leuven University in Heverlee (Belgium). The authors found that there was no significant correlation between prediction and control performance and that "a better prediction performance does not necessarily indicate an improved control performance"; the white-box model performed worse in prediction but led to better MPC performance. They eventually suggested using a modelling approach that combines both physics-based and data-driven methods.

Saloux and Zhang [8] evaluated the performance of three data-driven model-based control strategies to improve the cooling performance of commercial and institutional buildings: (a) chiller sequencing, (b) free cooling, and (c) supply air temperature reset. These strategies rely on simple yet accurate models, calibrated with operational data, and aim to be readily implementable in existing buildings using simple control rules. They were applied to an existing 36,000 m^2 commercial building in Montreal (QC, Canada) and simulations showed that the three measures together could reduce building cooling energy by 12% and cooling system electric energy by 33%.

Almobarek et al. [9] performed a systematic review of the literature on predictive maintenance applications of chilled water systems (CWS) and focused on two aspects: (1) the identification of operational faults and (2) the methods to better predict them. The authors covered chillers, cooling towers, circulating pumps, and terminal units and pinpointed the lack of studies tackling the entire CWS (rather than focusing on specific components); they also suggested that more attention should be given to cooling towers and pumps. The authors provided exhaustive lists of system faults and predictive tools for control, discussing operational parameters and data collection considerations. They finally identified research gaps such as the lack of information about the fault type or the data collection and the need for maintenance programs to go beyond fault detection and prediction and address the faults in the actual system.

Almobarek et al. [10] conducted an industry survey to complement the aforementioned systematic review outputs [9]. This survey targets the identification and frequencies of more operational faults and fault solutions for chilled water systems. The authors contacted

761 maintenance officers in different commercial buildings in Riyadh (Saudi Arabia) and compiled a total of 304 responses. The authors presented exhaustive tables of the faults and their solutions for each component (chillers, cooling towers, pumps, and terminal units). They also investigated the optimal data sampling time and history for the major faults, aiming to create better datasets to train machine learning models for predictive maintenance applications.

Finally, the closing article by Almobarek et al. [11] addressed the need for maintenance programs raised in the aforementioned system review [9] to implement predictive maintenance in existing buildings. They proposed a methodological framework to describe the requirements (drawings, measuring devices, and operational data), develop machine learning algorithms, and conduct quality control (ensure proper operation and correct faults). Within this framework, a decision tree model was developed to predict faults and was implemented in a university building in Riyadh (Saudi Arabia); the results showed that the developed model improved the fault prediction by more than 20% in all chilled water system components compared to the existing control system.

3. Perspectives and Conclusions

The eleven articles published in the Special Issue showcase just a few of the practical data-driven solutions that can be developed to encourage the widespread adoption of advanced controls in buildings. In the context of climate change, building performance targets are slightly reoriented from energy efficiency to decarbonization, where energy flexibility plays a pivotal role [1]. Virtual sensors [2] are emerging as a credible, cost-effective alternative to physical sensors for tracking critical variables, while data-driven modelling is becoming the cornerstone of many advanced control strategies [1]. Ongoing efforts to improve models for indoor air temperature [3] and building energy loads [4] are and will remain essential to strengthening confidence in data-driven solutions. These solutions could be applied at various scales [1], from setpoint tracking [5] to the adjustment of building indoor conditions [6] and the optimization of heating and cooling system operations [6–8,10,11], with different levels of complexity, such as model-based controls [6,8], predictive control [7], and predictive maintenance [10,11].

These publications illustrate the opportunities to optimize the operation of real-world buildings but also the efforts needed to take building controls to the next level. A tremendous amount of work is still required in various areas to improve the current scientific knowledge and enable the widespread adoption of practical advanced control solutions on a large scale.

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