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Optimizing legacy building operation: The evolution into data-driven predictive cyber-physical systems

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ABSTRACT

Fossil fuels serve a substantial fraction of global energy demand, and one major energy consumer is the global building stock. In this work, we propose a framework to guide practitioners intending to develop advanced predictive building control strategies. The framework provides the means to enhance legacy and modernized buildings regarding energy efficiency by integrating their available instrumentation into a data-driven predictive cyber-physical system. For this, the framework fuses two highly relevant approaches and embeds these into the building context: the generic *model-based design methodology for cyber-physical systems* and the *cross-industry standard process for data mining*. A Spanish school's heating system serves to validate the approach. Two different data-driven approaches to prediction and optimization are used to demonstrate the methodological flexibility: (i) a combination of Bayesian regularized neural networks with genetic algorithm based optimization, and (ii) a reinforcement learning based control logic using fitted Q-iteration are both successfully applied. Experiments lasting a total of 43 school days in winter 2015/2016 achieved positive effects on weather-normalized energy consumption and thermal comfort in day-to-day operation. A first experiment targeting comfort levels comparable to the reference period lowered consumption by one-third. Two additional experiments raised average indoor temperatures by 2 K. The better of these two experiments only consumed 5% more energy than the reference period. The prolonged experimentation period demonstrates the cyber-physical system-based approach's suitability for improving building stock energy efficiency by developing and deploying predictive control strategies within routine operation of typical legacy buildings.

1. Introduction

1.1. Motivation

On a global scale, buildings are major consumers of energy that produce significant amounts of greenhouse gas emissions. For example, US building stock (residential and commercial) accounted for 41% of the US' primary energy use in 2010 [1], of which fossil fuels served 75%. In Europe, the ODYSEE and MURE databases indicate that buildings accounted for 40% of the EU-28 final energy use in 2012, with residential buildings being responsible for two-thirds of the total building consumption [2]. These figures stress that improving the energy efficiency of building stock is paramount to address resource scarcity and realize international climate preservation goals. Different studies of buildings over their life-cycle phases show that for typical buildings, irrespective of the type of construction, the operational phase accounts for up to 90% of lifetime energy use [3]. For low energy buildings, the operation phase's proportion still reaches 50%. Buildings use 60% of their consumption for thermal end uses: space heating, space cooling, and water heating [1]. Thus, one promising direction for improving the energy efficiency of buildings is to focus on improving the operational strategies of their thermal systems by predictive analytics – an approach complementary to refurbishment measures.

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1.2. State of the art

Current research on predictive building control strategies achieves high increases of performance by relying on predictive models learned from sensor data:

- [4] optimizes the operation of a multi-zone heating, ventilation and air conditioning (HVAC) system using neural networks for room temperature and energy consumption, taking relative humidity and room temperature as the input. The system controls the supply air's static pressure set-points to minimize energy subject to comfort conditions. The study's approach to validation is computational, based on data of a single day. Energy savings range between 2% (most strict comfort constraints) and 17% (most relaxed constraints).
- Related to [4], [5] extends the energy optimization to consider also indoor CO_2 levels. Compared to seven other regression models, a neural network ensemble performed best. A modified particle swarm optimization algorithm solves for Pareto-optimal solutions of indoor air quality, comfort, and energy consumption. Different weightings of these objectives create different Pareto-optimal trade-offs. Regression models created from a recorded two week period indicate average estimated electricity savings of 12–17%.
- [6] uses neural networks and multi-objective optimization for HVAC operation to minimize economic cost while ensuring user comfort. The study takes into account indoor temperatures, schedule information, cost, and weather variables. Energy consumption is documented for three out of a total of six experiments conducted in winter and summer seasons at University of Algarve, Portugal. The experiment lengths are relatively short with a maximum of two days. The results suggest financial savings while spending more energy to ensure minimized comfort violation: "savings in the order of 50% are to be expected".
- Starting from a thermal building simulation, [7] proposes – after a pre-processing stage of sensitivity analysis and principal component analysis (PCA) – to use neural networks to learn building behavior regarding energy and comfort subject to control actions. The genetic algorithm [8] is then applied to derive building control rules. A knowledge base stores these, enabling facility managers e.g. to strive for energy savings targets. The approach is verified using three months of simulation and two months of experiments for a care home in the Netherlands where heating supply, window opening, the degree of shading, and light levels can be controlled. Weather-normalized energy savings reach approximately 25%.
- [9] applies reinforcement learning to optimize heat pump operation. The study demonstrates energy savings of 4–11% for two different buildings by simulation of winter and summer seasons.
- [10] applies reinforcement learning to control the operation of blinds and lights in an office, taking into account also user feedback on the comfort achieved. Experiments show that 92% of the users reported high satisfaction, while the control also showed energy savings potential of up to 10% when considering lighting in combination with cooling load.
- [11] uses an ensemble of neural networks to assist batch reinforcement learning in creating an effective HVAC demand response controller able to control on-off decisions. A simulation of 40 days with different temperature regimes validates the approach. After collecting 16 data of days, the inferred control policies are stable within 90% of the mathematical optimum. A shorter experiment in a living lab verifies the findings qualitatively.
- For a Swiss low exergy residential building, [12] controls the mass flow parameter through a photovoltaic-thermal array to improve power output. Validation is performed by simulation: over the course of three simulated years, a 5–11% power improvement is achieved compared to a rule-based controller configured by domain experts.
- [13] applies reinforcement learning to data-driven predictive HVAC control. For reasons of scalability, the work uses weighted learning in a distributed multi-agent setting. A toy example optimizing the heating of two different zones validates the approach's concept.

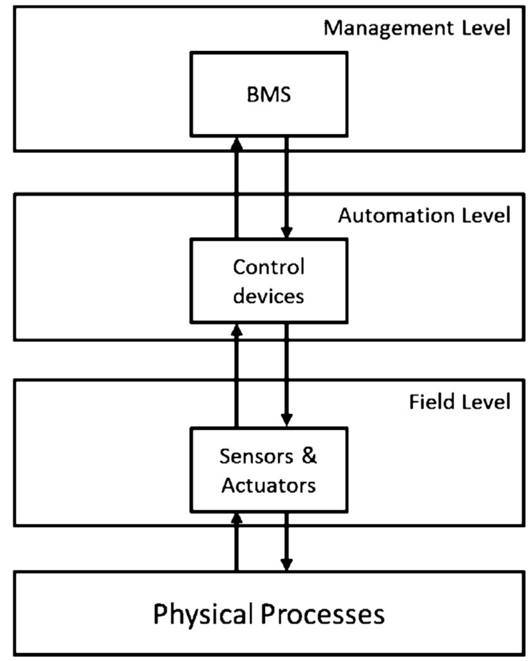

Fig. 1. The common three layer BMS structure described in [14]. Own illustration.

In larger facilities, it is common to encounter automation systems of varying complexity and sophistication. Commonly these are controlled by building management systems (BMS) intended to help facility staff to conveniently and efficiently operate building systems. Most often, these systems provide basic means of configuration, e.g. simple supervisory control rules and schedules. In building automation, hierarchical system structures are very common. According to [14], these are typically designed in a three-layered architecture as illustrated in Fig. 1:

1. The lowest layer, the so-called *field level*, consists of sensors and actuation devices.
2. The middle layer (*automation level*) consists of controllers implementing control loops to meet configured set-points.
3. The top layer, the *management level*, usually consists of the computer hosting the BMS offering a user interface that allows configuring set-points as well as rules and schedules to change these. Examples of such simple rules are linear heating set-point curves based on current outdoor temperatures as well as scheduled operation such as nightly heating set-back lowering operating temperatures.

1.3. Contribution

The referenced efforts demonstrate the effectiveness of applying different methods of regression and optimization to implement data-driven predictive control strategies in buildings. They focus extensively on the development and execution of control strategies as well as the required information to assess performance, but they do not reference or propose a general methodology that applies