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Automated control calibration exploiting exogenous environment energy: An Israeli commercial building case study

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A B S T R A C T

Building energy consumption used for internal heating and cooling purposes is one of the most viral research topics. Retrofitting and renovation activities in building applications aim towards utilizing modern construction materials, with improved thermal and insulation characteristics. It is more than evident that such an approach leads to an improved thermal shield for the building (improving passive building elements). In addition well calibrated rule based control designs are also being adopted in the last decades as a way to improve the energy efficiency in buildings (improving active elements management). Both of the above approaches though are considered as time static since disturbances with high uncertainty (weather conditions, human presence and activity) along with the unavoidable construction material aging phenomena affect building behavior and HVAC dynamics. As a result control recalibration activities seem more than necessary to maintain energy efficiency. Followed by the rapid evolution in the computing machines sector and simulation software kits, research effort has been focused on model-assisted and co-simulation based control strategies which utilize the available computational power of modern machines towards improving energy efficiency and comfort levels through appropriate design Building Optimization and Control (BOC) systems, utilizing available system models. However the main drawback in model-assisted strategies is the fact that they heavily rely on the available building model which requires a tedious offline pre-application period including many simulation tests and/or field experiments so as to fine tune and tailor manually the model and consequently the control logic implemented. Moreover, no matter how elaborate the building model is, aging characteristics and uncertain disturbances are factors which call for re-designing (periodically) the available simulation model and the respective control strategies.

This paper considers an alternative approach to BOC system design. The main attribute of the proposed methodology is that it can provide automated fine-tuning of the BOC system: no human intervention or a simulation model are required for the initial deployment of the controller as well as for the continuously applied fine-tuning procedure. Real-life experiments performed in a highly energy demanding building in Tel Aviv Israel, during spring time, demonstrate that the proposed approach can effectively provide intelligent decisions that none of the currently employed rule/event-based strategy can replicate.

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1. Introduction

A huge research effort has been focused on minimizing the energy needs in building (commercial or residential) daily operation applications over the recent past years, aiming at reducing the largest piece of the energy consumption pie, especially for internal climate-managing purposes (heating/cooling). Retrofitting and renovation activities based on new and thermally improved insulation materials have concentrated a significant amount of research effort enabling a modern building "thermal shield" with higher thermal resistances and capacities able to extend the benefits of the energy consumed for climate purposes [1–3]. Adopting such approaches improves the thermal characteristics of the building, mainly towards three directions: (i) minimizing the internal heat-losses, (ii) increasing the thermal storage capacity and (iii) benefiting from free energy sources [4,5]. The trend of increasing thermal resistance and capacity in modern buildings, also referred

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Nomenclature

BCS	Base case scenario
BOC	Building optimization and control
BEPS	Building energy performance simulation
CAO	Parameterized cognitive adaptive optimization
HVAC	Heating ventilating and air conditioning
MPC	Model predictive control
RB-BOC	Rule-based BOC
TABS	Thermally activated building systems

to as *high-inertia* or *heavy-weight* buildings, tends to decrease the building's sensitivity to external conditions, by mainly filtering the effects of ambient temperature fluctuations on the internal environment [6–8]. High-inertia buildings are in principle low-energy buildings (minimal heat-losses) since climating devices are utilized to satisfy the energy needs just for space heating or cooling [9,10]. It has to be underlined though that this does not directly imply improved thermal comfort conditions for the occupants. In fact, during seasons with high daily temperature fluctuations, a *delicate coordination among the passive and the active layers is necessary* [11–13]. As a consequence as thermal mass of the building increases such statement becomes even more evident since the control strategy must be *proactive*, in order to cope with the high thermal memory of the building, and *optimal*, so as to fully exploit the peculiar structure of the building.

Simple rule-based control strategies, which in most cases are adopted for building control, are not able to exploit the aforementioned energy positive characteristics. Attempts trying to increase the performance of rule-based control strategies require a tedious, time-consuming and rough manual rule tuning, which typically leads to complex rules based on specific field observations, experience and common control practice. In addition to the complexity of the tuning task, other factors might influence the quality of control [14]. In high-inertia buildings the *Building Optimization and Control (BOC)* task resides in the development of a series of control strategies or algorithms aiming at harmonizing the active devices with the passive structure of the building. An elaborate automatized tuning task is necessary for utilizing thermal storages for demand side management applications especially in high-inertia buildings [15]. Motivated by the difficulty of implementing complex networks of cooperating rules, a more elaborate control fine-tuning technique so as to fully exploit the advantages of a design with high thermal storage mass is presented herein.

1.1. Related work and contribution of the paper

Several approaches to rule-based BOC, have been suggested to tackle and exploit the slow dynamics of thermal systems in high-inertia buildings [16–20]. Due to the (i) necessity of designing accurate Building Energy Performance Simulation (BEPS) model, (ii) required extended optimization phase and (iii) prolonged operator training phase, most of these techniques require an insufficient, tedious and time/money "expensive" design and calibration phase in order to provide substantial performance improvements. Most modern state-of-the-art approaches for efficient BOC systems are based on Model Predictive Control (MPC) [21–23], Co-simulation [24–26], popular optimizers [27,28] or neural networks [29–34]. Despite the recognized improvements of these techniques over rule-based control strategies, dimensionality issues occur, due to the fact that the prediction horizon has to be several hours since slow dynamics and large time constants are involved, preventing extended exploitation of such techniques. Moreover as all real-life systems, buildings evolve and age too – phenomenon which demands a periodic re-calibration of the assisting simulation model so as to avoid misfits to the real-life building behavior. It is more than evident that such simplification enters a highly uncertain error in the control design problem, especially when the model is out-of-date with respect to real-life system behavior, rendering the entire scheme quite unreliable.

Cognitive adaptive control optimization methodologies, on the other hand, developed by the authors showed the ability to provide optimal control strategies in large-scale systems in an automated calibration manner [35–40]. The main ingredient of all of these methodologies [35,38,40], referred to as Cognitive Adaptive Optimization (CAO), has been shown that ***it can work efficiently even when no model of the building is available***. CAO has proven to be able to recognize the control effects on the building performance via a built-in control-performance model, in a reliable manner. Through this built-in adaptive control-performance model CAO is able to learn so as to fine-tune the existing controller in a periodic iterative manner and finally generate energy efficient control strategies. Three different versions of CAO were developed based on this concept:

1. *Model Based CAO (MB-CAO):* This approach employs a simulation – assistive online control strategy calibration. The high-level setup scheme suggests that: as application time evolves an available building simulation model is called periodically to run in parallel and assess the control strategy performance. This approach, as all model assistive approaches, demands a simulation model to be available for tests and therefore depends strongly on the model accuracy and responsiveness.
2. *Fully Adaptive CAO (FA-CAO):* This approach employs a model-free online control optimization scheme. The high-level setup scheme suggests that: as application time evolves the calibration process is based on high frequency data sampling from the real building plant (every control cycle time-step) in order to assess the control strategy performance. Even though no simulation model is used, this approach presents slow transient behavior in cases where high time inertia system dynamics are involved. The immediate control effects cannot be easily recognized within a small time interval and to this end such tool was considered as a highly computation expensive.
3. *Automated Fine-Tuning CAO (AFT-CAO):* This approach employs a model-free online control optimization scheme. The high-level setup scheme suggests that as application time evolves the calibration process is based on low frequency data sampling (once a day) from the real building plant in order to assess the control strategy performance.

For the purposes of the current work the Automated Fine-Tuning CAO was adopted so as to establish an automated, adaptive procedure for control strategy fine-tuning, at a periodic basis. The main reasons for this choice were twofold: (i) no elaborate simulation model was available for the current building and (ii) the Fully Adaptive CAO version has been already tested and evaluated both in simulation and real-life environments [40] while the experimental period was quite short. The key idea behind the application presented herein, is to demonstrate and evaluate AFT-CAO performance in extremely large scale complex real-life BOC systems, and underline its respective operational capabilities. From the application results analysis (see Section 4) can be observed that AFT-CAO was able to demonstrate high energy-saving potential, without the requirement of any necessary preparatory investigations of the system, at all. In addition it was able to achieve, in an online adaptive manner, significant improvements (around 45%) with respect to the manually tuned control strategy, which was already used in real-life practice.

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