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Proactive control for solar energy exploitation: A german high-inertia building case study

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HIGHLIGHTS

- Solar gains exploitation by utilizing large glass facades and concrete core thermal energy storing capacity.
- Efficient Building Energy Management in a well-insulated modern building construction.
- Energy consumption reduction by maintaining user comfort.
- High inertia large scale office building test case, located in Germany.

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ABSTRACT

Energy efficient passive designs and constructions have been extensively studied in the last decades as a way to improve the ability of a building to store thermal energy, increase its thermal mass, increase passive insulation and reduce heat losses. However, many studies show that passive thermal designs alone are not enough to fully exploit the potential for energy efficiency in buildings: in fact, harmonizing the active elements for indoor thermal comfort with the passive design of the building can lead to further improvements in both energy efficiency and comfort. These improvements can be achieved via the design of appropriate Building Optimization and Control (BOC) systems, a task which is more complex in high-inertia buildings than in conventional ones. This is because high thermal mass implies a high memory, so that wrong control decisions will have negative repercussions over long time horizons. The design of proactive control strategies with the capability of acting in advance of a future situation, rather than just reacting to current conditions, is of crucial importance for a full exploitation of the capabilities of a high-inertia building. This paper applies a simulation-assisted control methodology to a high-inertia building in Kassel, Germany. A simulation model of the building is used to proactively optimize, using both current and future information about the external weather condition and the building state, a combined criterion composed of the energy consumption and the thermal comfort index. Both extensive simulation as well as real-life experiments performed during the unstable German wintertime, demonstrate that the proposed approach can effectively deal with the complex dynamics arising from the high-inertia structure, providing proactive and intelligent decisions that no currently employed rule-based strategy can replicate.

1. Introduction

Motivated by the fact that around half of the energy produced on the planet is used for the daily needs of building systems, especially for climate-control purposes (heating/cooling), during the past decades a significant amount of research effort has been concentrated on energy efficient designs and constructions [1–3]. Energy efficient building design and construction techniques go under the name of “passive” designs, since they do not involve the use of literally “active” mechanical and electrical devices for climate control. Examples of passive design includes: passive solar building design, where windows, walls, and floors are made to store, cage and distribute solar energy in the form of heat in the winter and reject solar heat in the summer; passive cooling with

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Nomenclature

BCS	Base Case Scenario
BOC	Building Optimization and Control
BEPS	Building Energy Performance Simulation
HJB	Hamilton–Jacobi–Bellman
HVAC	heating ventilating and air conditioning
MPC	Model Predictive Control
PCAO	Parameterized Cognitive Adaptive Optimization
PVP	photovoltaic panel
RB-BOC	rule-based BOC
TABS	Thermally Activated Building Systems

different forms of ventilation and earth coupling; passive day-lighting to most effectively capture sunlight; superinsulation techniques [4,5]. Despite their heterogeneity, passive design techniques share the common goal of increasing the thermal mass of the building. A building with high thermal mass, also referred to as *high-inertia* or *heavy-weight building*, is able to store heat, providing thermal "inertia" against temperature fluctuations: transient thermal behavior and thermal storage capacity as a function of building inertia have been investigated and are still under investigation, e.g. [6–8]. High-inertia buildings are in principle low-energy buildings where active devices like heating, ventilation, and air conditioning (HVAC) units require little energy for space heating or cooling [9,10]. However, this does not directly imply improved thermal comfort conditions for the occupants. In fact, in order for thermal mass being effective in improving thermal comfort and energy consumption, especially during climates and seasons with high daily temperature fluctuations, a *delicate coordination among the passive and the active layers is necessary*, otherwise all the advantages given by the passive design will be lost, with undesirable results in the indoor comfort of the occupants [11–13].

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. The development of such strategies is more challenging than in conventional buildings. 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. For these reasons, the simple rule-based control strategies which typically escort passive designs are not able to guarantee energy efficiency: any attempt to increase the performance of rule-based control strategies requires a tedious, time-consuming and rough manual rule tuning, which typically leads to complex networks of cooperating 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. For example, in high-inertia buildings equipped with heating or cooling systems based on distribution of water, the quality of control is also determined by the hydronic circuit [14], i.e. on the process of optimizing the distribution of water to provide the intended indoor climate at optimum energy efficiency and minimal operating cost: a complex networks of cooperating rules is necessary for any hydronic circuit control to function properly. A similar elaborate ruled-based tuning task is necessary in high-inertia buildings utilizing thermal storages for demand side management applications [15]. Motivated by the difficulty of implementing complex networks of cooperating rules, more elaborate control techniques are required so as to fully exploit the advantages of a design with high thermal storage mass.

1.1. Related work and contribution of the paper

In the current state-of-the-art several approaches to rule-based BOC, such as intelligent comfort and predictive weather-data based controllers have been suggested to tackle and exploit the slow dynamics of thermal systems in buildings [16–20]. Unfortunately, most of these techniques require a tedious and "expensive" design and calibration phase in order to provide the aforementioned savings. The reasons are e.g. the design of an accurate Building Energy Performance Simulation (BEPS) model, the extended optimization phase, the prolonged operator training. Progress in building technologies, weather forecasting and low-cost embedded computing systems pave the way for implementation of intelligent strategies with "proactive" and "optimal" capabilities for BOC applications. Advanced state-of-the-art implementations of BOC systems mostly rely on Model Predictive Control (MPC) [21–23], Co-simulation [24–26], popular optimizers [27,28] or neural networks [29–34]. Despite the recognized improvements over rule-based control strategies, such methods do not efficiently scale to large high-inertia BOC designs. In fact, in such high-inertia building applications additional challenges must be faced. Due to the large time constants which are involved, it is more than evident that the prediction horizon has to be several hours so as to "predict" in an effective manner the model behavior and furthermore generate optimal control decisions. In most cases BOC schemes rely on simplified linear models that make prediction over several hours unreliable. Such simplifications are a necessary consequence of making calculations implementable in real-time. In general, in order to "predict" in an efficient manner the model behavior and generate optimal control decisions increased complexity and calculation are necessary, which, due to the high dimension of the arising optimization problems, put at stake most current state-of-the-art modern BOC methodologies (cf. Table 1 in this paper).

On the other hand, several adaptive control optimization methodologies developed by the authors showed the ability to automatically provide optimal control strategies in large-scale systems [35–40]. The most recent of these methodologies [40], referred to as Parameterized Cognitive Adaptive Optimization (PCAO), has been shown to possess adaptive self-learning abilities. In this paper we applied the PCAO methodology to the design of a BOC strategy for a low-energy, high-inertia building in Kassel, Germany. The advantage of the PCAO method over the mentioned state-of-the-art techniques is the fact that it is assisted by an elaborate simulation model of the building in order to attain energy efficient control of the building. The simulation model is able to

Table 1
Comparison of BEPS-based, PCAO and modern optimization algorithms on BOC design.

Test case (BEPS using TRNSYS)		
Methodology	Iterations	Energy Savings wrt the Best Practice (for the same user comfort conditions) (%)
PCAO	~50	30–50
Popular optimization algorithms	>10,000	0–5