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Energy-efficient HVAC management using cooperative, self-trained, control agents: A real-life German building case study

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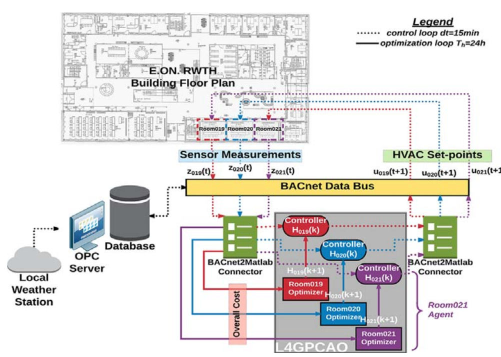
HIGHLIGHTS

- Model-Free, Agent-based Control and Optimization Solution.
- Energy efficient building management preserving acceptable comfort Levels.
- Real-life application results during heating period.
- Significant improvements respect to a common commercial control solution.

GRAPHICAL ABSTRACT



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ABSTRACT

A variety of novel, recyclable and reusable, construction materials has already been studied within literature during the past years, aiming at improving the overall energy efficiency ranking of the building envelope. However, several studies show that a delicate control of indoor climating elements can lead to a significant performance improvement by exploiting the building's savings potential via smart adaptive HVAC regulation to exogenous uncertain disturbances (e.g. weather, occupancy). Building Optimization and Control (BOC) systems can be categorized into two different groups: centralized (requiring high data transmission rates at a central node from every corner of the overall system) and decentralized[1] (assuming an intercommunication among neighboring constituent systems). Moreover, both approaches can be further divided into two subcategories, respectively: model-assisted (usually introducing modeling oversimplifications) and model-free (typically presenting poor stability and very slow convergence rates). This paper presents the application of a novel, decentralized, agent-based, model-free BOC methodology (abbreviated as L4GPCAO) to a modern non-residential building (E.ON. Energy Research Center's main building), equipped with controllable HVAC systems and renewable energy sources by utilizing the existing Building Management System (BES). The building testbed is located inside the RWTH Aachen University campus in Aachen, Germany. A combined rule criterion composed of the non-renewable energy consumption (NREC) and the thermal comfort index – aligned to international comfort standards – was adopted in all cases presented herein. Besides the limited availability of the specified building testbed, real-life experiments demonstrated operational effectiveness of the proposed approach in BOC applications with complex, emerging dynamics arising from the building's occupancy and thermal

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[1] The terms "decentralized", "distributed" and "agent-based" are considered to have similar meanings herein.

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Nomenclature

AC	after cooler
BCS	base case scenario
BES	building energy system
BOC	building optimization and control
CCA	concrete core activation
HJB	Hamilton-Jacobi-Bellman
HVAC	heating ventilating and air conditioning
L4GPCAO	Local4Global PCAO
MCIS	monitoring, control and interface system
MPC	model predictive control
NEC	net energy consumption
NREC	non-renewable energy consumption
PCAO	parameterized cognitive adaptive optimization
RBC	reality based control
SoS	system of systems
VFC	volume flow controller

characteristics. L4GPCAO outperformed the control strategy that was designed by the planers and system provider, in a conventional manner, requiring no more than five test days.

1. Introduction

Around one third of the energy produced on the planet is used in Building Energy Systems (BES). Over 30% of the energy consumed in buildings is used for indoor climating purposes (heating, cooling and ventilation) [1] while around 75% in residential and 25% in non-residential BES [2]. Currently, the heating and cooling load can be decreased using different passive approaches - such as proper architectural design and selection of building envelope material [3–8]. These approaches are usually referred in literature as building envelope “passive” designs, since their respective active control capabilities are implicit and considered very low or zero. It must be underlined that passive designs can reduce the overall building thermal losses and improve the exploitation potential of solar radiation gains but cannot always guarantee acceptable comfort levels. Moreover, retrofitting existing buildings is usually inhibited by financial considerations and cannot always target properly the reduction of energy consumption in buildings [9]. All advantages provided by the passive designs can be lost, or can act controversially, with undesirable results in the indoor comfort of the occupants if poor/simplified control strategies are adopted [10–12]. In order to become more energy and thermally effective, a delicate coordination among the passive and the active building envelope layers is required capable of harmonizing the weather and usage schedule effects on the building too.

Building Optimization and Control (BOC) integrates advanced building management systems or domotic automation solutions implementing control strategies aiming at energy demand reduction, renewable energy exploitation and thermal comfort preservation. Such control strategies must be proactive, in order to cope with the thermal memory of the building, and optimal, to fully exploit the specific structure of the building. Unfortunately, the design of such control strategies is not an easy task, especially in cases where complexity and size of the building increase. Conventional solutions are trying to solve quite complex and nonlinear problems based on very rough assumptions or rules. Although conventional control strategies may have a considerable impact towards the environmental footprint of the building, the efforts for increasing performance in real-life practice results a tiresome, time-consuming and tedious manual rule tuning process, which lead to complicated networks of combined rules, based on specific field observations, experience and common control practice. Although advanced control and optimization approaches are available and tested in research, their availability in commercial BMS is seldom [13]. Moreover model-assisted techniques like Model Predictive Control, Genetic Algorithms, and Neural Networks have also emerged within the recent past years and are considered as commonly accepted BOC systems that take advantage of adaptive and machine-learning control techniques in an attempt to regulate the climating active elements in a more conditions-tailored manner. However, these techniques require elaborate (to achieve significant improvements) or reduced, oversimplified models (to ensure adequate operational responsiveness) to operate satisfyingly-enough [14–22]. As a result, these approaches are usually trying to balance between the huge amount of time, effort and money in order to construct a very detailed building model or the increased probability to result poor performance due to model inaccuracies. To this end within the recent past years, modern, model-free, BOC approaches able to operate without requiring any system model to be available, have been proposed in literature [23–27]. Unfortunately, the majority of the proposed model-free approaches deploy a centralized architecture, suffering from scalability problems, assuming that the available system information can be commuted at a central node while all HVAC systems can also be centrally controlled. The main problems in such BOC cases arise when the problem size increases significantly, where spatial, operational and data transmission limitations may restrict a central control applicability. This applies especially to modern building automation systems wherein system-of-system characteristics are immanent [28]. To bypass scalability problems and cope with large-scale control problems where limited communication is feasible, model-free decentralized approaches have been proposed in literature while the real-life application of such an approach is studied herein.

1.1. Related work and contribution of the paper

The current state-of-the-art techniques are focusing on the development of computationally efficient decentralized BOC solutions to bypass operational constraints in building ecosystems similar to Systems-of-Systems’ (SoS’) architectural organization cases. More specifically, real-time model-free adaptive decentralized optimization and control techniques for dynamic nonlinear problems – also referred as Distributed or Agent-Based control techniques - where only limited knowledge of the usually complex system is available, have also been proposed in literature [29–32]. In such cases though, applicability is limited in practice due to the amount of data that is required to be transmitted, alongside with the respective high data-communication rates among neighboring agents (agent-clusters, agent-neighbors). This feature is considered essential to achieve acceptable estimation performance at the local level. Usually, the size of the defined inter-communicating neighboring agents is inversely proportional to the adaptation gain and the frequency of the periodic signal that is used to achieve extremum seeking and to ensure low communication costs. Another important drawback, inherited from their design principles, is the assumption that the overall objective function depends explicitly – in a linear manner – on the locally calculated objectives i.e., the overall objective function is a weighted summation of its locally available versions, which in most real-life applications might not be the case.

Contrary to the aforementioned decentralized optimization strategies, the Local for Global Parameterized Cognitive Adaptive Optimization (L4GPCAO) approach is able to handle efficiently