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Comprehensive smart home energy management system using mixed-integer quadratic-programming

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HIGHLIGHTS

- An aggregate thermal and electrical building model is presented.
- An MIQP-MPC optimizes the thermal comfort as well as the energy efficiency.
- The MIQP-MPC computes the global optima depending on user weights.
- Flexibility in control is provided by adding occupancy predictions.
- Optimal utilization of thermal storage minimizes necessary battery capacity.

GRAPHICAL ABSTRACT

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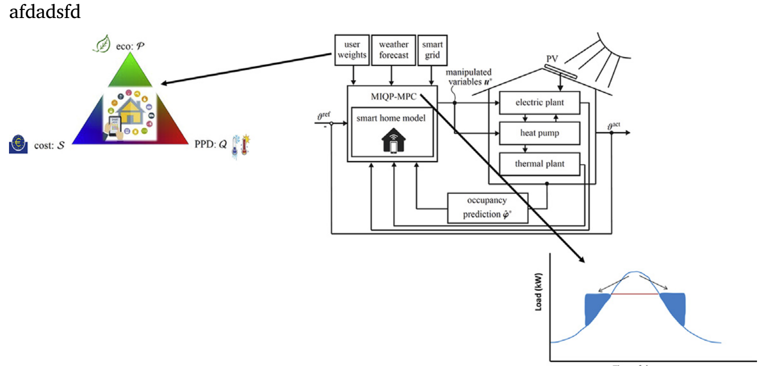

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ABSTRACT

Handling of varying energy sources and flexible connection to smart grids is a current challenge. Minimizing the overall monetary cost and maximizing the use of renewable energy sources are not the exclusive optimization goals, but also guaranteeing the thermal comfort is an important goal. This paper deals with a comprehensive approach of a mixed-integer quadratic-programming model predictive control scheme based on the thermal building model and the building energy management system. Calculating the *global optima* while handling continuous and binary constraints as well as variables and considering both the thermal and electrical part of a smart home are the key aspect of the proposed model predictive controller. By inclusion of disturbance forecasts, occupancy prediction, and individual user weights the control scheme is optimally suited for implementation in real buildings. Furthermore, the occupancy prediction in this research is based on an unsupervised method, which is useful for an effective implementation. This work demonstrates the optimal management of appliances such as heating, a battery storage, a freezer, a dishwasher, a photo-voltaic system, and the opportunities to buy from and sell to the smart grid. Optimal utilization of the building's thermal storage capacity helps to minimize necessary battery capacity. Simulation results underline the efficient global optimization while demonstrating all proposed features of the complex control scheme.

1. Introduction

Buildings in Europe are responsible for approximately two-thirds of the total primary energy consumption [1]. The building energy consumption in Europe amounts to 40–42%, where 35–40% are related to CO_2 emission, [2,3]. However, the potential in energy savings in [2] are estimated to be between 27% and 30 %. In addition, today's heating and cooling makes up almost half of the mentioned energy demand in

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buildings to guarantee user comfort, thus, intelligent building automation solutions are of increasing importance to ensure energy reduction in developed countries [4].

Model predictive control (MPC) optimally utilizes predictions of future disturbances (ambient temperature, solar radiation, occupancy) [5], and it is the ideal control strategy to deal with conflicting optimization goals, which naturally arise in building automation. Maximization of user comfort and minimization of energy cost are the typical optimization problems in modern smart homes, but also in the smart home energy management system different goals occur such as maximization of usage of alternative energy sources and the resulting green footprint and minimizing monetary cost. Furthermore, MPC is perfectly suited for including thermal and technical constraints in the optimization criterion, considering large time constants (due to thermal inertia and good insulation), and decoupling of multi-variate control problems, thus rendering MPC a powerful control scheme. MPC also enables integration of smart homes into future smart grids [6].

This research focuses on modeling a smart home including the thermal and the electrical model. A self adaptive unsupervised occupancy feature extraction and prediction is proposed. Furthermore, smart appliances are modeled as well as different sizes of battery storages. Moreover, a mixed-integer quadratic-programming (MIQP-MPC), a user-adaptive constraint handling, and a flexible MPC tuning tool have been developed and tested in different simulation studies. Because of the MIQP's global control scheme the overall global optimum is guaranteed. The developed concept is flexible, effective, and user-friendly, which is a necessary condition in smart homes. Furthermore, flexible pricing and load curtailment are presented and demonstrate the embedding in future smart grids.

Creating a suitable dynamic building model is one of the primary challenges of designing MPC [7]. Different types of modeling approaches in case of residential buildings exist. High-order dynamic white-box models are possible to use, but are generally not perfectly suitable for optimization and control algorithms, because they are computationally expensive which is not optimal in sense of real-time optimization like MPC [8]. Thus reduced order models are reasonable for MPC design in residential buildings [9]. However, data-based models (black-box models) are well known and perfectly suitable for MPC design because of their low dimension and fast computation time [10]. A further approach based on a mixture between white and black-box models are the so-called gray-box models, see [11].

Besides the thermal model, the energy management system has to be modeled in detail. The authors of [12] focused on a general mixed-integer nonlinear-programming and occupancy has been neglected completely, in contrast to this work where a clearly defined mixed-integer quadratic-programming (MIQP) is used and a more realistic building model has been assumed, because a full occupancy prediction has been added as additional feature to cover one of the most significant disturbances. Another multi-objective control and management for smart energy-efficient buildings is presented in [13], where a hybrid multi-objective genetic algorithm is used, which does not guarantee the overall optimal solution in contrast to the proposed approach where the global optimum is guaranteed by the closed-loop solution of the MIQP.

In this work the main focus is on the electrical and the thermal model, thus, the smart grid is not modeled in detail. However, different important cases for the connection between the smart home and the smart grid are demonstrated in this work. In [14] an MPC-based optimal scheduling of grid-connected low energy buildings with thermal energy storages is presented. In contrast to [14], where only energy-efficiency is the key aspect, in the presented research the focus is on multiple optimization goals: the thermal comfort, the energy-efficiency and the monetary cost.

MPC is a well established method for constrained control and has also been in focus of researchers in the area of buildings [4,15]. As presented in [16] the disturbances, especially occupancy, and their forecasts and predictions are the key aspects for an optimal MPC design, besides a well-suited model. The importance of occupancy and its prediction is discussed in [15], thus, the same method as presented in [15] has been adopted for this research. In contrast to [17] where the detection of presence and sleep patterns is done by supervised learning, the presented scheme in this work focuses on the extraction of typical occupancy patterns from historical data using an unsupervised method.

The main focus of this work is the comprehensive approach for a smart home energy management system, which includes the formulation of the MIQP-MPC to optimize the energy management system and the thermal comfort simultaneously and the unsupervised occupancy prediction. Different formulations and presentations of MIQP as well as mixed-integer linear-pro-gramming (MILP) or hybrid MPC schemes for smart buildings exist. The authors of [18] present a hybrid MPC scheme to optimally manage the thermal and electrical subsystems of a small-size building, with the objective of minimizing cost while keeping the room temperature within prescribed time-varying bounds. In contrast to [18] the adaptive occupancy prediction is included. Here, due to the adaption of the thermal constraints more energy can be saved during periods without user presence. Another work of Jin et. all, see [19], describes a user-centric system called Foresee, which uses a computationally-tractable formulation of a convex MPC problem. However, the MIQP presented in this work also handles the scheduling of switching components. Furthermore, by using the thermal storage of the building it is demonstrated that only a small-size battery storage is necessary to optimally energize the building without comfort loss. The authors of [20,21] are also using MILP for the energy management systems in residential buildings. A simple but efficient MILP based rolling optimization for residential buildings under real-time pricing policy has been developed in [21]. Moreover, in [20] the main focus is on two hierarchical hybrid MPCs which would require an elaborate implementation in a smart home. However, in a smart home a simple yet versatile model is required including all disturbances and comfort goals. In contrast to given references, the thermal comfort and the individual weights of the users are included during the optimization. Furthermore, a key aspect of the presented work are the individual user weights, which can be freely chosen by the occupants on-line. In addition the steps of an real implementation are introduced and outlined.

Next to the thermal storage of the smart home itself a small-size battery is assumed to store electrical energy for the building in this work. The "optimal" battery sizing for a smart home via convex programming is discussed in detail in [22]. However, by also considering the thermal storage the size of the battery can be further reduced as illustrated in this work. In addition, the complete building structure, thermal and electrical part, is included in this work in contrast to [22] where only the electrical part is considered.

An interesting topic while considering energy management for smart homes is scheduling in general. In this work scheduling is implemented by smart appliances such as a freezer oder dishwasher. In [23] an overview of energy management architectures for smart homes has been illustrated by introducing different configurations and scheduling strategies. The authors of [24] present the load commitment in a smart home, thereby minimizing the total cost, however, no comfort criterion for the user is assumed, which is insufficient for smart homes. In [25,26] a distributed energy resources scheduling problem of smart homes has been investigated, which is in both research works combined with a stochastic MPC, in contrast to this work where a MIQP-MPC is used.

Different references in literature, as given above, have proposed energy management algorithms for smart home that integrate renewable energies and the smart grid connection. All these researches have the same general objective: minimizing the daily energy cost without affecting the comfort of occupants. In this research both objectives are included in the optimization goals and especially the thermal comfort in buildings should have the highest priority. Thus, the optimal use of energy resources while guaranteeing user comfort in smart homes is the main topic of this research. In addition, the unsupervised occupancy