Advanced control strategies toward achieving nearly-zero energy consumption in buildings

PEBBLE Project Consortium

Abstract

In this paper the main concept and results of the PEBBLE Project are presented: PEBBLE is an ongoing FP7 Project aiming at the development of advanced ICT tools to support the operation of nearly-zero- and positive-energy buildings. In the design and operation of such buildings a pragmatic target is maximization of the actual net energy produced (NEP) by intelligently shaping demand to perform generation-consumption matching. With the belief that maximization of the NEP for Positive-Energy Buildings is attained thru Better ControL dEcisions (PEBBLE), a control and optimization ICT methodology that combines model-based predictive control and cognitive-based adaptive optimization is presented. There are three essential ingredients to the PEBBLE system: a) thermal simulation models; b) sensors, actuators, and user interfaces; and c), generic control and optimization tools. The potential for energy savings using advanced control strategies is illustrated using simulation-based studies: there are significant benefits in terms of energy-performance of using advanced control strategies, compared to traditional rule-based ones. Ongoing work about demonstration and evaluation of the PEBBLE system in three real world buildings is described.

I. Introduction

In the design and operation of positive-energy buildings a pragmatic target is maximization of the actual net energy produced (NEP) by intelligently shaping demand to perform generation-consumption matching. To achieve this, informed decisions in (almost) real-time are required to operate building subsystems and to account for unpredictable user-behavior and changing weather conditions. These decisions have direct consequences to occupant thermal comfort, energy efficiency and, ultimately, to the NEP. The complex interplay between the many parameters precludes empiricism or rule-based decisions and necessitates the development of generic decision tools.

With the belief that maximization of the NEP for Positive-Energy Buildings is attained thru Better ControL dEcisions (PEBBLE), a control and optimization ICT methodology that combines model-based predictive control and cognitive-based adaptive optimization is proposed. There are three essential ingredients to the PEBBLE system: first, thermal simulation models, that are accurate representations of the building and its subsystems; second, sensors, actuators, and user interfaces to facilitate communication between the physical and simulation layers; and third, generic control and optimization tools that use the sensor inputs and the thermal models to take intelligent decisions. Building occupants have a dual sensor-actuator role in the PEBBLE framework: through user-interfaces humans act as sensors communicating their thermal comfort preferences to the PEBBLE system, and in return the PEBBLE system returns information with the goal of enhancing energy-awareness of the users. The generality of the proposed methodology affords a universality that transcends regional, behavioral, environmental or other variations. For this reason, the PEBBLE system will be demonstrated and evaluated in three buildings possessing a variety of design and performance characteristics, located at different places across Europe. The PEBBLE system is not just about improved energy-efficiency or generation-consumption matching, it is about utilizing harmoniously, and most effectively all installed systems in a building, taking into account human factors, and adapting the decisions in (almost) real-time as and when uncertainties occur.

In Figure 1 a schematic of the PEBBLE project is presented. The building is perceived as a dynamical system comprising the various subsystems and building occupants. This last part is especially important

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as occupant actions (e.g. opening and closing windows) and activities (e.g. sedentary work) directly influence the thermal behavior of the building and the type of decisions that must be taken. The building responds with respect to external (weather) and internal (user) excitations, according to dynamics prescribed by the building construction, with controllable elements that operate according to the decisions taken by the PEBBLE system.

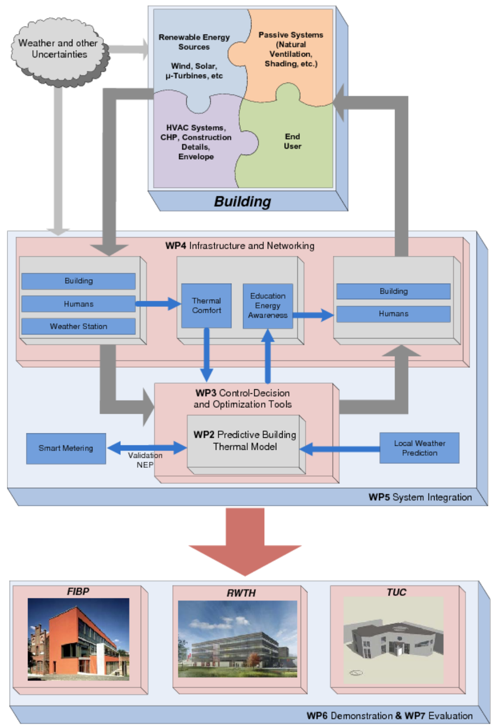

Fig. 1. Overview of the PEBBLE Project

II. Simulation Models

The PEBBLE system will be demonstrated and evaluated in three buildings possessing a variety of design and performance characteristics, located at different places across Europe, with variable weather characteristics. The assembled portfolio of three buildings strenuously tests, in complementary ways, the PEBBLE methodology.

Detailed simulation models for the three buildings to be investigated are prerequisites for the Building Optimization and Control (BO&C) process. Buildings are complex systems and a detailed simulation needs to take into account the actual climate data, geometries, building physics, HVAC-Systems, energy generation systems, natural ventilation, user behavior (occupancy, internal gains, manual shading) to name but a few. To obtain an accurate simulation model, detailed representation of the building structure and the subsystems is required, but it is the integration of all the systems that requires significant effort. A number of simulation tools are available with varying capabilities — see [1] for a comprehensive comparison. Within the PEBBLE project three such integrated solutions are used: the TRNSYS software [5], the Modelica language with a purpose-built component library for building simulation [4], and EnergyPlus [2]. More than one building thermal simulators are used to demonstrate the universality of the developed BO&C system and its independence on the building thermal modelling and simulation software.

A. The PEBBLE Buildings

- FIBP: The first building is the Centre for Sustainable Building of the Fraunhofer Institute for Building Physics, located in Kassel, Germany. The building is equipped with a surface heating and cooling system with thermally activated building constructions. Each office room is equipped with a separately regulated heating/cooling circuit in the ceiling and in the floor slabs. In addition to these, a number of other control elements, sensors, energy-efficiency and user comfort systems have been or will be installed. This building is simulated in TRNSYS (Figure 2).

Fig. 2. The building in Kassel simulated in TRNSYS

- RWTH: The second building is the E.ON Energy Research Center Building of RWTH Aachen University, located in Aachen Germany. The building apart from being a lot bigger than the other two demonstration buildings is also challenging thermally due to its multifunctionality, having both office and conference spaces as well large laboratories which need to be appropriately climatized. In this case, a good energy performance has to be assured by a modern building-technology portfolio: gas-powered heat pump technology in combination with a geothermal field, low-temperature surface heating and cooling including concrete core activation, ventilation with heat recovery and a sorption supported climatization concept. In addition the building has installed: a photovoltaic array and a heat-recovery system for the server rooms. In winter the excess heat from the server rooms can thus be used to heat the office and conference spaces. This building is simulated using building simulation libraries built using the Modelica language (Figures 3 and 4).

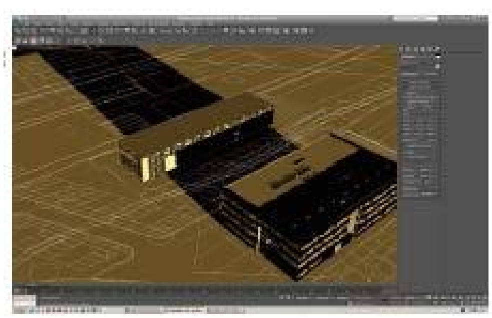

Fig. 3. Shading at 21/12 at 09:00

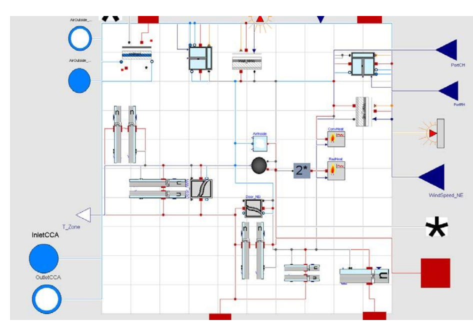

Fig. 4. Simulation of RWTH building in Modelica

- TUC: The third building is the Maintenance support building of the Technical University of Crete, located in Chania, Greece. In addition to thermal-comfort problems for the building users, based on energy audits and simulation results the energy consumption of the specific building is quite high at $130\,\mathrm{kWh/m^2a}$. The TUC building is unspectacular in most ways and in that sense typical of many existing office buildings in Greece and elsewhere. It has a glass roof (that can be used for buoyancy-driven natural ventilation) and manually-controlled shading devices and windows. The demonstration phase in the PEBBLE project is going to proceed in two steps: in the first phase, “obvious” low-cost modifications are going to be applied to the building; in the second phase, the following will be installed: a $2.5\,\mathrm{kW}$ wind-generator, a $4\,\mathrm{KW}$ PV array, automatically controlled shading devices and windows. These systems will be installed before the PEBBLE demonstration starts at the partners own expenses and effort. This building is simulated in EnergyPlus (Figures 5 and 6).

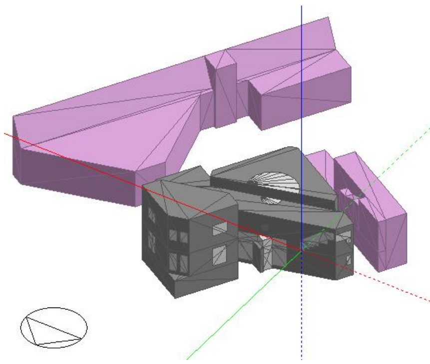

Fig. 5. Geometry of the simulation model created in Design-Builder

Fig. 6. Building shading at 21/06 at 09:00

III. Building Optimization and Control

A prerequisite for the deployment of efficient nearly-zero energy building (NZEB) BO&C systems is the development of a new BO&C methodology that meets the following two objectives:

- On one hand, it is model-based, i.e. involves and it is based on accurate models of the overall NZEB operations but, on the other hand, it is computationally efficient and scalable, i.e. it is applicable to NZEBs of arbitrary size and scale containing a large number and variety of energy-influencing control and optimization elements.
- It is able to efficiently and robustly take care of the inaccuracies involved in the NZEB models and, most importantly, to robustly and rapidly optimize the overall NZEB system performance whenever changes due to e.g. weather changes or changes in the user behavior patterns affect its operations. In other words, an automated and adaptive system is required which will continuously and efficiently optimize the performance of the BO&C system in order to compensate for the inevitable inaccuracies of the NZEB models and forecasts and their deterioration due to medium- and long-term weather variations and changes in the user behavior patterns, NZEB infrastructure, etc.

The fully-automated adaptive fine-tuning methodology of [9], [7], [8], [10], [3] can be used towards such a purpose. The functioning of such methodology — as applied to fine-tuning of BO&C systems for NZEBs — may be summarized as follows (Figure 7):

- As a first step a building thermal model is developed, using thermal circuits, which consist of Resistance-Capacitance (RC) networks [11]. These RC networks describe the temporal storage and attenuation of thermal energy through the building’s structural elements and, given as inputs weather and occupancy data predictions for the following day, return as outputs internal thermal conditions. The goal of this thermal network representation is to develop an approximate state-space model to be used for designing an initial controller for all building climate-control devices (HVAC, heater, cooler, etc.). This controller is designed (using an approximately optimal model-predictive control design strategy) to minimize primary-energy consumption, while preserving comfortable internal conditions (estimated by the evaluation of relevant thermal comfort indices). Unavoidable are modeling errors, as are the inputs whose future actual values diverge from the predicted ones. This controller serves as the entry point for the Cognitive-Adaptive-Optimization algorithm (CAO, Figure 7) which further improves the controller.

- The initial state-space description using the previous RC network is replaced by a more detailed building thermal simulation model, developed using a building thermal simulation environment (like EnergyPlus, TRNSYS or Modelica). Using the simulator and weather and occupancy forecasts, an off-line CAO scheme is applied (Figure 7), and the initial controller is further improved and adjusted to the following day's predicted conditions.

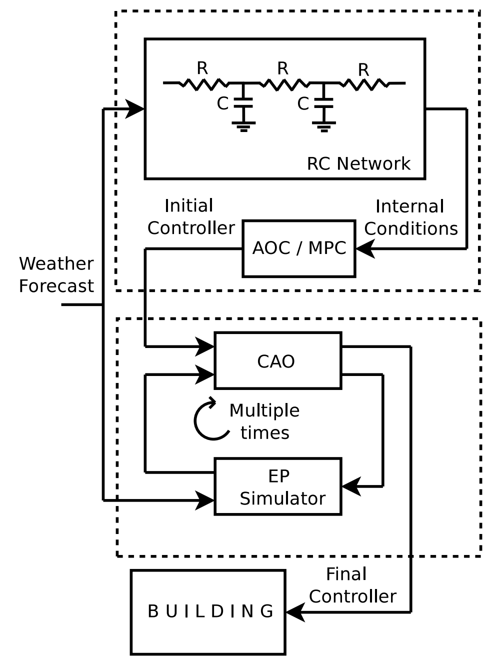

Fig. 7. Model-assisted control

IV. Performance Potential

The PEBBLE system is tested on a sub-building, containing fewer zones, of the building located in Kassel, and is compared to traditional rule-based approaches, leading to better performance with respect to energy consumption and user comfort, as shown in Figure 8. For more details on the methodologies, the implementation and additional results, the interested reader is referred to [3], [6].

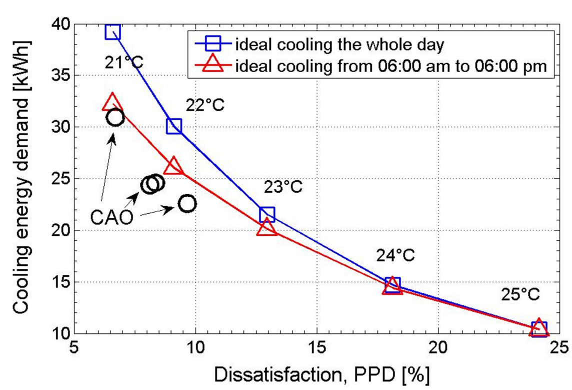

Fig. 8. PEBBLE BO&C system compared to rule-based control

More complex simulation studies indicate that better decisions alone can contribute to 20% or more of energy requirements reduction in most typical cases of building operation.

V. Acknowledgements

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