enerMAT - Design and Optimization of Building Energy Management Systems

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Kurzfassung

Building Energy Management System (BEMS) bezeichnen eine Software, die Gebäude derart steuert, dass bei Einhaltung von nutzungsspezifischen Anforderungen (Komfortgrenzen) ein energieminimaler Betrieb erreicht wird. Durch den Einsatz parametrisierter Zustandsgraphen werden lokale Regelungen mit global günstigen Führungsgrößen versehen. Entwurf und Optimierung eines BEMS erfolgt in drei Schritten. Durch Analyse eines komplexen Modelles des Gebäudes werden die Betriebszustände erkannt und das zu entwickelnde BEMS als ein Zustandsdiagramm entworfen. Je Zustand werden die zu berechnenden Führungsgrößen aus den jeweils relevanten Eingangsgrößen durch Ansätze bestimmt, die durch einstellbare, offene Parameter verändert werden können. Im zweiten Schritt wird das Zustandsdiagramm mit dem vorhandenen Modell zu einem Gesamtmodell vereint und die Funktionsweise untersucht. Dazu sind Szenarien erforderlich, die alle Zustände des Zustandsdiagrammes erreichen. Im dritten Schritt werden durch Einsatz von Optimierungsverfahren die einstellbaren, offenen Parameter des Zustandsdiagrammes optimal festgelegt.
Im Projekt enerMAT wurden BEMS für drei Demonstratoren entwickelt. Für den Demonstrator „Konferenzraum“ wurde die Entwicklung des BEMS im vergangenen ITI-Symposium veröffentlicht. Die Entwicklung der BEMS für die Demonstratoren „Bürogebäude“ und „Musterhaus“ werden in diesem Beitrag gezeigt.

Abstract

A building energy management system (BEMS) is software for controlling a building such that comfort restrictions are met as well as energy consumption is minimised. Applying state charts the BEMS prescribes global advantageous set

points of local controllers. The design and optimization of the BEMS is split into three steps. First a complex model of the building is analysed to identify states which are connected to form the BEMS as a state chart. At each state the set points are calculated using functions which combine input values, and which can be varied by adjustable parameters. Second the state chart is combined with the building model to a total model, which is investigated. This requires scenarios which reach each state of the state chart. Third the adjustable parameters are calculated applying optimization methods.
The research project enerMAT comprises three demonstrators. The BEMS of the "conference room" demonstrator was already published at the ITI symposium in 2014. The BEMS of the other demonstrators "Office Building" as well as "Residential Building" are discussed in this paper.

1 Introduction

A building energy management system (BEMS) is software for controlling a building as well as for the visualization of building relevant data. The aim of the control is an energy consumption minimizing management of the building at which the comfort restrictions are met. The BEMS prescribes set points as well as parameters of local controllers but does not interfere with their structure. In the literature several kinds of BEMS can be found that are based on different ideas, for example:

- BEMS based on rule-sets [1]
- BEMS based on ontologies [3]
- knowledge based BEMS or BEMS based on context-aware technology [4]
- BEMS based on optimization e.g. predictive model control [6]
- BEMS based on artificial neuronal networks [7]
- BEMS based on fuzzy logic [5]

Also combinations of the aforementioned BEMS types are possible [2]. enerMAT prefers UML statecharts (Unified Modeling Language) as a basic design approach of BEMS since states are induced naturally. If a comfort temperature range is defined then the three states "temperature o.k.", "too hot", and "too cold" exist compulsorily. Other states refer to HVAC devices, which can be "working" or "not working". Another simple case is a window, which is "open" or "closed". Each state requires its own reaction. Statecharts can handle lots of states as well as transitions between them. Since the aim of the statechart is controlling the set points of local HVAC devices, at each state of the statechart valid set points have to be calculated.

Due to the basic approach of enerMAT the starting point of BEMS design is a complex simulation model of the building. It should contain the relevant building physics at a "reasonable" level, the HVAC components together with their local controllers, the climatic inputs, the user requirements, and the calculation of values which are to be optimized, e.g. the energy consumption. By analyzing this complex model the states are identified and a statechart can be designed. Furthermore, the input values (e.g. values of several temperatures, climate data, predicted data…) are identified, and set points of local controllers are defined which are outputs of the BEMS. The set points are calculated at each state of the state chart individually combining the input values by applying reasonable functions which often are heuristically motivated. These functions can be adjusted by changing one or more parameters (adjusting parameters) within reasonable ranges. This way the whole BEMS can be adjusted. Starting with reasonable adjusting parameters the BEMS should calculate reasonable set points. Furthermore, the statechart can be formally checked applying formal verification methods.

Once the BEMS is designed, it is added to the complex model which has to be checked for many different use cases. Thus meaningful scenarios are required which guarantee that all states in the BEMS are reached. We use long term simulations, e.g. one year simulations. During the next step the influence of the adjusting parameters on the objective function (e.g. energy consumption) is analyzed. Both the robustness as well as the obviousness of limitations of the adjusting parameters should be checked. Finally, the complex model including the BEMS is used to run optimizations with the aim to find a set of adjusting parameters which minimizes the objective function. Since optimizations can be very time consuming different strategies are needed to reduce the required time.

This paper shows the design and optimization of BEMS for the demonstrators “Office Building” and “Residential Building”. The above mentioned steps are briefly demonstrated. For information on the third demonstrator “Conference Room” please refer to the 2014 ITI symposium.

2 BEMS for the FASA office building demonstrator

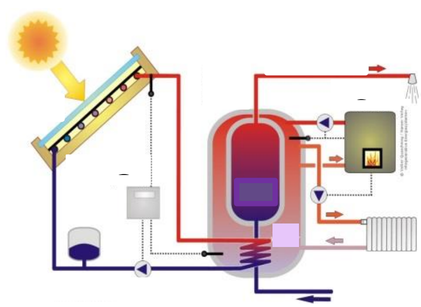

Figure 1: Solar heated office building – View and energy schematic

The office building in Chemnitz is mainly heated by a large solar thermal collector. The hot water is stored in a huge buffer tank which supplies the underfloor heating in the single rooms. In winter the solar energy is not totally sufficient therefore an additional stove is installed which also heats mainly the buffer. Furthermore, a heat pump is used to change the water layer structure within the boiler. The heat pump should be used as rarely as possible since it consumes electrical energy. The model is structured into the energy supply side and the energy consumption side. Since the target of the supply side is to maximize the solar earnings over the whole year, and the target of the consumption side is to use as little energy as possible. Without any essential connections between both sides, the BEMS is separated into the energy supply BEMS and the energy consumption BEMS.

2.1 BEMS for energy supply

The local controller operating the solar panel works autonomously in a satisfying way. Currently missing is an information when the stove should be started and how much firewood is required. An additional BEMS was developed to provide this information.

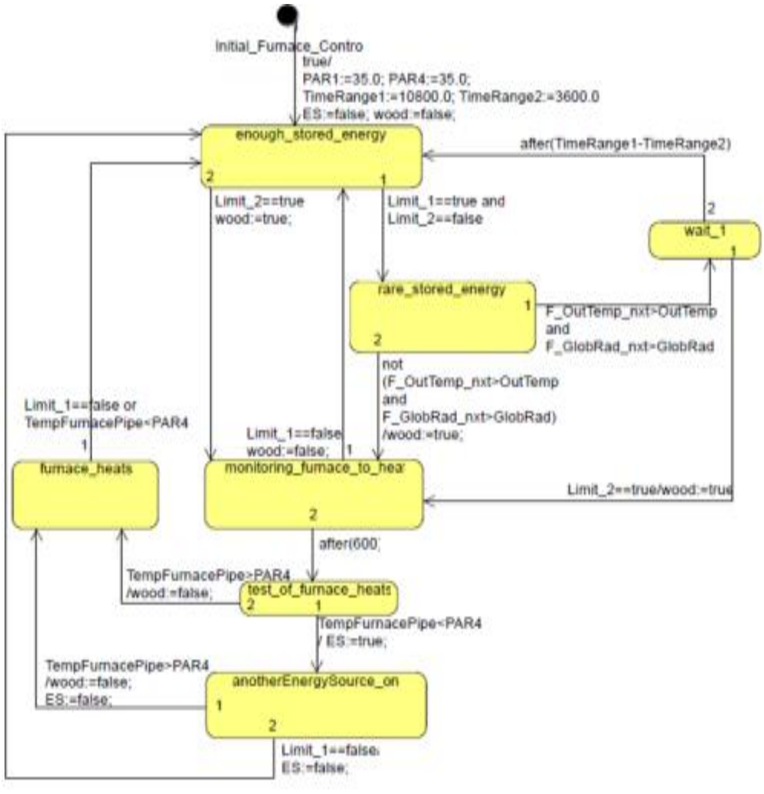

Figure 2: BEMS for energy supply of the FASA office building demonstrator

Figure 2 shows the state chart. If enough energy in the buffer tank is available, limits are checked to find out if the available energy becomes low or if heating the stove is necessary. If energy is low and solar radiation is expected, it is sensible to wait. If additional heating is needed (value *wood* is true) it is checked whether heating has actually started.

Adjusting parameters c_0, c_1 are used for the calculation of the Boolean limit values (limit1, limit2) which show whether enough energy is available. A reference temperature $Tref$ is calculated with the outdoor temperature $Tout$:

$$Tref = \min(80, c_0 + c_1(25 - Tout))$$

The Boolean limit values are calculated by comparing several underfloor heating supply temperatures Ts_1, Ts_2, …measured at the tank with $Tref, e.g.$:

$$limit1 = (Ts_1 < Tref + 5 \; and \; Ts_2 < Tref) \text{ or } (Ts_3 < Tref + 5 \; and \; Ts_4 < Tref)$$

Further adjusting parameters c_2, c_3 are used to calculate the burn time Bt, which is proportional to the mass of wood to be burned:

$$Bt = c_2 + c_3(25 - Tout))$$

When simulating the whole model including the BEMS for the half of the year using an arbitrarily chosen set of parameters, the energy supplied by stove and heat pump is:

Detailed total model:
Adjusting parameters: $c_0 = 30, \; c_1 = 1, \; c_2 = 18, \; c_3 = 0.5$
Supplied energy: $energy\ heat\ pump = 3632\ kWh, \; energy\ stove = 15114\ kWh$
Days with temperature violation: *64*

Unfortunately, this simulations takes around 5 hours (used hardware: Windows 7 Enterprise 64bit, Intel® Core™ i7-4600U CPU @ 2.7 GHz, 8 GB RAM). Since this is far too much for the application of optimization methods, the simulation model is simplified drastically. The number of building zones is reduced from 26 (one zone for each room) to two (one zone for each floor). The energy supply side remains unchanged. The above mentioned simulation takes now around 5 to 10 minutes. The results are as follows:

Simplified total model:
Adjusting parameters: $c_0 = 30, \; c_1 = 1, \; c_2 = 18, \; c_3 = 0.5$
Supplied energy: $energy\ heat\ pump = 3976\ kWh, \; energy\ stove = 16320\ kWh$
Days with temperature violation: *64*

Although the simplified model results differ slightly from the detailed model results, it is a good approximation of the detailed model which describes the building behavior in principle correctly. Since it is fast, it can be used for optimization. A further acceleration was reached by defining the adjusting parameters c_0 and c_2 to be of integer type during optimization. The following intervals for the adjusting parameters were defined heuristically:

$$0 \leq c_0 \leq 30, \qquad 0 \leq c_1 \leq 2, \qquad 0 \leq c_2 \leq 20, \qquad 0 \leq c_3 \leq 1$$

The objective function is the sum of energy supplied by the heat pump and by the stove. Furthermore, penalty terms are added to guarantee a certain temperature minima at the buffer. Most important is a low energy consumption of the heat pump. The optimization results in the following parameters:

Simplified total model, optimization results:
Adjusting parameters: $c_0 = 30,\ c_1 = 1.826,\ c_2 = 10,\ c_3 = 0.795$
Supplied energy: $energy\ heat\ pump = 3877\ kWh,\ energy\ stove = 17437\ kWh$
Days with temperature violation: *62*

These results have to be checked using the detailed model. It cannot be expected that the adjusted parameters are optimal ones using the detailed model, but they should be "good" parameters. Otherwise the model simplification would not be acceptable. Using the adjusting parameters of the simplified model optimization, the detailed model results are:

Detailed total model, adjusting parameters from simple model optimization:
Adjusting parameters: $c_0 = 30,\ c_1 = 1.826,\ c_2 = 10,\ c_3 = 0.795$
Supplied energy: $energy\ heat\ pump = 3656\ kWh,\ energy\ stove = 16735\ kWh$
Days with temperature violation: *52*

This result is better in terms of temperature violation than the above shown result without optimization.

2.2 BEMS for energy consumption

The aim of the BEMS is to minimize the energy consumption in the office rooms. Each room is equipped with an underfloor heating having time constants of more than one hour. Because minimizing the total energy consumption can be reached by minimizing the consumption of each room a single-room-BEMS is developed.

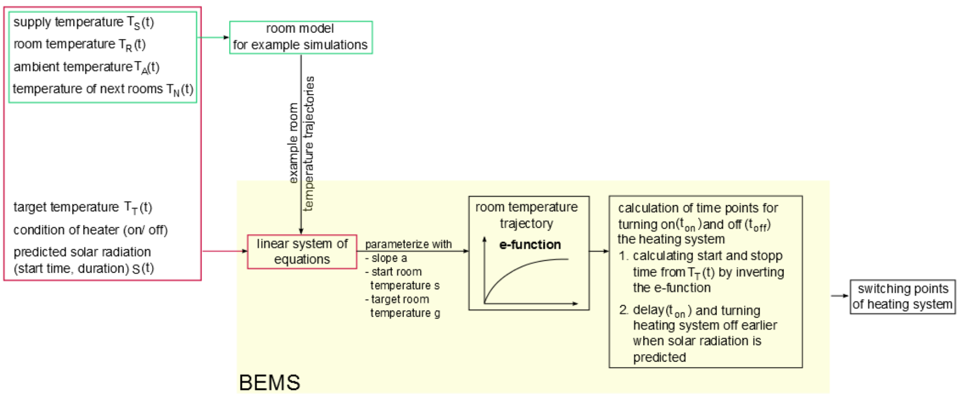

Figure 3: Description of the BEMS development

A technical restriction is to have one heating period a day. The aimed comfort temperature is assumed to be constant within a known period (night setback).

Due to the simplicity there is no statechart used but the two states are coded in Modelica directly. The BEMS calculates online the switching points of the heating according to the following schema:
Since the temperature follows roughly an exponential function after switching an analytical exponential function $T(t) = g - (g - s)e^{-at/(g-s)}$ is identified. Its parameters are calculated by a linear expression, whose coefficients are determined by example simulations of a model of the room. Once the linear expression is determined the function T can be calculated from the BEMS input values without any simulation. *T(t)* is used to calculate the switching points of the underfloor heating to meet both the starting and ending points of the aimed room temperature. A heuristic expression with adapting parameters is used to change the heating interval according to solar radiation expected.

3 BEMS for the residential building

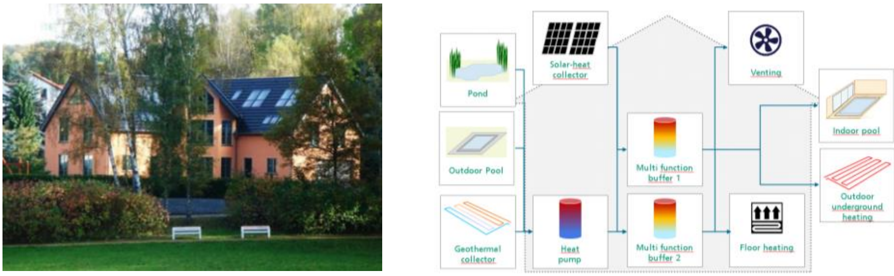

Figure 4: Residential building – View and energy schematic

The residential building is heated by a mix of renewable energy sources: a heat pump supplied by thermal energy from a pond, an outdoor pool, and a geothermal collector. Furthermore, a solar heat collector is available. Via two buffer tanks the underfloor heating are supplied with heat. With this demonstrator it is also helpful to structure the BEMS into the BEMS for the supply side and the BEMS for the consumption side. The BEMS for energy consumption of underfloor heated office rooms is not considered here since it is quite similar to the above described BEMS. Other heat consumers are also not considered. The BEMS of the energy supply side has to determine the energy source in such a way that sufficient energy is available within a long term perspective.

4 Strategies of Optimization

The performance of one simulation run is usually quite bad, therefore it is often too time consuming to finish optimization runs within reasonable time. To overcome these difficulties, several strategies can be applied:

- **Take simplified models instead of accurate ones.**
  It is possible to over-simplify models. Therefore, it needs to be investigated, how simple a model can be to generate still reasonable optimization results. At least the following consideration is useful: If simplified models are used for optimization, the parameters obtained from

optimization should be applied to the more accurate model. Such a verification simulation should prove that the parameters still produce good results.

- **Reduce the number of parameters during optimization**.
  A low number of parameters will accelerate the performance of the optimization runs. Parameters which have not a great influence on the optimization result can be identified by performing a sensitivity analysis.
- **Find suitable time intervals for the parameter optimization.**
  Often some states become active within dedicated time intervals only. Therefore, it is sometimes possible to optimize groups of parameters separately within shorter time intervals. This improves the performance. E.g. typically parameters which influence heating devices should not be optimized within summer months.
- **Do not simulate unreliable parameter values.**
  Sometimes, the optimization algorithm choses unreliable as well as not realistic parameter constellations which cause a bad simulation performance or simulation crashes. Such obviously bad parameter constellations should be selected before simulation starts. This selection can be included into the simulation model.
- **Use parallelization.**
  Both optimization as well as simulation can be accelerated by parallelization.
- **Chose good process parameters of the optimization method.**
  The optimization method can be adapted by suitable optimization process parameters. This influences the performance of optimization drastically.

Summary

During the enerMAT project four quite different BEMS were developed. The development and optimization of three of them are presented in this paper. The project's idea was demonstrated briefly: Starting with an overall building model relevant states are identified to design a statechart which contains adapting parameters. These parameters are determined by optimization runs with the aim of fulfilling user requests. A bottleneck in this process is the often bad simulation and optimization performance. Some strategies are described to improve the performance.

The potential of this approach is by far not exhausted yet: The optimization can comprise both adjusting parameters of the BEMS as well as constructing parameters of the building. Thus more common target functions are possible. Investigations are necessary to support the development of the statechart.

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