APPLYING SIMULATION OF OPTIMAL SYSTEMS IN BUILDING ENERGY MANAGEMENT

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ABSTRACT
The technical systems of buildings have become increasingly complex during the last years. This has led to new challenges both in developing tools for operation, monitoring, fault detection and optimal dynamic control of the systems. The mathematical theory of optimal systems offers a means of tackling these problems in a formal and efficient way.
This paper presents a conseptual framework for applying simulation of optimal systems in building energy management and optimization. The two main application areas discussed are simulation for obtaining reference data of the optimal performance of the system for fault detection purposes and simulation for the realization of optimal control. The discussion is based on work carried out in the Technical Research Centre of Finland within the frameworks of the national research programme LVIS-2000 Future Building Services and IEA Annex 25.

1 INTRODUCTION

The rapid development of technical systems is leading to a situation where the building's processes are too complicated for the average operator to understand. Reasoning the causal relations of process phenomena has become significantly more difficult due to the complex interdependencies of the processes. Building's processes are normally supervised by a building automation system and suitable supervision or management software. The operator's task is mainly to initiate individual sequences and actions. In case of a process failure the commercially available supervision programs do not adequately assist in finding the underlying cause of the fault, nor do they often detect but the most critical and acute faults, leaving the operator with the problems of detecting slowly evolving faults and suboptimalities and reasoning the cause of the malfunction. When operating a complex building system it would obviously be beneficial for the operator to have tools for decision support in building optimization and fault recovery.

Optimal control of building energy systems - especially optimal control of intermittent heating, which serves as an example case in this paper - is a topic often addressed in building energy management. Previous studies have, however, concerned intermittent heating as a more or less traditional control problem. The aim of the work presented in this paper is to view individual aspects of building energy management, such as optimization of intermittent heating, as parts of an overall building optimization process, including both the design and operation aspects of the problem.

The issues of optimization and diagnosis are being addressed within IEA Annex 25, the main goal of which is to develop methodological procedures - within a defined concept - for automated real-time performance optimization, fault detection and diagnosis of HVAC processes (Hyvärinen and Kohonen 1993). The ultimate goal of the project is to produce building optimization

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and fault diagnosis (BOFD) prototypes implementable in building energy management systems (BEMS).

2 THE FRAMEWORK OF BUILDING OPTIMIZATION

Building optimization is the process of minimizing an overall objective function that includes all costs of building operation (e.g. energy, maintenance, personnel) under some environmental constraints (Nakahara 1993). Building optimization can be defined separately for the design and operation phases of the building life cycle. However, these phases are interdependent in the sense that design decisions naturally define the final operating domain for the building and, on the other hand, operational considerations should be taken into account in the design work.

Total building optimization, which would literally mean optimizing the life cycle as a whole, is unfortunately at the present state of technology and knowledge an unrealistically multidimensional task. Thus, in practice building optimization is performed on a per-phase-and-subsystem -basis, i.e. structural design, building services system design, operation of the building. In the normal building design and operation practice the interconnections between these steps and the corresponding subsystems are not taken into account, which inevitably leads to a suboptimal solution.

As the work has so far mainly focused on the operation phase, building optimization as referred to in this paper includes only operational "run-time" optimization. This means that building architecture, design and construction are for the time being considered as fixed restrictions to the optimization problem at hand. On the short run this is a reasonable simplification. In a wider perspective the design optimization issues should also be tackled, especially when retrofit design is considered.

3 SIMULATION OF OPTIMAL SYSTEMS IN BUILDING OPTIMIZATION

3.1 The concept in general

Simulation of optimal system serves two main purposes in the optimization of the operation phase of the building life cycle (figure 1). Firstly, from the monitoring and fault detection points of view, it is essential to obtain a measure which serves as a reference for the BOFD-system in order to detect critically suboptimal performance of the system. This can be achieved by monitoring and recording the system's state and inputs for a given period of time and using the recorded data as input for off-line simulation of the system's optimal behaviour. Comparing either the simulated optimal trajectory to the recorded real trajectory of the system or the simulated optimal value of the objective function to the value corresponding to the recorded data should reveal possible suboptimalities in the system's performance and give guidance to diagnosing the problem. (It should be noticed at this point that simulation of the optimal performance is strictly a computational task; all the possible intelligence of the BOFD-system is incorporated in the processes of comparison, detection and reasoning or converting the simulated optimal control to subsystem and component dependent set points.)

Secondly, and more traditionally, optimal system simulation is used as a starting point for calculating optimal set points for subsystem and component controllers in order to realize optimal performance. This calls for on-line simulation including a load prediction algorithm.

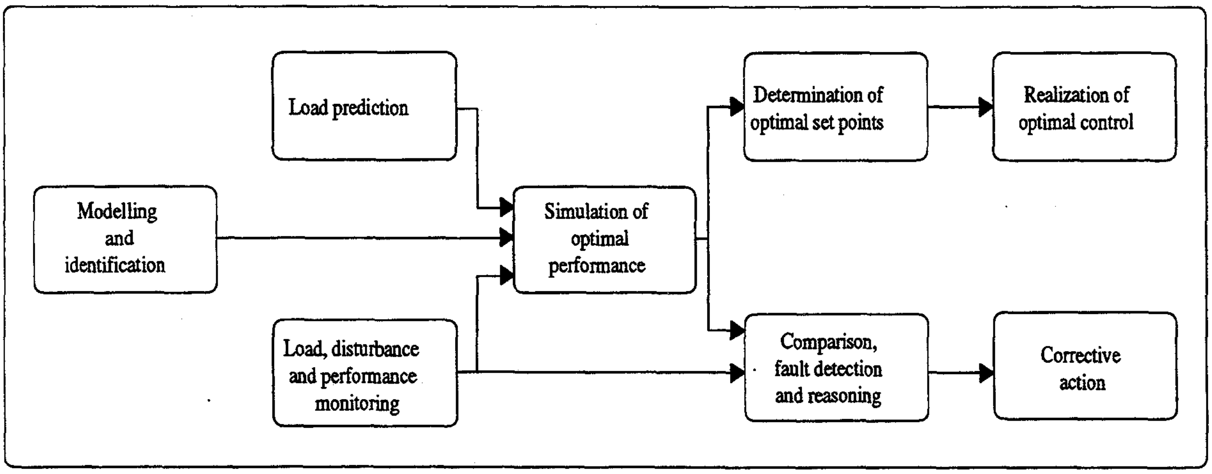

Figure 1. The concept of applying simulation of optimal systems in building energy management, optimization and fault detection.

Both the concepts described in figure 1 include the same main functions: modelling and identification of the building system, formulation of the objectives of optimization and simulation of the optimal performance of the system corresponding to the described objectives. Practically the only difference between the two approaches can be found in the disturbance and load data used for the simulation. Reference simulations for the detection of suboptimal performance are based on recorded load data and therefore do not include uncertainties other than those caused by possible sensor and measurement defects. Real time optimal control algorithms on the other hand rely on stochastic or other types of load prediction models, which add the amount of uncertainty in the simulation results, especially when the considered time period is longer than few hours (Benard 1989).

Because of their similar structure the optimization concepts can be realized using the basically the same algorithms. So far individual algorithms for identification of building models and simulation of optimal systems have been developed at VTT.

3.2 Mathematical formulation

The concept of optimality implies that there is an objective function which measures the performance of the system and which should be minimized (or maximized, depending on the context) under given constraints. Typically the objective function is a function of the state of the system and the amount of control energy used over some finite period of time. A general formulation of the objective is

$$I = K\left[x(t_f),t_f\right] + \int_{t_0}^{t_f} L[x(t),u(t),t]dt \qquad (1)$$

where x is the state of the system, u is the control quantity and t denotes time, with subscripts 0 and f representing the beginning and the end of the considered time interval, respectively.

For the sake of mathematical and computational simplicity it would be beneficial if the system dynamics could be characterized in the form of a linear differential state equation

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) + C(t)w(t) \qquad (2)$$

where w is a disturbance vector and A, B and C are system dependent coefficients. A linear representation has naturally considerable limitations, since many of the heat and mass transfer processes in a building are by nature profoundly non-linear. As the primary interest of simulation of the optimal performance is either in obtaining a higher level performance indicator or target value or in establishing a target trajectory for the control of the system, the simplifications of linear models can be justified; the target does not have to be accurately established to the smallest system detail if the remaining tasks of the BOFD-system are able to take the simplifications into account (refer to figure 1 and paragraph 3.1).

Given the equations above, simulation of the optimal behaviour of the system involves solving the control u^* which - with the corresponding optimal trajectory $x^*(t)$ - minimizes the objective function. Several methods exist for performing the minimization. A straightforward solution is obtained for example by methods based on calculus of variations, such as the Minimum Principle of L.S. Pontryagin (Athans and Falb 1966). The Minimum Principle states that, assuming there exists an optimal control u^*, 1) there exists a continuous vector-valued function $z^*(t)$ (so called costate vector) which together with the optimal trajectory $x^*(t)$ form the solution of the equations

$$\dot{x}^*(t) = \frac{\partial H}{\partial z}, \quad \dot{z}^*(t) = \frac{\partial H}{\partial x} \qquad (3)$$

where H is the Hamiltonian of the considered problem:

$$H = L[x(t),u(t),t] + z^T(t)\dot{x}(t) \qquad (4)$$

2) the optimal control $u^*(t)$ minimizes the Hamiltonian at every time instant during the considered period of time.

The form of the boundary condition imposed on the costate vector depends on the target set of the final system state. For example, if the final state is free (target set is the entire n-dimensional hyperspace R^n) the boundary condition is of the form

$$z^*(t_f) = \left.\frac{\partial K}{\partial x}\right|_{t=t_f} \qquad (5)$$

If the target set is described by a hyperplane in the state space, the vector

$$z^*(t_f) - \left.\frac{\partial K}{\partial x}\right|_{t=t_f} \qquad (6)$$

is normal to the hyperplane at the point $x^*(t_f)$. Naturally no boundary condition for the costate vector is needed if the target is a fixed point in the state space.

After establishing the boundary condition of the costate vector the optimization problem is reduced to solving a two point boundary value problem for a set of two differential matrix equations.

3.3 Case: optimal intermittent heating

Let us consider an office room the dynamics of which are described by the differential equation (Aho and Xu 1993)

$$\dot{x}(t) = A(t)x(t) + bu(t) + C(t)w(t) \tag{7}$$

The objective of intermittent heating can be stated simply as follows: keep the thermal environment in the office room comfortable during the occupied hours with as small heating energy cost as possible. This objective can be mathematically formulated for the unoccupied period as

$$\begin{aligned} I &= \int_{t_0}^{t_f} q(t)u(t)dt, \\ p^T x(t_f) &= T_d \end{aligned} \tag{8}$$

where t_0 is the ending time of the previous occupied period, t_f is the starting time of the next occupied period, q is the time dependent cost per energy unit, T_d is the desired operative temperature at the beginning of the occupied period and p is a weighing vector which describes an approximate operative temperature as a linear combination of the state variables.

Using the Minimum Principle the following set of equations can be derived to describe the optimal trajectory and control of the office room system:

$$\begin{aligned} \dot{x}(t) &= A(t)x(t) + bu(t) + C(t)w(t) \\ \dot{z}(t) &= -A^T(t)z(t) \\ u(t) &= \begin{cases} u_{\max}, b^T z(t) < -q(t) \\ 0, b^T z(t) \geq -q(t) \end{cases} \end{aligned} \tag{9}$$

The set of equations (9) forms a restricted end-point problem: the final state is free in the hyperplane described by

$$p^T x(t_f) = T_d \tag{10}$$

According to the Minimum Principle the final value $z(t_f)$ of the costate vector must be normal to the plane (10) defining the acceptable final states. After some manipulation this yields the following set of equations:

$$\begin{aligned} \dot{x}(t) &= A(t)x(t) + bu(t) + C(t)w(t) \\ \dot{z}(t) &= -A(t)z(t) \\ u(t) &= \begin{cases} u_{\max}, b^T z(t) < q(t) \\ 0, b^T z(t) \geq q(t) \end{cases} \\ x(t_0) &= x_0 \\ z(t_f) &= \frac{\beta q}{p^T b} p \end{aligned} \tag{11}$$

where β is an iteration parameter. From equation set (11) the optimal trajectory and control can be solved iteratively (figure 2). In the calculations the fourth order Runge-Kutta -method (Press et al. 1988) has been used for numerical solution of differential equations.

Figure 3 presents an example of the resulting optimal operative temperature and heating power obtained by solving equation set (11) with a given set of parameters. The two cases shown in the figure correspond to district heating (constant heat price 0.16 FIM/kWh) and direct electric heating (electricity rate at night 0.19 FIM/kWh and during the day 0.44 FIM/kWh). The benefit of the presented control optimization is clear especially in the electricity case: optimal control in this case takes advantage of the cheap night time electricity for preheating the room during the early morning hours. This leads to a slightly higher total energy consumption

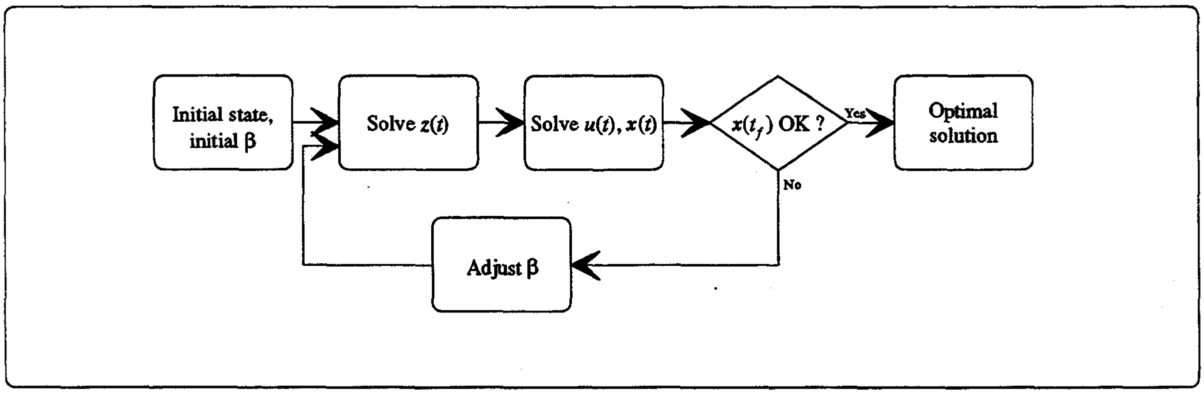

Figure 2. Iterative solution of the optimal control of intermittent heating.

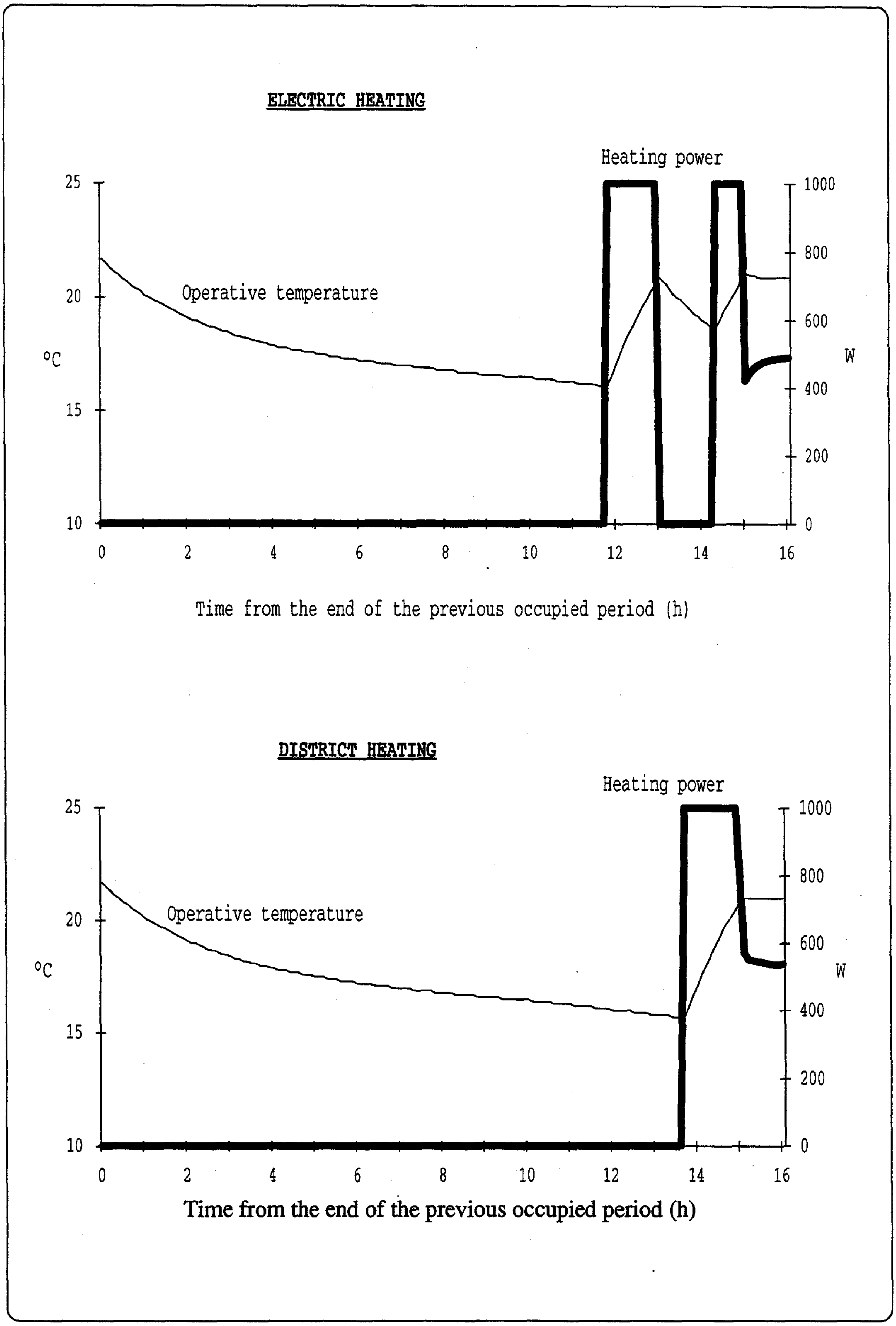

Figure 3. Example of the results of intermittent heating optimization. Cases: electric heating (above), district heating (below).

than in the district heating case, but the total energy cost is minimized as required by the objective function.

In addition to optimization of intermittent heating control, the output of simulations of optimal systems such as the presented one can be used for example to evaluate the operation of night set back schemes, traditional start/stop-controllers etc. In these cases the simulation would serve as a reference of the theoretically lowest energy cost achievable by intermittent heating, against which the realized energy cost can be measured and appropriate actions taken in order to tune the existing control scheme.

4 CONCLUSIONS AND FUTURE WORK

Simulation of optimal systems has shown to be a promising and useful tool for building energy management and optimization. The two main application areas are detection of suboptimal performance and optimal control of the building system. Detection of suboptimal performance is achieved by using recorded system data as input for the simulation and comparing the recorded performance to the simulated optimal performance. Optimal control is aimed at by simulation of the optimal behaviour of the system with a predicted load profile.

Future work at VTT around building optimization will include further development of the idea of optimal system simulation as a BOFD tool and development of algorithms for the subtasks of optimal system simulation, such as load prediction and system identification. The final goal is a prototype optimal system simulation package installable in a building energy management system.

ACKNOWLEDGMENTS

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