PARAMETER IDENTIFICATION FOR THE CONTROL OF THERMAL COMFORT

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KEYWORDS

Parameter identification, Indoor climate control, Thermal comfort, Room model, Controller parameter

ABSTRACT

The demand-adjusted control of thermal comfort in buildings is a step ahead in comparison with the indoor temperature control. It allows HVAC (Heating Ventilation and Air-Conditioning) systems working in compliance with real heating and ventilation demands, e.g. presence depended heating. The latter contains great potential to reduce the energy consumption of heating facilities in comparison with standard steady-state approaches.

The online parameter identification of residential buildings for an automated demand-adjusted decentralized indoor climate control is proposed. The basic parameter for the realisation of such a control system is the objective thermal comfort. A special physical model is used, in order to analyse the dynamic thermal properties of a given room. This includes the estimation of non-measurable physical values at any point in space and time in the room. The model properties are the basis of a correct parameterisation of the controller. The system functions are generated for any desired operating point of the control system. Thus the controller parameters can be adapted to any of these operating points, in order to increase the thermal comfort and to decrease the energy consumption.

INTRODUCTION

Strategies to reduce and optimise energy consumption are a global challenge, both economically and environmentally. Investigations show, that a large part of total energy consumption is used for residential buildings (Fig.1a). This consumption consists mainly of energy required for heating.

Thus a simple optimisation of the heating energy consumption could have more potential of energy saving than a big progress in other branches.

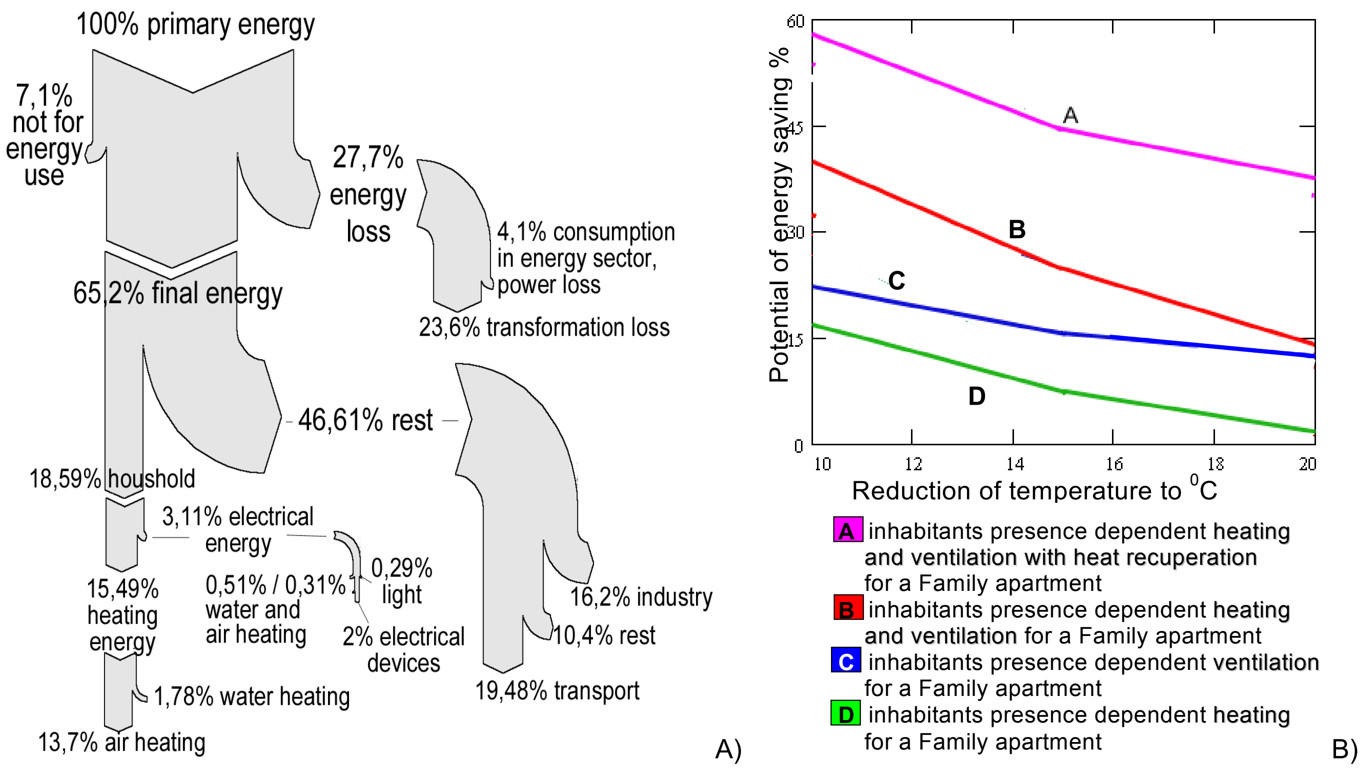

FIG. 1 - A) ENERGY CONSUMPTION IN GERMANY (DATA IN ACCORDANCE WITH [7, 8]) AND B) POTENTIAL OF HEATING ENERGY SAVING IN PRIVAT BUILDINGS

Beginning in the early 70's, in many countries a number of attempts to force the reduction of energy consumption in the private sector has been launched. For example in Germany four legislative papers were issued in 1976, 1982, 1994, and 2001 [1, 2]. New construction techniques and insulating materials have been developed which remarkably reduce the heat losses of buildings, enabling high energy savings at the cost of a diminished natural air and heat exchange. In this situation, appropriate heating and ventilation of the rooms must guarantee sufficient indoor air quality [3, 4]. Improvements of HVAC systems in residential buildings aim at a reduction of energy consumption and an adjustment of comfortable climate in rooms. To meet these demands, decentralized automated thermal climate control, in the sense of demand-adjusted heating and ventilation separately for each room, offers great technical possibilities (Fig. 1b) [5, 6, 7, w1].

The demand for heating and ventilation can be defined according to the control value in the time or/and amplitude domain, i.e. inhabitant's presence dependent or/and activity dependent. In both cases the HVAC system should allow dynamical action with bigger state deviation in comparison to conventional systems. Hence, in order to provide optimal regulation, the control algorithm should gather data about the room's behaviour. The core of a demand-controlled system must be therefore a thermodynamic model of the room.

Large number of models has been developed in recent decades (e.g. [9, 10, 11]). Unfortunately, sophisticated models are either too complex for on-line control devices or need huge sets of experimental data to manipulate with.

Simplified models are adjusted to a specific task and cannot be used with new terms of reference. Furthermore, with known models it appears to be impossible to use the control system in critical states, like asymmetric radiation, distributed thermal load, etc..

Therefore, a novel approach to the thermodynamic model adapted to the needs of a demand-adjusted room climate control is proposed. In this sequel, the technique of room modelling for controller needs will be presented and an example for a real-world realisation will be discussed.

CONTROL CONDITIONS AND THERMAL COMFORT

The sole criterion to develop any climate control device is the improvement of thermal comfort [12]. The theoretical and practical foundations for subjective thermal comfort in residential buildings are described in an international norm [13]. The analysis of important parameters influencing thermal comfort is leading to the conclusion that the set of physical parameters commonly taken into account by climate control systems is of limited use to the discussed problem of demand-adjusted control [14].

TABLE 1 - DIFFERENCES IN TYPICAL PARAMETER SETS FOR ROOM THERMAL CONTROL (IN ACCORDANCE WITH [5, 13, 15, 16, 17])

N	COMFORT PARAMETER	CONVENTIONAL HVAC SYSTEM	DEMAND-CONTROLLED HVAC SYSTEM
1	Air temperature	Very important	Very important
2	Air velocity	Not important	Important
3	Air humidity	Not important	Important
4	Metabolic rate	Neglected	Very important
6	Clothing	Neglected	Very important
5	Radiation temperature (distribution of wall temperature)	Neglected	Important
7	Mechanical work	Neglected	Neglected

This is easy to understand if one typical example of presence-demanded heating is considered (presence – heating; absence – no heating). The walls have a slower dynamic behaviour in comparison with air in the room. Because usually the air temperature in a room is nearly stable, the wall temperature changes can be neglected and the wall temperatures are set to a constant value depending on the measured mean air temperature. Contrary to conventional control systems, the proposed approach allows large dynamic bands of environmental physical parameters. Because the air- and the wall temperature are “independent” parameters, due to different dynamic by spontaneous state changing, the changing of the wall temperature should not be ignored, and hence for any room state the comfort state can be adjusted.

In Table 1, results of parameter analysis for the modern room climate control and differences in comparison with earlier control realizations [5, 15] are shown. All following examples are based on measurements and calculations for the 'office room' (Room 0103) of the Smart-HOME Research Lab on the University campus (Fig. 2).

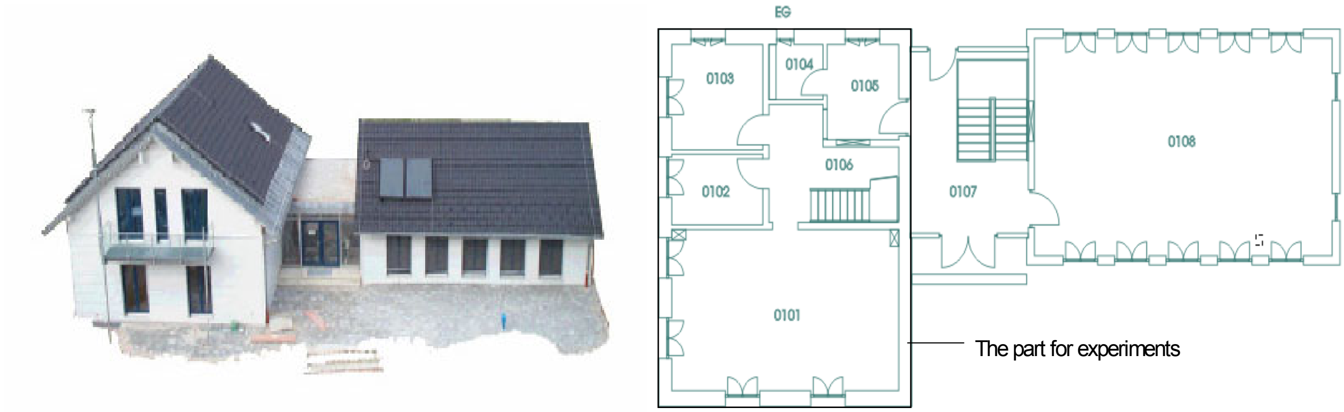

FIG. 2 - A) SMART HOME LAB AT THE BUNDESWEHR UNIVERSITY MUNICH – GENERAL VIEW AND B) LOCATION OF TEST ROOMS [W3].

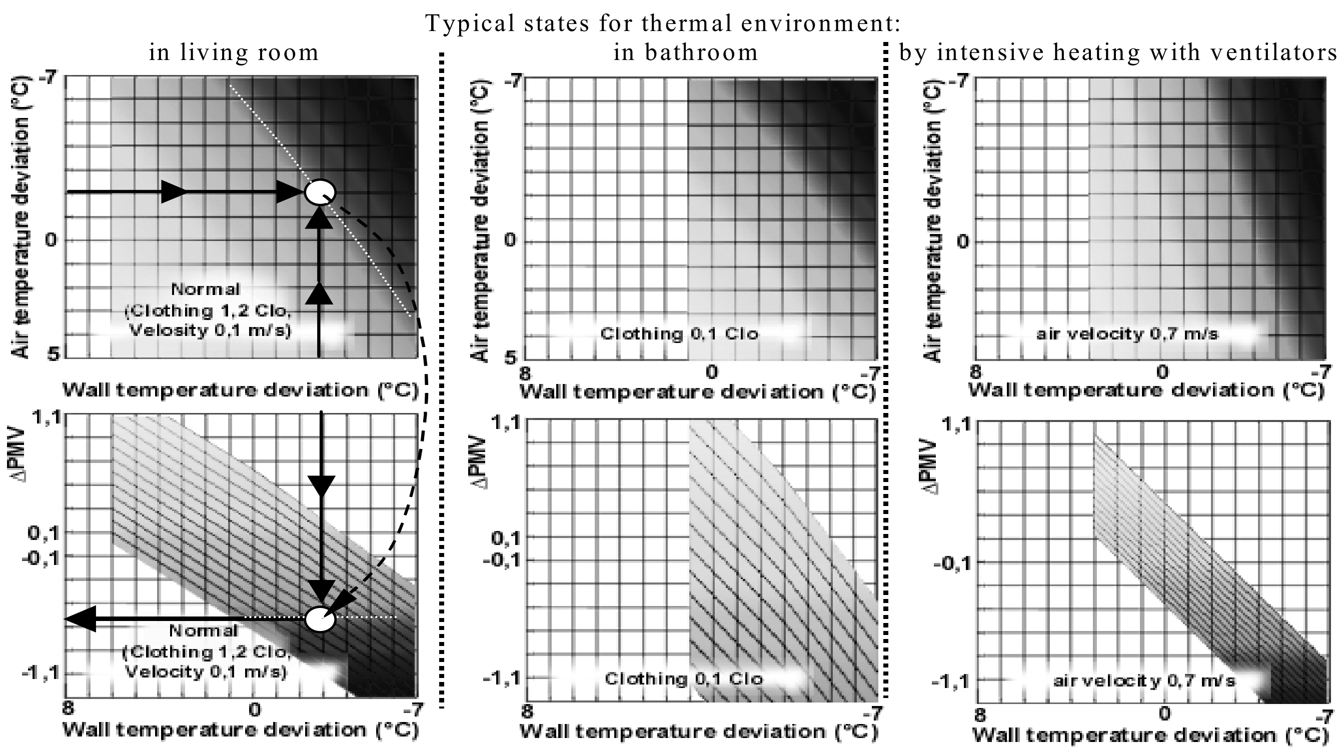

FIG. 3 - CALCULATED SAMPLES OF PMV CHANGING SUBJECT TO DIFFERENT PARAMETER CHANGINGS FOR THE OFFICE ROOM (0103) IN THE RESEARCH LAB

The dependency of a significant comfort factor, the Predicted Mean Vote (PMV) [16], on the changing of room parameters is calculated for two cases:

— Transient room state by air heating (i.e. ideal heating by ventilation devices),
— Transient room state by radiation heating (i.e. ideal heating by radiation panels).

"Transient" means, that the room conditions by heating of a cool room are taken into account. That is when values of important physical parameters have in a shortest time the largest deviation from the appropriate steady-state. Some typical examples of comfort factor dependencies are shown in Fig. 3.

They are used in order to demonstrate the sensitivity of human thermal perception influenced by different physical values for demand-controlled heating and ventilation systems. The comfort surface was obtained in 3D i.e. as a function of 2 parameters - mean wall temperature and air temperature (here they are given as deviations from the normal values 21°C and 19.5°C accordingly). The third parameter changing in Fig. 3 is given as the additional set of 2 projections for described comfort function in 3D domain. For both discussed heating cases, the influences of same physical parameters (here clothing, air velocity, etc.) on the PMV factor are nearly similar and for control aims could be assumed identical.

OBTAINING OF CONTROL PARAMETERS

One problem is, that a lot of control parameters (Table 1), which are needed for a new approach, cannot be measured easily. Furthermore, for a comfort-driven climate control, the establishment of nearly all air-conditioning parameters at the person's localization in the room and parameters such as type of clothes etc. have to be known. Hence, the extended set of control parameters defines an additional task for the measurement environment or/and for the thermodynamic modelling. The second problem is a practical implementation of a controller that allows the correct work with the extended set of control parameters.

The proposed technique uses an extended thermodynamic model as an observer and as a base for many sets of simple room models (like Proportional Timedelay (PT) characteristics or similar) for certain operating states. Such dual model structure is useful for maintenance of cheap and standard heating and ventilation controllers. The desired changing of controller properties is realised due to on-line changing of controller parameters.

MODELLING OF DYNAMIC STATE CHANGES

Steady-state conditions cannot be assumed for demand-controlled rooms. The most effective energy-saving mode is presence dependent heating and ventilation. This is leads to heating pauses and dynamic state changes as discussed in the example on page 3. The circumstances, caused by the comprehensive definition of the thermal comfort in controlled rooms and the needs in dynamic objectiveness of the thermal model, define the following model and controller requirements:

— detailed consideration of a large number of physical phenomena,
— simultaneous consideration of a large variety of physical parameters in the controlled room,
— simplicity for on-line processing,
— easy configuration for easy handling in large-scale production.

The complex thermodynamic model is based on a modified Glück-model [18]. The original structure of the model consists of a geometric room model with multi-sectioned wall surface and multi–zoned air volume inside a room with mechanisms of convective, radiative and conductive heat transfers. Furniture geometry can be co-defined and points of internal heat sources with radiative and convective character could be integrated. The solving method is a mixture of Finite Difference Method (FDM) and empirical equations. It gives to the model a precision of Computational Fluid Dynamic (CFD) and a short calculation time of special physical contributions. Thus in comparison with other known models in public domain it has the best (calculation time)/(features) coefficient [w2].

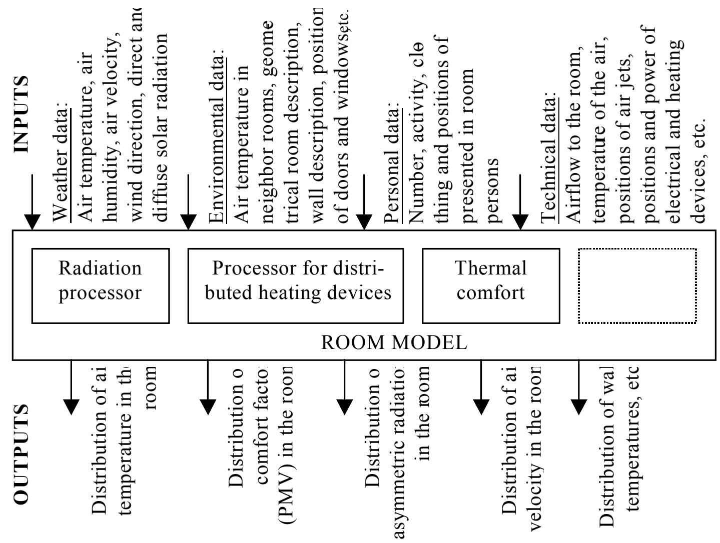

FIG. 4 - STRUCTURE OF INPUT AND OUTPUT DATA FOR THE MODIFIED GLÜCK-MODEL

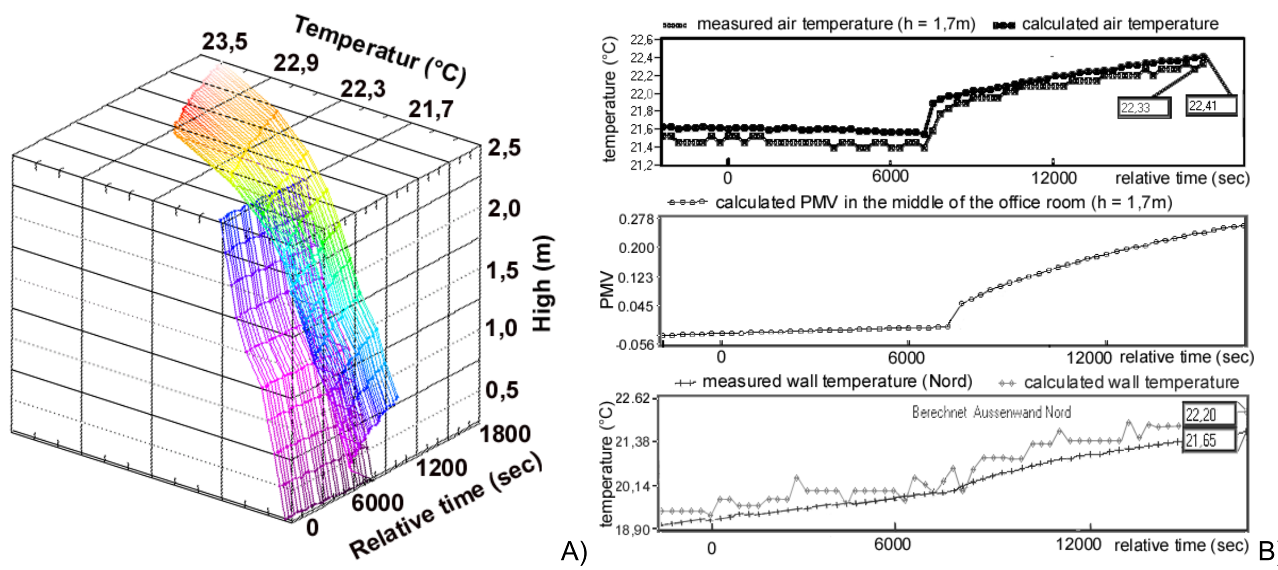

FIG. 5 - A) CALCULATED AIR TEMPERATURE B) CALCULATED AND MEASURED AIR TEMPERATURES, WALL TEMPERATURES AND PMV VALUES

Structures for object oriented manipulation of typical furniture elements, inhabitants, lighting, radiators etc. have been developed additionally. As important facts, the inclusion of the influence of solar radiation on the heat transfer coefficients of the wall elements and the solar energy flow inside the room, as well as mechanisms of energy transmission outwards, have been added. Furthermore, a user-friendly interface and a block structure, adapted for automation, have been realized in a LabVIEW environment.

The modified Glück-model (Fig. 4) allows estimating the thermodynamic state of the system at any position in the room (Fig. 5).

The calculation time depends on the accuracy of the result. The implementation of similar algorithms in other programming environments (i.e. C++) could reduce the computation time to a twentieth.

MODELLING OF STANDARD FUNCTIONS

The dilemma of the contradiction of simplicity and easy configuration on the one hand and a complex non-linear description of the energy distribution in the room with a lot of significant variables and parameters on the other hand is an important problem of new control approaches. The requirement for simplicity and easy configuration is usually met in control engineering by the classical linear approach (P, I, PI, PID, PTn controllers) [19, 20]. In order to realise control systems with linear object description, a large number of dependencies should be designated. The scheme of an Many Input – Many Output Linear Timeinvariant System (MIMO LTI)-system appears in Fig. 6.

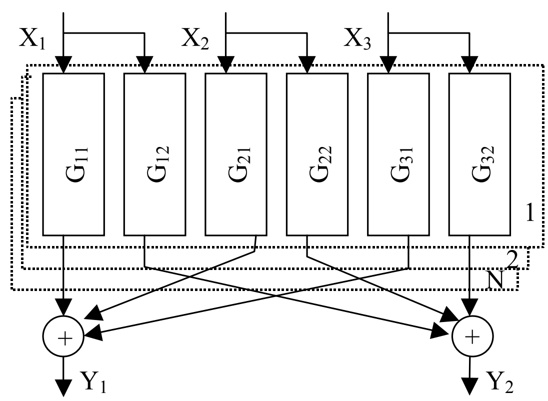

FIG. 6 - GENERAL STRUCTURE OF LINEAR MODELS FOR CONTROL AIMS: X_a –INPUT; Y_b – OUTPUT; G_{ab} – LINEAR PROCESS CHAINS; 1, 2,…, N – PARAMETER SETS FOR DIFFERENT CONTROL CONDITIONS

There are two problems to get linearity for physical descriptions: The experiment time needed and the impossibility to carry out “clean” experiments for identification of independent linear functions with experimental methods. In best case, the time *t* for experiments with the process chain can be approximated:

$$t = K_X \cdot K_Y \cdot N \cdot (\tau_{\max} \cdot \varsigma)\,, \tag{1}$$

where K_x and K_y are the numbers of inputs and outputs respectively, N is the number of linear state dependencies for a non-linear system, τ_{max} is the maximal time constant of the system, and ξ is a coefficient for independent measurement attempts (e.g., ξ takes into account the cooling time after the heating experiment etc.). In most practical cases it is to assume $\xi > 2$.

The time constants of buildings are normally big (ca. n*10 hours). According to eq. (1), a system identification of a system with 10 inputs, 1 output, and a time constant of 20 hours with a 3-point linear approach would take at least 2 months.

To obtain the G_{ab}-dependence (Fig. 6) without disturbances, all variables and parameters except X_a and Y_b have to be "frozen". This is impossible on a real world complex object like a building with numerous inter-dependencies and mutual disturbances. Again, there is no way out without a comprehensive thermal building modelling.

The proposed modelling technique consists of two parts. First of all, there is the complex model with a minimum set of equations (see pg.6). It is given by physical phenomena and variables, which are important for the problem. But the model is still non-linear. The second part in the modelling process is an automatic mechanism for identification of LTI system functions at given operating points (Fig. 7). In all cases, the calculation time for such applications should be relative short, in order to allow finite time pre-processing operation. The critical component here is again the complex thermodynamic model of the building.

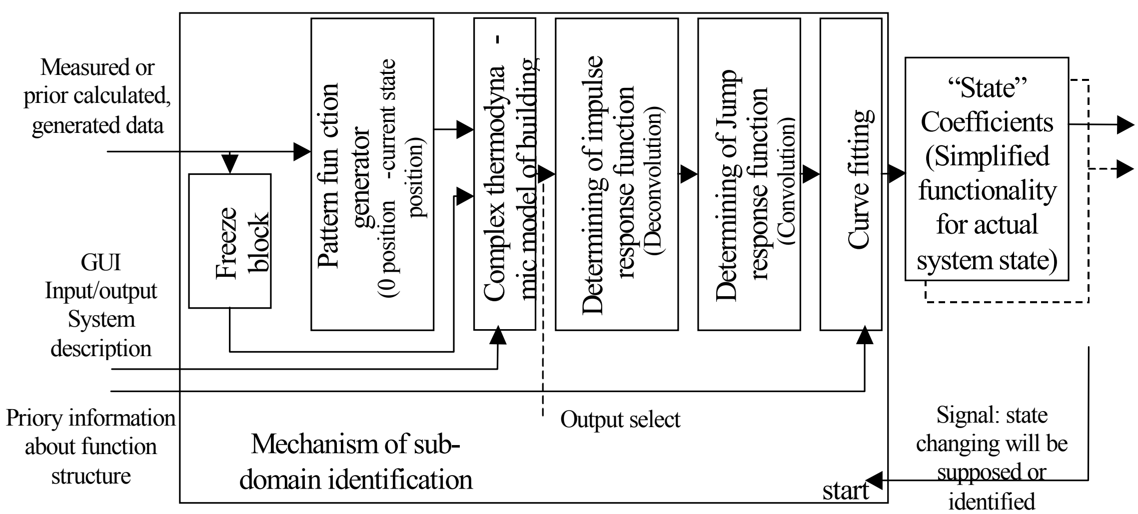

FIG. 7 - SYSTEM IDENTIFICATION ALGORITHM

There are three possibilities of identification in applications with a dual model structure as described above:

1. Off-line: The user measures the required data in front of the identification process. This data will be used for the validation of user-inputs and as input parameters of the model. After that, typical state conditions will be simulated and control parameter sets will be calculated (Fig. 8a).

2. On-line: A number of simultaneous calculations - one for each functionality - to compute the model set for the current system operating state point have to be executed on a powerful computation platform (Fig. 8b).
3. Hybrid: At system start a powerful computation platform is installed, which executes on-line calculations for real-world conditions. Afterwards, the parameter sets will be redefined and new parameter sets will be stored in a cheap control device (Fig. 8c).

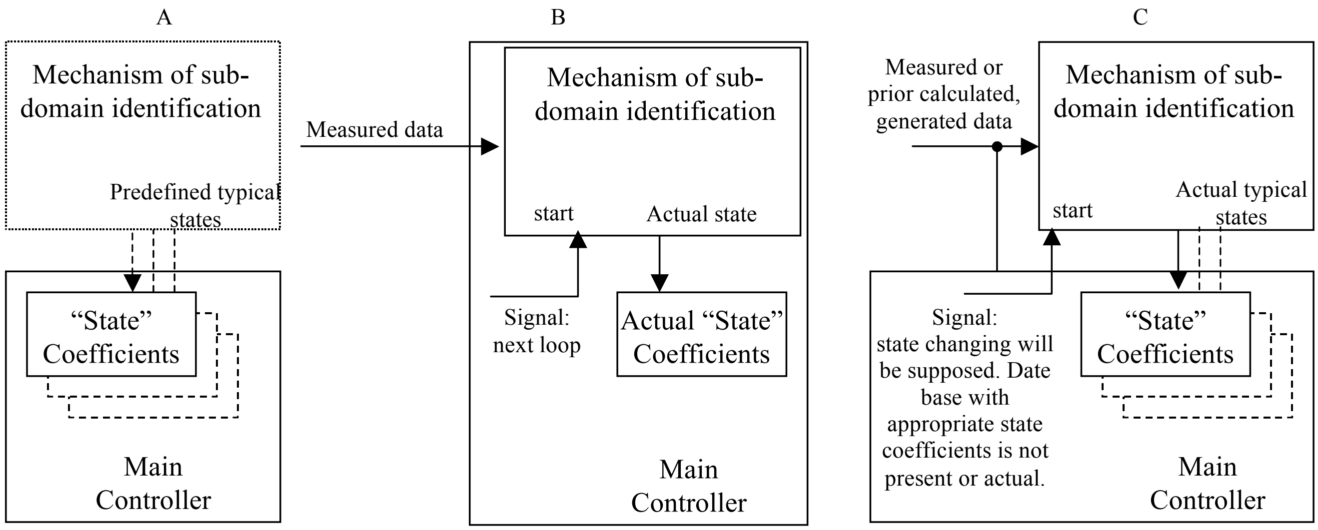

FIG. 8 - IDENTIFICATION OF SYSTEMS WITH DUAL MODEL STRUCTURE.
A) OFF-LINE, B) ON-LINE IDENTIFICATION AND C) HYBRID TYPE.

For the Smart HOME Laboratory the functions of heating response have been represented as functions with PT3-characteristic. The coefficients of these functions are automatically obtained using the Levenberg-Marquardt algorithm as shown in Fig. 6.

Functional dependencies have been received for heating power, power of electrical devices in the room, number of occupants in the room, sunshine, etc. as causes and air temperature in the room at different positions as well as with PMV factor as effects. Table 2 shows some data sets.

TABLE 2 - SAMPLES OF CALCULATED COEFFICIENTS FOR OFFICE ROOM

N	DEPENDENCE	K	T_1	T_2	T_3
1	Heating power -Air temperature	0,07	797	1045	994
2	Heating power - PMV	0,0061	1497,9	1495,2	1495,8

Calculation speed under a LabVIEW environment is about 20-40 minutes on a PC, that allows today off-line or hybrid type system identification. For this purpose an embedded PC can be used as a controller.

CONTROLLER DESIGN

A great number of control approaches provide the indoor air temperature as the only important environmental variable. In doing so P, PI [21], Fuzzy [22] or predictive [23] controllers have been used. Some more extensive approaches include the presence of persons [24] or the indirect involvement of comfort using representative measurable values [5]. Regarding the PMV as controlled variable, the room is a time-variant system with distributed parameters.

But as mentioned above, it is possible to describe this system by PT_3 transfer functions. Different time constants determine different behaviour on selected operating points. The disturbances in the system are deterministic as well as stochastic signals. A parameter optimised controller has been chosen, which will be adapted to the respective operating point via adjustment rules and which enables the control with both types of disturbance signals. A controller of this class is a PID controller. In consideration of the disturbances, two control strategies have been tested. The first is shown in Fig. 9a.

It is a feed forward PID control. The manipulated variable *u* is influenced by an additional open loop control *Gs* subject to the disturbances *z*. The second control strategy is an adaptive PID controller as shown in Fig. 9b. The adaptation of the controller parameters is oriented on the time variation of the error variable *e* and the disturbances *z*. The parameter settings for the PID-controllers are based on case scenarios (bedroom, bathroom, living room, kitchen at night and day respectively as well as heating, cooling and air conditioner maintenance, etc.)

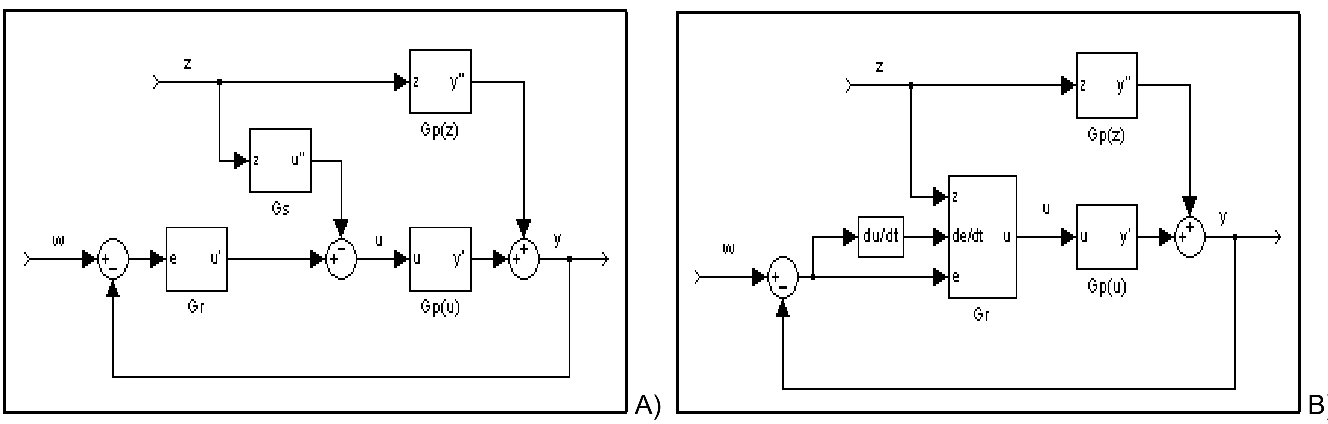

FIG. 9 A) FEED FORWARD AND B) ADAPTIVE CONTROL CIRCUIT

CONCLUSIONS

A simplified mixed type physical thermodynamic modelling technique has been discussed. It has been developed for specific tasks of demand-adjusted decentralised room climate control. The applied analysis of the task demand-adjusted decentralised room climate controls is discussed too.

The complex model is a substitution of the real process. It has been optimised for the sprcific control demands such as on-line calculation and precise dynamic. Using this model and modelling technique, parameters for an LTI system, that represents the real process on desired operational points, have been obtained. Thus it is possible to adapt controller parameters to any desired operational point. The modelling technique has been tested in real-world experiments.

As a result, an energy saving up to values in Fig. 1b will be expected. Simultaneously to an energetic contribution with this new approach it is possible to provide better thermal comfort in all types of buildings.

ACKNOWLEDGEMENTS

This work is supported by the Bayerische Forschungsstiftung under Grant 283/98 (Intelligent Instrumentation of Homes, IWO-BAY).

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