AN INTEGRATED BUILDING / SYSTEMS SIMULATION APPROACH TO ENERGY CONSERVATION

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Starting from current energy-conscious building practice, additional energy savings can only be achieved when the building, HVAC system(s), and occupants are approached as an integrated, dynamic system. Since this is not a trivial task, the design profession must be provided with tools which enable this.
Some recent advances in the field of integrated, building/ plant design support tools are described. An overview of the adopted approach is given. The research conducted thus far and directions for future work are indicated. By means of case-study material, early application in a real building performance evaluation context is demonstrated.

INTRODUCTION

From extensive theoretical and experimental research, the building (research) community acquired over the past decades a reasonably good idea of how to achieve energy conservation in buildings. When restricting to environmental conditions common to for example The Netherlands and other temperate climatic regions, the best strategy seems to first minimize heat transmission losses via the building envelope. The next step is to lower - ie optimize - energy consumption related to infiltration and ventilation. And finally to ensure that the remaining heat load is offset by high efficiency heat production.

All these measures have been taken in the past, but there is still a need to further lower energy consumption for heating purposes (in The Netherlands the government aims at a further 25% reduction - in terms of the 1989 consumption - by the year 2000).
We have now come to a point, however, where it becomes increasingly difficult to achieve additional energy savings. When concentrating on technical options (ie no psychological or sociological options in terms of occupant behaviour), an area with clear remaining potential for improvement seems to be the heating, ventilating and air conditioning systems. But in the current context, HVAC systems should not be researched in an isolated mode.

Need For An Integral Approach

The thermal interaction, under the influence of occupant behaviour and outdoor climate, between building and heating / cooling and ventilating system is still difficult to predict. One of the main reasons for this is the high diversity in dynamic properties. In practice this often results in non-optimal, malfunctioning, or even "wrong" building/system combinations. That this is not an over-statement has often been demonstrated (eg Hensen 1986, 1987). This concerned predictions and measurements for an extensive real scale experiment with several types of low-energy houses. Without going into details, one of the main conclusions was that there is definitively need and room for improvement on the plant and the control side. As another example: the actual seasonal efficiency of condensing boilers was in practice markedly lower than could be expected from experimental results collected in a laboratory environment (because return water temperatures were actually higher than anticipated).

These are merely a few practical examples drawn from a large class of problems for which the complete "system" consisting of building structure, occupants, HVAC plant, and prevailing climate must be evaluated as a whole and simultaneously. Other examples belonging to the same problem domain and which definitively need this integral approach are: Sick Building Syndrome, Building Energy Management Systems, passive solar applications, HVAC system and control development, extraordinary building / system combinations (eg in case of re-destination of historical buildings or in case of relatively new developments like atria).

There are several reasons why the above mentioned problems and the need for an integral approach have become more important during the last decades: (1) reduction of heating / cooling demand enabled drastic lowering of the system's heating / cooling capacity but also caused the system to become much more sensitive to "thermal disturbances"; (2) energy conscious behaviour which implicitly makes higher demands upon the system, and which causes the building / system combination to frequently operate far outside the design region; and (3) aiming for higher comfort levels also makes higher demands upon the building / system tuning.

The work underlying this paper starts from the premise, that additional energy savings can only be achieved when the building (including it's distributed flow paths), HVAC system(s), and occupants are approached as an integrated, dynamic system. This is not a trivial task. So the design profession must be provided with tools which enable such an integral approach.

OUTLINE OF THE APPROACH

The objective is development / enhancement of building performance evaluation tools addressing the dynamic thermal interaction between a building and its indoor climate control system, which results from the different dynamic characteristics of the building and plant. In this context, thermal comfort and energy consumption are the objective functions.

Early research in this area focussed on the relation between building design and energy consumption (eg Clarke 1977, Bruggen 1978), with the auxiliary system usually regarded as parameter instead of as a variable. Only recently more attention has been paid to the plant side of the overall problem domain (eg CEC 1983, 1987, 1991, and Lebrun 1988). In the former approach the influence of the plant system is more or less neglected by oversimplification of the plant. In the latter approach the complex building energy flow paths are usually grossly simplified.

Here we started from the principle that neither approach is preferable for the majority of problems indicated above: both building and plant have to be approached on equal levels of complexity and detailedness. This contribution now continues with an overview of the research and of the results obtained thus far. A more rigorous description may be found elsewhere (Hensen 1991).

In view of the hectic developments in the area of information technology, it is difficult to predict the future options for building designers and system consultants. There is no doubt however that these will be much larger than at present (see eg Augenbroe and Laret 1989). In practice this means that it is not yet clear what kind of form the design tools should take. Because of this unclearness and to link up with established and recently initiated international research (intelligent knowledge based systems, energy kernel system (see eg Clarke and Maver 1991, Sowell et al. 1989), we started from an existing platform and focussed on enhancement of knowledge concerning computer simulation of building and heating system.

This platform is the energy simulation research environment *ESP*[R] (Clarke 1977, 1985, Clarke et al. 1991) as currently under development and subjected to a rigorous validation programme (CEC 1989) at various centres throughout Europe including the Universities of Strathclyde and Eindhoven. Starting from such a platform offers vast advantages for any individual research group. The most important ones are: (1) as an individual group it is not necessary to have expertise in all areas, (2) areas not addressed within a specific research project will still be state-of-the-art, (3) as more people are using the system, any bugs or flaws are likely to surface sooner, and (4) results transfer to the international research community is implicit and therefore very efficient.

ESP^R is a building energy simulation environment which is based on a numerical approach using finite volume, state-space conservation equations, in which all heat fluxes are handled simultaneously. The system is very graphically oriented, offers climate, construction, profiles database management, and incorporates shading, solar beam tracking, view factors, window power spectrum response, comfort assessment, condensation, air flow modelling (pressure and buoyancy driven infiltration and zone coupled flows). At the project commencement, the system was examined on its facilities and capabilities in the area of simultaneous building and plant energy simulation. One of the outcomes of this was that there was a need to develop further the fluid flow and the plant simulation side, and to enable better integration with the building side.

Fluid Flow Simulation

Within the *ESP^R* approach, during each simulation time step, the problem is constrained to the steady flow (possibly bi-directional) of an incompressible fluid along the branches of a network which represents the building/ plant mass flow paths. Information on potential mass flows is given by a user in terms of node descriptions (representing building zones, points in the HVAC system, etc), fluid types (currently air and water are supported), flow component types (cracks, vents, ducts, pipes, pumps, etc) and interconnections. In this way a nodal network of connecting resistances is constructed. This may then be attached, at its boundaries, to known pressures or to pressure coefficient sets which represent the relationship between free-stream wind vectors and the building external surface pressures to result. The flow network may consist of several decoupled sub-networks and is not restricted to one type of fluid. Conservation of mass at each internal node yields a set of simultaneous non-linear equations subjected to a given set of boundary conditions. The solution method employes a simultaneous whole network Newton-Raphson technique.

The current *ESP^R* fluid mass flow simulation module *mfs* module may be operated in stand-alone mode (eg to prove integrity of a defined flow network). However, *mfs* appears to fuller advantage when it is used in tandem with *ESP^R*'s main building and plant energy simulation module *bps*. This enables energy, air quality and comfort studies of combined building and plant configurations in which the fluid flow rates may vary with time due to changing temperatures, pressures or flow path characteristics. For more information the reader is referred to other publications which describe *mfs* in the specific context of air flow simulation (Clarke and Hensen 1990), plant fluid flow simulation (Hensen and Clarke 1990), or coupled heat and mass transfer in buildings (Hensen and Clarke 1991), respectively.

Plant Simulation

With respect to dynamic plant simulation techniques, two main approaches can be distinguished: (1) the sequential modelling technique, of which TRNSYS (SEL 1988) is a well known representative, and (2) the simultaneous modelling technique, which involves representation of the plant by discrete nodal schemes, and derivation of energy and mass flow equation sets which represent whole-system, inter-node exchanges over time and space dimensions.

The current research uses a modular-simultaneous technique which starts from the "control volume conservation, state-space approach" as described by Tang (1985). In this technique, plant system modelling is achieved by a modular, component-wise approach. Each plant component model consists of one or more finite volume, state-space equations, representing the conservation of heat and mass. The plant system is a combination of component models forming a complete set of state-equations for the whole system. At run time, each component has a corresponding subroutine whose mission is to generate the coefficients of these matrix equations.

Although it may appear that there are many plant component models readily available from literature, this is deceptive to say the least. The reasons for this are: (1) most models encountered are described in an analytical fashion (ie no numerical formulation), (2) almost all numerical models encountered are geared at the sequential modelling technique, (3) most models encountered are steady-state approaches, and (4) (almost) same model descriptions keep on re-occurring.
No model was found in literature which could readily be used as it was. Developing or adjusting models is often difficult and time-consuming. Only recently have incentives taken place to facilitate this process by for instance establishment of a data-base of component models (Lebrun & Liebecq 1988), development of a "neutral format model" which should be usable for various simulation environments (Sahlin & Sowell 1989), or development of other concepts which are aimed at making reuse of models easier (Mattsson 1989).

The currently supported plant component types include: humidifier, heating coil, cooling coil, fan, heat recovery unit, boiler, radiator, pipe, pump, thermostatic radiator valve, room thermostat, etc. The present status of the plant modelling potential is that real systems can be modelled, for example (wet) central or air heating systems, packaged air conditioning systems, etc. More esoteric systems are not yet possible.

Coupling of Building and Plant

In a mathematical/ numerical sense, this effectively means combining the energy and flow balance matrix equations for both the building and its plant (Clarke 1985). While in principle it is possible to combine all building / plant and heat / fluid flow matrix equations into one overall 'super-matrix', this is not done primarily because of the advantages which accrue from problem partitioning.
The most immediate advantage is the marked reduction in matrix dimensions and degree of sparsity. A second advantage is that it is possible to easily remove partitions as a function of the problem in hand; for example when the problem incorporates building only considerations, plant only considerations, plant + flow, and so on. A third advantage is that, potentially, different partition solvers can be used which are well adapted for the equation types in question - highly non-linear, differential and so on.
Obviously there are often dominating thermodynamic and/ or hydraulic couplings between the different partitions. If a variable in one partition (say air temperature of a zone) depends on a variable of state solved within another partition (say the temperature of a radiator), it is important to ensure that both values match in order to preserve the thermodynamic integrity of the system. Without going into details, two methods are offered to handle these couplings: (1) a time step control facility, and (2) an iteration mechanism (for more information see Clarke 1985 and Hensen 1991).

CASE STUDY

Application of the system can be demonstrated by means of a case study. This particular project - on building and plant thermal interaction - was inspired by experimental findings from pilot measurements which were carried out near the start of the project. These measurements, reported in (Hensen et al. 1987), were carried out in a relatively small flat with ditto heating system (wet central heating system, controlled by a mechanical room thermostat). Technical considerations led to some modifications of the heating system during the measurements, one of which was disabling the thermostat's acceleration heating (which is used to raise the temperature of the sensitive element more rapidly towards the switch-off temperature in order to decrease the room air temperature differential). The acceleration heating is very important with respect to the boiler switch frequency. In this specific case and given the prevailing environmental conditions, the burner cycle time (burner-on till burner-on) was about 90 times longer when the acceleration heating was disabled. The total burner-on time - for an equal period of time - was approximately 50% shorter, suggesting a strong decrease in fuel consumption. It should be noted however, that in this specific case both the number of cycles per hour (at average heating season

conditions ≈ 30) and the boiler stand-by heat losses may be regarded as well above average.
A longer cycle time has also consequences with respect to the fluctuation of the air temperature. Without the acceleration element the fluctuation of the mean room air temperature during one cycle, is much larger. Whether the resulting conditions would be acceptable to the occupants was investigated by means of a literature study on thermal comfort in transient conditions. The results of this study are reported elsewhere (Hensen 1990).

The objective of the present case study was to see whether the above observations can be repeated - by computer simulation - for a more general case, and to investigate whether decrease of thermostat acceleration heating might be a potential energy conservation strategy.

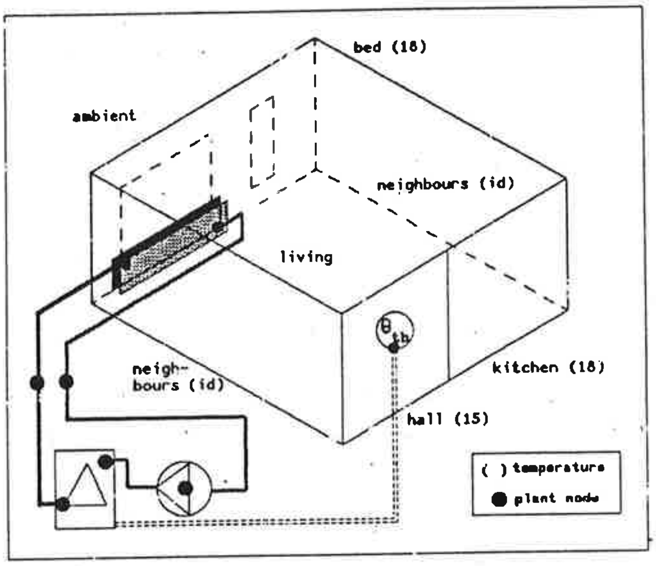

Figure 1 Schematic representation of a building and plant configuration comprising a living room serviced by (part of) a wet central heating system.

Imagine a building and plant configuration as schematically shown in Figure 1. The room is part of a reference house for energy related research as described in (NOVEM 1990), which represents a typical Dutch, garden-orientated, terraced house. The exterior envelope is insulated according to prevailing regulations. For the present study, the air temperatures of the spaces adjoining the living room are kept at constant values as indicated. The living room is serviced by (part of) a wet central heating system, comprising: a (two node model) radiator, a (two node model) high efficiency condensing boiler (scaled down to accommodate the current single radiator system), a pump delivering a fixed water flow rate, piping as indicated, and a mechanical room thermostat located in the living room. Two plant control loops were defined to drive the system: (1) to actuate the boiler on the basis of the temperature sensed by the room thermostat, and (2) to simulate the acceleration heating of the room thermostat.

The degree of heat input is the primary parameter to be considered in the following. To illustrate the influence of the degree of acceleration heating, Figure 2 shows some simulation results comprising a two hour period of a Dutch climatic reference year for energy research (Bruggen 1978). The simulations were performed for two values of thermostat heat input: 0.05 and 0.10 *W*. For the given conditions, this gives either approximately 1 or 2 cycles per hour, resulting in air temperature differentials of approximately 1 and 2 *K* respectively. Figure 2 also indicates the set point differential. It may be seen that in the 0.05 *W* input case, the sensed temperature still rises even after the burner is switched off. This is due to the fact that at those points in time the room air temperature is actually higher than the thermostat set point. Note that there are two transient factors which play a role in the time lag and damping of the sensed temperature when compared to the room

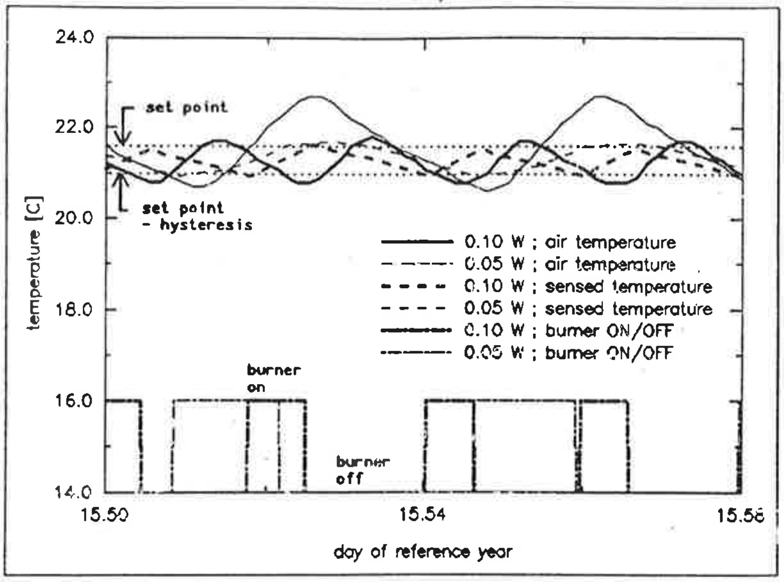

Figure 2 Influence of acceleration heating on fluctuation of mean living room air temperature and on temperature as sensed by the room thermostat during a two hour simulation period.

air temperature: (1) the sensed temperature depends on both air temperature and building construction temperatures (which lag behind because of thermal inertia of the building materials), and (2) thermal inertia effects of the heating system itself.

To investigate whether the overall gas consumption is also affected, several simulations - comprising the period January 12 to January 15 inclusive - were performed for various degrees of acceleration heating. When compared to average climatic conditions for The Netherlands, the data for January 13 represent an extremely cold day, while the data for January 15 represent a fairly average day.

Table 1 Results of simulations - comprising the period January 12 to January 15 inclusive - for various degrees of acceleration heating applied to the mechanical room thermostat

description		parameter value or result				
acceleration heating	W	0.20	0.10	0.05	0.01	0.01
set point	°C	22.4	21.5	21.5	21.5	20.8
overall average air temperature	°C	20.6	20.7	21.1	21.5	20.8
idem but Jan 13 only	°C	20.4	20.7	21.1	21.3	20.4
idem but Jan 15 only	°C	21.3	21.3	21.6	22.0	21.3
average cycle freq. Jan 13 only	h^{-1}	4.0	1.8	1.0	0.8	0.8
average cycle freq. Jan 15 only	h^{-1}	4.5	2.0	1.1	0.9	0.9
air temp. differential Jan 13 only	K	0.3	1.3	2.3	3.3	3.3
air temp. differential Jan 15 only	K	0.3	1.0	2.1	3.0	3.0
total gas consumption	m_0^3	16.1	16.0	16.6	17.1	16.0
idem but Jan 13 only	m_0^3	4.9	5.0	5.2	5.4	5.1
idem but Jan 15 only	m_0^3	2.9	2.7	2.9	3.0	2.7

From results not presented here it is clear that when the simulations would start from a constant thermostat set point, this would lead to different average room air temperatures. Obviously the results would then be incomparable. Therefore some of the thermostat set points where chosen (by trial and error) such that the resulting average room air temperature (for January 15) would be equal. The most important simulation results - with respect to the investigated problem - are collected in Table 1. When the cycle frequencies and the corresponding air temperature differentials are compared with the thermal comfort criteria as indicated before, all cases presented in Table 1 fall within the comfort limits for transient conditions.

When comparing the gas consumption results for the cases with equal average air temperature, Table 1 indeed evidences that it is possible to conserve energy - while maintaining thermal comfortable conditions - by decreasing the burner cycle frequency. Lowering the cycle frequency from 4.5 to 2.0 h^{-1}, results in a gas consumption reduction of only 1% when the whole period is taken into account, but in a 7% reduction when just the "average heating season day" (ie January 15) is taken into account. This suggests that the optimal strategy is to apply the "cycle frequency control" strategy selectively; ie weather dependent.

Obviously the above has to be investigated further with respect to what is the optimal strategy (ie development of rules for intelligent controllers), and for which type of systems is it applicable. In the present context, this case study should be regarded as a demonstration of applying the approach presented in this contribution.

CONCLUSIONS

This contribution describes a "modular-simultaneous" approach for the simulation of combined heat and fluid flow in a building / plant context. The present performance of the model indicates that it is now feasible to simulate building / plant configurations in the transient state and on equal levels of detailedness on inexpensive computer.
While the model is robust and well adapted for its task, several future developments have been identified. These include the development of additional fluid flow components (especially improved large opening models), the development of additional plant component models in the required 'state-space' format, and experimental validation of the simplifying assumptions in the component models. In a more general sense there is also much work still needed in the areas of verification, user interface (front-end, results analysis), software structure and integration in CABD, application, and technology transfer.

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References

Augenbroe, G.L.M. and L. Laret 1989. "COMBINE (Computer Models for the Building Industry in Europe) Pilot study report," Information package for the DG XII programme "JOULE", Commission of the European Communities DG XVII, Brussels.

Bruggen, R.J.A. van der 1978. "Energy consumption for heating and cooling in relation to building design," PhD dissertation Eindhoven University of Technology (FAGO).

CEC 1983. *System Simulation in Buildings. Proceedings of the International Conference held in Liège (Belgium) on 6-8 December 1982*, Commission of the European Communities, Brussels. J. Lebrun (ed.), CEC report XII/425/83-EN

CEC 1987. *System Simulation in Buildings. Proceedings of the International Conference held in Liège (Belgium) on 1-3 December 1986*, Commission of the European Communities, Brussels. J. Lebrun (ed.), CEC report XII-469-87-EN

CEC 1989. "The PASSYS Project Phase 1. Subgroup Model Validation and Development Final Report 1986-1989," 033-89-PASSYS-MVD-FP-017, Commission of the European Communities, DG XII of Science, Research and Development, Brussels.

CEC 1991. *System Simulation in Buildings. Proceedings of the International Conference held in Liège (Belgium) on 3-5 December 1990*, Commission of the European Communities, Brussels. J. Lebrun (ed.), CEC report in print

Clarke, J.A. 1977. "Environmental Systems Performance," PhD thesis University of Strathclyde, Glasgow.

Clarke, J.A. 1985. *Energy simulation in building design*, Adam Hilger Ltd, Bristol (UK).

Clarke, J.A. and T.W. Maver 1991. "Advanced design tools for energy conscious building design: development and dissemination," *Building and Environment*, vol. 26, no. 1, pp. 25-34.

Clarke, J.A. and J.L.M. Hensen 1991. "An approach to the simulation of coupled heat and mass flow in buildings," in *Proc. 11th AIVC Conf. Ventilation System Performance held at Belgirate (I) 1990*, vol. 2, pp. 339-354, IEA Air Infiltration and Ventilation Centre, Coventry (UK).

Clarke, J.A., J. Hand, P. Strachan, J.L.M. Hensen, and C.E.E. Pernot 1991. "ESP[R] A building and plant energy simulation research environment," Energy Simulation Research Unit, ESRU Manual U91/2, University of Strathclyde, Glasgow.

Hensen, J.L.M. and P.J.J. Hoen 1986. "Energieproeftuin: a real scale experiment with low-energy dwellings in The Netherlands," in *Proc. Int. Climatic Architecture Congress*, Louvain-la-Neuve (B).

Hensen, J.L.M. 1987. "Energieproeftuin: results of an experiment on low-energy housing in The Netherlands," in *Proc. European Conference on Architecture*, Munich.

Hensen, J.L.M., L.C.H. Dings, and W.J.A. van de Ven 1987. "Meetproject Someren," rapport FAGO 87.08.K., Technische Universiteit Eindhoven, Eindhoven.

Hensen, J.L.M. 1990. "Literature review on thermal comfort in transient conditions," *Building and Environment*, vol. 25, no. 4, pp. 309-316.

Hensen, J.L.M. and J.A. Clarke 1991. "A fluid flow network solver for integrated building and plant energy simulation," in *Proc. 3rd Int. Conf. on System Simulation in Buildings, Dec 1990*, pp. 151-167, University of Liege.

Hensen, J.L.M. 1991. "On the thermal interaction of building structure and heating and ventilating system," PhD dissertation Eindhoven University of Technology (FAGO).

Hensen, J.L.M. and J.A. Clarke 1991. "A simulation approach to the evaluation of coupled heat and mass transfer in buildings," in *Proc. 2nd IBPSA World Congress "Building Simulation '91", Nice, Aug 1991*, pp. 219-226, Int. Building Performance Simulation Association.

Lebrun, J. and G. Liebecq 1988. "System simulation in buildings; models of HVAC components," in *Proc. USER 1 working conference at Ostend*, pp. 17-22, Society for Computer Simulation International, Ghent (B).

Lebrun, J. and G. Liebecq 1988. "System Simulation Synthesis Report," Energy conservation in buildings & community systems programme; Final report Annex X, International Energy Agency. Operating agent: University of Liège, J. Lebrun, report AN10 881020-RF

Mattsson, S.E. 1989. "Concepts supporting reuse of models," in *Proc. Building Simulation '89*, pp. 175-180, International Building Performance Simulation Association IBPSA, Vancouver.

NOVEM 1990. *Referentie Tuinkamerwoning*, Nederlandse Maatschappij voor Energie en Milieu, Sittard.

Sahlin, P. and E.F. Sowell 1989. "A neutral format for building simulation models," in *Proc. Building Simulation '89*, pp. 147-154, International Building Performance Simulation Association IBPSA, Vancouver.

SEL 1988. "TRNSYS, a transient system simulation program," Engineering Experiment Station Report 38-12, University of Wisconsin-Madison, Solar Energy Laboratory, Madison, WI. Manual for version 12.2 and later

Sowell, E.F., W.F. Buhl, and J-M. Nataf 1989. "Object-oriented programming, equation-based submodels, and system reduction in SPANK," in *Proc. Building Simulation '89*, pp. 141-146, International Building Performance Simulation Association IBPSA, Vancouver.

Tang, D. 1985. "Modelling of heating and air-conditioning system," PhD thesis University of Strathclyde, Glasgow.