APPLICATION OF MODELLING AND SIMULATION TO HVAC SYSTEMS

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ABSTRACT *This paper attempts to describe the advantages and disadvantages of different modelling approaches for design and performance evaluation of heating, ventilating, and air-conditioning (HVAC) systems for buildings. Merits and drawbacks of the various modelling methods are illustrated by case study material. Finally some conclusions and directions for future work are indicated.*

Keywords: building energy modelling, building energy simulation, HVAC systems

1. Introduction

When speaking about ‘a building’, often, we actually mean the whole of building form and fabric, heating, ventilating, and air-conditioning (HVAC) and other systems. This ‘whole’ comprises a wide area, where many problems occurring in practice are in fact caused by the complexity due to interactions between the various sub-fields.

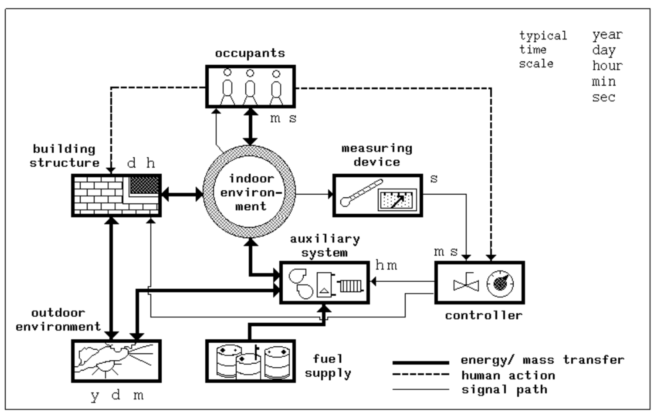

Figure 1 The building as an integrated, dynamic, thermal system

Some of the (thermal) interactions are indicated in Figure 1., which is obviously merely a gross simplification of reality, because in the real world this is a n-dimensional problem involving the 3-dimensionality of building and plant, the dimension of time, and the dimension of the various aspects like: thermal environment, air quality, lighting, acoustics, etc.

On average we spend around 90% of our whole life inside buildings. Energy consumption in buildings accounts typically for over 30 - 40% of the national total annual energy consumption. Heating, ventilating, and air-conditioning (HVAC) systems are major energy users in buildings. When considering the costs of a new building, some 30% up to 50% is related to HVAC systems in case of commercial buildings, and 5% up to 10% in case of domestic buildings. Hence, both with respect to environmental impact and economics, the ability to make sensible and well based decisions regarding the choice and design of HVAC systems, is of the utmost importance.

Like many other design problems, HVAC systems can only be meaningfully assessed when treated as a sub-set of some complex set of interactions. In other words, a piecemeal approach, in which a particular region (here the HVAC system) is considered in isolation, is often inappropriate and potentially misleading.
One of the most powerful techniques currently available for an integrated approach is modelling and simulation.

2. HVAC System Modelling and Simulation Approaches

Energy simulation in the building context has until recently been focused primarily on the building side of the overall problem domain (see eg Clarke 1985). We now see that modelling of HVAC systems and associated (air) flow phenomena in the context of building design and building performance evaluation, is rapidly gaining more and more interest in both the building and environmental engineering communities.

In comparison to those for building side issues, the range of modelling and simulation approaches for HVAC and other environmental control systems is much greater.
When allowing very coarse distinctions, one could categorize simulation systems and models as: steady-state or dynamic, general or domain specific, stand-alone or integrated, open or closed, conceptual or explicit, process based or component based, sequential or simultaneous, input/output oriented or based on conservation representations, etcetera.

In terms of steady-state versus dynamic, the current consensus amongst the modelling community still seems to be that dynamic system operation can be approximated by series of quasi steady-state operating conditions, provided that the time-step of the simulation is large compared to the dynamic response time of the HVAC equipment. Obviously this is not the case in dynamic control system simulations in which calculations need to be performed almost on a second-by-second time scale.

In terms of general versus specific, non-domain specific simulation systems such as MATLAB/SIMULINK, TUTSIM, EASY5x, etc,[‡] are quite popular in other engineering areas. However they are apparently not often used for building energy simulation; check for instance the proceedings of past conferences on System Simulation in Buildings (held at the University of Liege in 1982, 1986, 1990, and 1994) or the proceedings of past IBPSA (International Building Performance Simulation Association) conferences (Vancouver 1989, Nice 1991, and Adelaide 1993).
As elaborated elsewhere (Schijndel and Hensen 1993), in case of block diagram programs the main reason for this is that, unless the building and plant is very strongly simplified, the number of 'blocks' will be very large resulting in excessive CPU usage, and administration problems (spaghetti structure). Other important reasons are: non-availability of typical building energy 'boundary condition generators' (for instance for processing weather data, predicting insolation and shading, etc); non-availability of typical building energy 'result analyzers' (for instance for assessing comfort, converting energy to fuel, etc); users have to take care of numerical modelling issues such as time and space discretisation (accuracy and stability) and avoidance of 'algebraic loops' (solvability); users first have to learn the syntactical and semantical properties of the program.

Although HVAC oriented programs like TRNSYS and HVACSIM+ could in origin be labeled as stand-alone, these and most currently used building energy simulation packages now aim to enable an integral approach of building and plant.

Open versus closed (meaning extensions can only be achieved via editing and re-compiling existing code) is an important issue in terms of flexibility. However, since most current building energy modelling systems are effectively closed - and due to space constraints - this issue is also not considered here.

Another way of discriminating between various approaches to building systems modelling and simulation is by considering the level of abstraction - ranging from purely conceptual to fully explicit - in terms of user specification and/or mathematical/ numerical representation as summarized in Table 1. (For more elaborate descriptions of levels of abstraction, including example applications for each level, see Hensen 1995.)

Table 1 HVAC system modelling abstraction levels

level		type
A	room processes only; ideal plant	CONCEPTUAL
B	system wise in terms of (real) systems like VAV, WCH, etc	|
C	component wise in terms of duct, fan, pump, pipe, etc	V
D	subcomponent level in terms of energy balance, flow balance, power balance, etc	EXPLICIT

In the case of **LEVEL A**, specification and representation of plant systems is purely conceptual in that only the room processes are considered. This means that a user may specify whether heat supply or removal is completely from the air (representing air heating or cooling), from within a construction (representing for instance floor heating or a cooled ceiling), or a mix of convection and radiation (in case of for example radiators or convectors). Disadvantages of this approach are that only the room processes are considered. All other processes in the plant (generation, distribution, and control) are assumed to be ideal. Subsequently this approach only results in 'gross' energy

[‡] instead of full references, a table identifying the author organization of each simulation system is attached

requirements and will not be able to predict fuel consumption or energy required for distribution of working fluids. The main advantages of this approach are versatility and flexibility, and a user needs only to know about the room side processes. ESP-r is one of the many simulation systems operating on this level.

In the case of **LEVEL B**, the specification by the user is in terms of (real) systems like variable-air-volume, variable temperature constant volume, constant-volume zone re-heat system, four pipe fan coil, residential wet central heating, etc. Behind the scenes the mathematical and numerical representation is often a combination of Level A and Level C approaches. The main disadvantage of this approach is the restriction imposed on the user due to the limited number of systems which are usually on offer. The main advantage of this approach is the relative ease of problem definition for the user. Examples of simulation systems operating on this level are DOE-2, BLAST, and TSBI3.

In the case of **LEVEL C** both the specification by the user and the internal representation is in terms of individual plant components like fan, duct, heating coil, boiler, pump, pipe, etc., which are connected to form complete systems. Two main approaches can be distinguished in terms individual component models: input-output based (each separate part of the system (building zone, single component, sub-system etc.) is represented by an equivalent input-output relationship), and conservation equation based (each plant part is described by time-averaged discretised heat and mass conservation statements which are combined to form the plant system matrix, and which are solved simultaneously for each simulation time step).
Advantages of the input-output method are: a mixture of modelling methods (analytical, numerical, internal look-up table, etc.) may be used for the different configuration components thus enabling piecemeal component model development from simple to more complex descriptions; and because of the highly modular structure it is relatively easy to add or change certain component models. Most contemporary system simulation environments use this input-output based modelling technique. Well known examples are TRNSYS and EMGP 3.
The main advantages of the conservation equation method is its simultaneous solution method. The main disadvantage is that does not allow a mixture of modelling methods. Examples of conservation equation based systems are HVACSIM+ and ESP-r.

In the case of **LEVEL D** the specification by the user is in terms of individual components linked to form complete systems as in the case of Level C. However, at this level the internal representation is further divided in for instance energy balance concepts, flow balance concepts, power balance concepts, etc. Each balance is then solved simultaneously for the whole system. This problem partitioning technique has several advantages. The first advantage is the marked reduction in overall 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 energy balance only considerations, flow balance only considerations, energy + flow, flow + power, and so on. But the most important advantage is that different partition solvers can be used which are well adapted for the equation types in question - highly non-linear, differential and so on, thus enabling solution of "integral system" problems which cannot be handled at level C. ESP-r, for example, operates on this Level D.

3. Applications

There are a whole range of issues in HVAC design and performance prediction which would/could benefit from an integrated approach using modelling and simulation as opposed to the currently used more traditional engineering techniques. Examples are: critical sizing, operation optimization, real time pricing operation, predictive control, mixed mode systems, structure supported systems, new developments, etc.

The best way to illustrate both several application areas and modelling approaches as discussed in the previous section, is by presenting case studies. Due to space constraints, this needs to be limited to two very brief descriptions. (Other, and more elaborate, case studies may be found in, for example, Aasem et al 1994, and Clarke et al 1995.) Although these examples could have been modelled using other building energy simulation environments, the following examples are based on ESP-r.

3.1. Critical Sizing using Conceptual Modelling

Consider the building as indicated in Figure 2, which consists of 3 zones: demo/sales area, office, and attic. The building - located in the Greater London area - is used for demonstration and sales purposes. Both in view of the products being marketed and the customers/personnel involved, the air temperature in the demo/sales area should be kept within certain limits.
For summer conditions, the initial suggestion is to keep the indoor air temperature below 26°C continuously.

In the traditional approach, manual calculations would be performed to calculate the necessary size of the cooling equipment and the rest of the HVAC system. This would typically be based on extreme weather conditions, and in one way or another (usually quite simplified) the dynamic characteristics of the building would be taken into account. (Building thermal dynamics are very important for cooling problems.) Usually the traditional approach

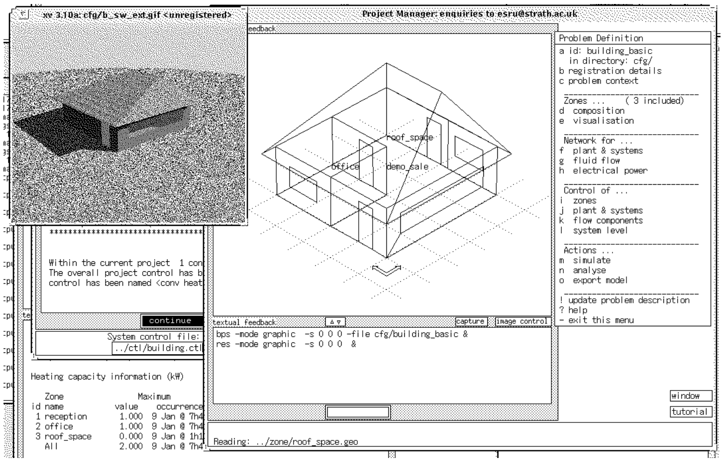

Figure 2 Graphical feedback of building model

involves a not very trivial procedure (neither in terms of development nor application).

Using dynamic building energy simulation, on the other hand, it is relatively easy to generate superior information in terms of cooling equipment sizing, even when using a conceptual approach to modelling the system.
This conceptual approach makes use of the fact that the energy balance of the building effectively comprises two unknowns: indoor air temperature and cooling/heating load. If one of the two is ‘fixed’ all other temperatures and energy fluxes can be calculated.

Table 2 Frequency distribution of cooling loads for demo/sales area

load *W*		occurrence hours	freq %	cumm %
3000	2500	18	2	2
2500	2000	104	8	9
2000	1500	205	9	19
1500	1000	338	12	31
1000	500	580	22	53
500	0	1104	47	100

The above was done for all hours of the July - September period of some climatic reference year applicable to the London area. From this it was found that the maximum (dynamic) cooling load for the demo/sales area would be 2910 W, with a frequency distribution of loads as indicated in Table 2.

Table 3 Demo/sales area air temperature occurrences and cooling energy demands in case of reduced cooling capacity

cooling capacity *W*	air temperature demo/sales area <= 26 *h*	26-27 *h*	27-28 *h*	28-29 *h*	29-30 *h*	> 30 *h*	cooling energy *MJ*
2910	2208	0	0	0	0	0	3067
2500	2179	27	2	0	0	0	3060
2000	2071	100	32	5	0	0	2988
1500	1950	115	66	55	19	3	2794
1000	1748	183	76	70	50	81	2408
500	1409	278	145	92	65	219	1652
0	869	267	275	208	150	439	0

From Table 2 it is obvious that the cooling plant would operate at very low loading levels during most of the time. The next question is: what are the consequences of installing a lesser capacity cooling system. For this, a sequence of simulations were carried out in which the plant cooling capacity was step-wise decreased. The results, in terms of air temperature occurrences and cooling plant energy consumption are summarized in Table 3.

Although this case study represents a - perhaps - simplistic approach to system simulation (for which almost no parameters were needed to describe the system), some valuable design conclusions can be drawn. It is only with results such as in Table 2 and Table 3 (which can only be generated using dynamic simulation), that the designer, in consultation with the client, will be able to critically size the system.

3.2. Control Performance Evaluation using Explicit Modelling

This second case-study concerns a historical building in Edinburgh, Scotland, which is being converted into a museum and art storage. In view of the artifacts being displayed and stored in the museum, some spaces need very strict temperature and humidity control. A study (Clarke et al 1996) was carried out in order to predict the performance of a HVAC system as suggested by the client (see Figure 3).

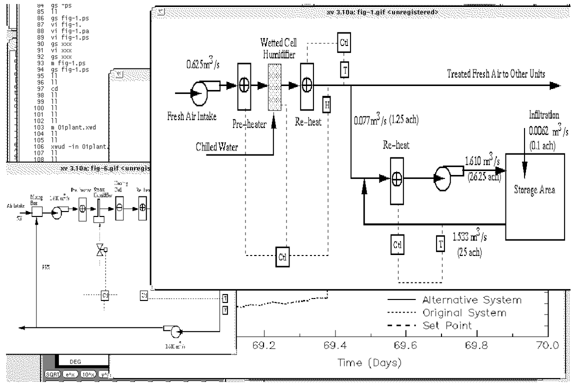

Figure 3 Models of the HVAC systems being considered

Some results in terms of relative humidity control are shown in Figure 4. From the simulation results it was evident that for low latent load levels, the HVAC system as originally proposed would be capable of maintaining the desired temperature and relative humidity levels across a range of typical and design weather conditions. However, should these latent loads increase then an alternative HVAC system offering closer control on humidity would be required. Figure 4 compares relative humidity control possible with two HVAC system arrangements: the originally proposed system, and a modified system (bottom left in Figure 3) in which each storage space is independently serviced.

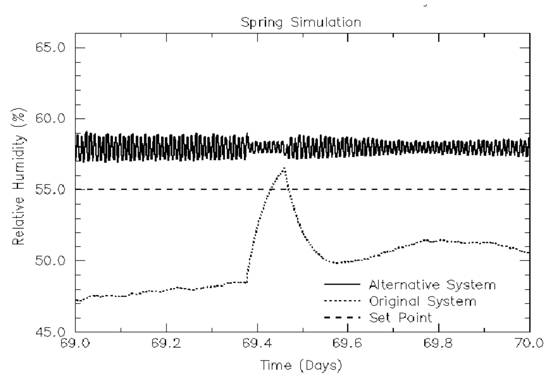

Figure 4 Relative humidity predictions for the originally proposed system, resp. the alternative system

As implied by Figure 3, this case represents an explicit HVAC modelling approach. Relative to the first case, the number of parameters which are needed to describe the actual system components and their control is very high. However the information to be gained from the simulations is also much richer. In contrast to the conceptual level where simulations are based on some presumed indoor temperature profile (or maximum available capacity), at this level of abstraction it is actually possible to predict air temperature, relative humidity and fuel consumption given a building, plant, and control configuration.

4. Conclusions and Future Work

It may be concluded that - except for highest level conceptual modelling - HVAC modelling and simulation is rather complicated from a user point of view. Not surprisingly the complications grow with the level of explicitness. This is because at the same time, the required/ assumed user knowledge of HVAC systems increases, the sheer number of plant definition parameters grows, the availability of data for those parameters decreases (manufacturers often do not have the data available which is needed for the models), and analyzing the (increasing amount of) results becomes more complicated.

Also from a developer point of view the complications (and challenges !) increase with the level of explicitness and detail. This is due to the physics underlying say a component, but more often it is due to the interactions with other parts of the HVAC system or with the building. Especially with regard to the latter, it is important that when system simulation is used for building performance evaluation the building should not be represented as just another plant component imposing a load on the system, but should be represented taking into account all energy and mass flow paths by modelling the overall system in an integrated fashion.

In the area of HVAC system simulation there is just a lot of work to be done. When compared to the building side, one could argue that every "new" component is like a new type of building in itself.
We should not only work towards enabling re-use of existing component models (ie co-operation at source code level by exchanging component models (for instance incorporation of TRNSYS models in ESP-r (Hensen 1991)) or in a more generic way by expressing models in NMF (Sahlin et al 1995)), and towards enabling coupling of programs on the product model and results level (as in the COMBINE initiative (Augenbroe 1994)), but also towards concurrent coupling of programs at run-time level. The latter can be done for domain specific programs but would potentially have much more scope (in terms of research, application, education, etc) if it was also done for general non-domain specific simulation environments.

Energy simulation for building form and fabric design is receiving wide acceptance in practice. Although there is an even greater need, modelling and simulation for HVAC design and performance evaluation is only just starting.

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EASY5x	Boeing Computer Services, USA	**EMGP 3**	University of Leuven, Heverlee, Belgium
ESP-r	University of Strathclyde, Glasgow, Scotland	**HVACSIM+**	Nat. Institute of Standards and Technology, Gaithersburg MD, USA
MATLAB / SIMULINK	The Math Works Inc., USA	**TRNSYS**	University of Wisconsin, Madison WI, USA
TSBI3	Danish Building Research Institute, Horsholm, Denmark	**TUTSIM**	Twente University of Technology, Enschede, Netherlands

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