Integrated Simulation for HVAC Performance Prediction: State-of-the-art Illustration

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Summary

This paper aims to outline the current state-of-the-art in integrated building simulation for performance prediction of heating, ventilating and air-conditioning (HVAC) systems. The ESP-r system is used as an example where integrated simulation is a core philosophy behind the development. The current state and future developments are illustrated with case studies. It is argued that for building simulation to penetrate the profession in the near future, there is a need for appropriate training and professional technology transfer initiatives.

Background

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. 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.

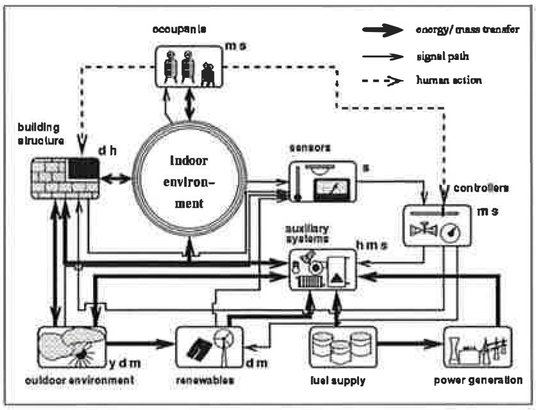

Figure 1. The building as an integration of energy systems

To provide substantial improvements in energy consumption and comfort levels, there is a need to treat buildings, with their individual subsystems, as complete optimised entities - as schematically indicated in Figure 1 - not as the sum of a number of separately designed and separately optimised components.

Building simulation is ideal for this because it is not restricted to the building structure itself but includes the indoor environment, while simultaneously taking into account the outdoor environment, mechanical, electrical or structural systems, and traditional and renewable energy supply systems. Building simulation can be used to characterise and assess proposed new equipment and system integration ideas, and to aid in the identification of such ideas. Simulation can thus be used for building analysis and design in order to achieve a good indoor environment in a sustainable manner, and in that sense to care for people now and in the future.

Although a number of sophisticated computer programs have been developed in recent years these are typically used by researchers, engineers concerned with very large building projects and for code compliance (usually translated to simpler computer or worksheet form). It is paradoxical that although architectural practices for larger firms have moved to computer design programs for the physical elements of buildings and building systems (piping, ductwork, etc.) there has been little effort by the design community to learn and apply energy analysis as a standard part of the design process. This is generally left to "specialists" at HVAC consulting firms after the building has been defined.

Since there are real opportunities to affect the building energy use through tradeoffs in building siting, orientation, spatial definition and envelope configuration, waiting until these have been completed, and perhaps even the HVAC and other systems are defined, can result in missed opportunities for energy savings.

Although most practitioners will be aware of the emerging building simulation technologies, few as yet are able to claim expertise in its application. This situation is poised to change with the advent of:

- performance based standards;
- societies dedicated to the effective deployment of simulation - such as IBPSA[1];
- appropriate training and continuing education;
- and the growth in small-to-medium sized practices offering simulation-based services.

One thing is clear: as the technology becomes more widely applied, the demands on simulation programs will grow. While this is welcome, in that demand fuels development, it is also problematic because the underlying issues are highly complex. Although contemporary programs are able to deliver an impressive array of performance assessments, there are many barriers to their routine application in practice. Four main issues, which must be addressed, are:

- Firstly, since all design assumptions are subject to uncertainty, programs must be able to operate on the basis of uncertainty bands applied (automatically) to their input and output data. Such a

[1] IBPSA: International Building Performance Simulation Association - http://www.ibpsa.org

facility is currently under development for ESP-r (16) so that performance risk may be assessed on the basis of prediction ranges resulting from uncertainty considerations applied to the input (design) parameters.

- Secondly, validation and calibration testing procedures must be agreed and routinely applied as the modelling systems evolve in response to user requirements.
- Thirdly, program interoperability must be enabled so those design support environments evolve in response to inter-disciplinary design needs. This was the goal of the EC's COMBINE project (4) in which a prototype Intelligent, Integrated Building Design System was developed (8).
- Finally, a means is required to place program development on a task-sharing basis in order to ensure the integrity and extensibility of future systems. This was the objective of the EPSRC funded Energy Kernel System (7), which sought to eliminate the inefficient theoretical and software de-coupling of current programs.

In terms of the building life cycle, currently modelling and simulation is mainly restricted to the detailed design phase. However there is a definite need for use of modelling and simulation both in earlier and later stages. Practitioners need early stage, strategic design tools. Modelling and simulation should be incorporated. Modelling and simulation can also play important roles in commissioning, auditing, control and maintenance of building systems.

HVAC system modelling and simulation approaches

Traditionally energy simulation in the building context focused primarily on the building side of the overall problem domain. We now see that modelling of HVAC systems and associated (air) flow phenomena in the context of building design and building performance evaluation, is 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 categorise 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, etc.

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, there exist several non-domain specific simulation systems that are quite popular in other engineering areas (e.g. TUTSIM). However they are not often used for building energy simulation. Evidence hereof consists of the proceedings of past conferences on System Simulation in Buildings (held at the University of Liege in 1982, 1986, 1990, 1994 and 1998) or the proceedings of past IBPSA conferences (Vancouver 1989, Nice 1991, Adelaide 1993, Madison 1995, Prague 1997 and Kyoto 1999).

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.

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 summarised in Table 1. (For more elaborate descriptions of levels of abstraction, including example applications for each level, see (15).

Table 1 HVAC system modelling abstraction levels

level		type
A	Room processes only; ideal plant	CONCEPTUAL
B	System wise in terms of real systems (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

At 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 result in `gross' energy 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 able to operate on this level.

At 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 that 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 and BLAST.[2]

At 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, and - nowadays - many of these incorporate numerical facilities enabling a simultaneous solution. A well known examples is TRNSYS.
The main advantage of the conservation equation method is its implicit simultaneous solution method. The main disadvantage is that it does not allow a mixture of modelling methods. Examples of conservation equation based systems are HVACSIM+ and ESP-r.

[2] Instead of full citations, a table is attached which indicates the author organizations of the non-commercial software mentioned in this paper.

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, allows simulations on this Level D.

It will be obvious that there is no single `best level'. As illustrated below, the optimum level depends on the application problem at hand.

ESP-r - an example of state-of-the-art in integrated simulation

The ESP-r system (6) has been the subject of sustained developments since 1974. The aim, now as always, has been to permit an emulation of building performance in a manner that a) corresponds to the reality, b) supports early-through-detailed design stage application and c) enables integrated performance assessments in which no single issue is unduly prominent. ESP-r is available under research (cost-free) and commercial (low cost) license from the University of Strathclyde. In both cases source code is made available.

ESP-r comprises a central Project Manager (PM) around which is arranged support databases, a simulator, performance assessment tools and a variety of third party applications for CAD, visualisation, report generation, etc. (Figure 2). The PM's function is to co-ordinate problem definition and give/receive the data model to/from the support applications. Most importantly, the PM supports an incremental evolution of designs as required by the nature of the design process.

The typical starting point for a new project is to scrutinise and make ready the support databases. These include hygro-thermal and optical properties for construction elements and composites, typical occupancy profiles, pressure coefficient sets for use in problems involving air flow modelling, plant components for use in HVAC systems modelling, mould species data for use with predicted local surface conditions to assess the risk of mould growth, and climate collections representing different locations and severity. ESP-r offers database management for use in cases where new product information is to be appended.

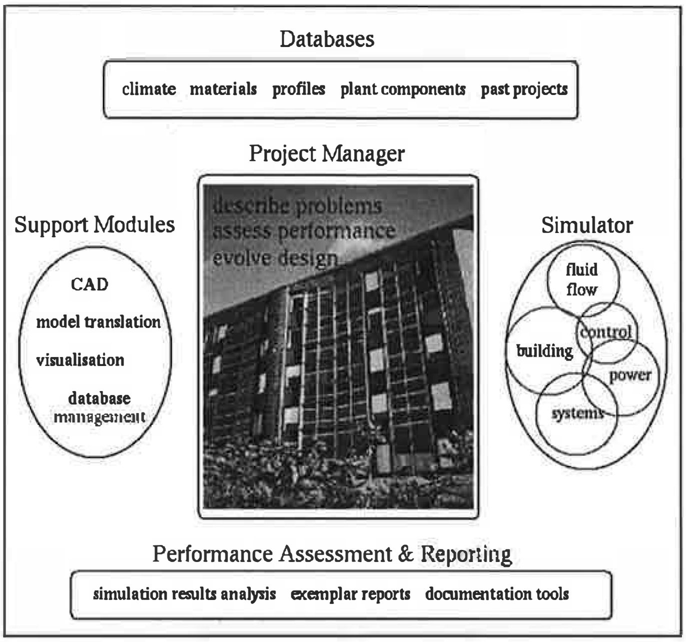

Figure 2. Architecture of ESP-r showing the central Project Manager and its support tools

Although the procedure for problem definition is largely a matter of personal preference, it is not uncommon to commence the process with the specification of a building's geometry using a CAD tool. ESP-r is compatible with two commercial CAD systems, either of which can be used to create a building representation of arbitrary complexity (Figure 3 - left).

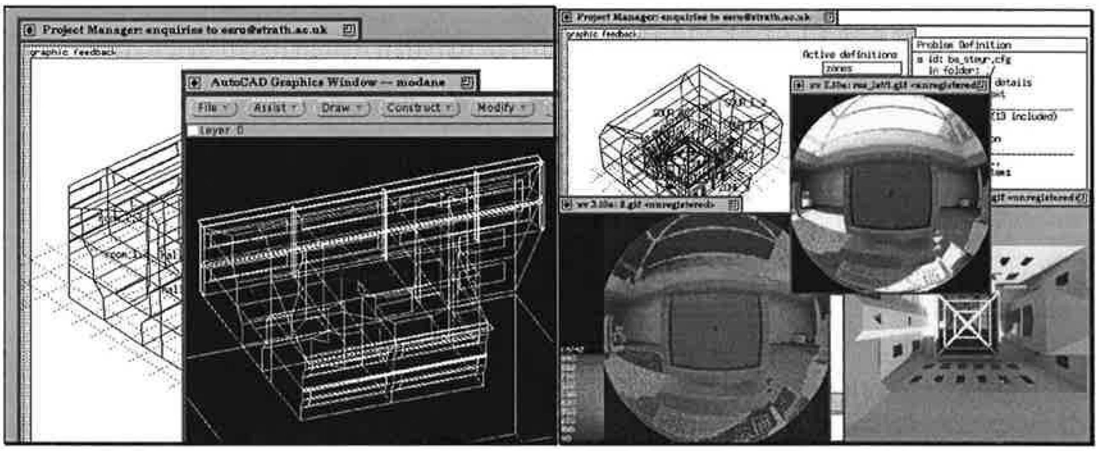

Figure 3. Defining problem geometry using AutoCad (left) and using RADIANCE to quantify luminance for a visual comfort/impact assessment or illuminance as input to a lighting controller (right)

After importing this building geometry to the PM, constructional and operational attribution is achieved by selecting products (e.g. wall constructions) and entities (e.g. occupancy profiles) from the support databases and associating these with the surfaces and spaces comprising the problem. It is at this stage that the simulation novice will appreciate the importance of a well-conceived problem abstraction, which achieves an adequate resolution while minimising the number of entities requiring attribution.

The PM provides coloured, textured physically correct images via the RADIANCE system (22) and wire-frame photomontages via the VIEWER system (20), automatically generating the required input models and driving these two applications (Figure 3 - right).

As required, component networks are now defined representing HVAC systems (1, 5, 13), distributed fluid flow (for the building-side air or plant-side working fluids) (13, 14) and electrical power circuits (19). These networks are then associated with the building model so that the essential dynamic interactions are preserved.

Control system definitions can now proceed depending on the appraisal objectives. Within ESP-r this involves the establishment of several closed or open loops, each one comprising a sensor (to measure some simulation parameter at each time-step), an actuator (to deliver the control signal) and a regulation law (to relate the sensed condition to the actuated state). Typically, these loops are used to regulate plant components, to associate these components with building zones, to manage building-side components such as blinds, and to co-ordinate flow components (e.g. window opening) in response to environmental conditions. Control loops can also be used to change portions of a problem with time (e.g. substitute alternative constructions) or impose replacement parameters (e.g. heat transfer coefficients).

For specialist applications, the resolution of parts of the problem can be selectively increased, for example:

- ESP-r's default one-dimensional gridding scheme representing wall conduction can be enhanced to a two- or three-dimensional scheme to better represent a complex geometrical feature or thermal bridge (17).
- A one-, two- or three-dimensional grid can be imposed on a selected space to enable a thermally coupled computational fluid dynamics (CFD) simulation (9, 18).
- Special behaviour can be associated with a material, e.g. electrical power production via crystalline or amorphous silicon photovoltaic cells (11).
- Models can be associated with material hygro-thermal properties to define their moisture and/ or temperature dependence in support of explicit moisture flow simulation and mould growth studies(3).

The PM requires that a record be kept of the problem composition and to this end is able to store and manipulate text and images which document the problem and any special technical features. It is also possible to associate an integrated performance summary with this record (Figure 4) so that the design and its performance can be assessed without having to commission further simulations.

The problem - from a single space with simple control and prescribed ventilation, to an entire building with systems, distributed control and enhanced resolutions - can be passed to the ESP-r simulator where, in discretised form, the underlying conservation equations are numerically integrated at successive time intervals over some period of time. Simulations, after some minutes or hours, result in time-series of "state information" (temperature, pressure, etc.) for each discrete region.

ESP-r's results analysis modules are used to view the simulation results and undertake a variety of performance appraisals: changes to the model parameters can then follow depending on these appraisals. While the range of analyses are essentially unrestricted, interrelating the different performance indicators (Figure 4), and translating these indicators to design changes, is problematic because of the lack of performance standards and the rudimentary level of simulation scholarship and training.

Example applications

There are a whole range of issues in HVAC design and performance prediction that 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, integrated energy performance evaluation, operation optimisation, 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 previously discussed modelling approaches, 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, (2 and 10).). Although the following examples could easily have been modelled using other building energy simulation environments, they are all based on ESP-r for obvious reasons.

Critical sizing using conceptual modelling

Consider the building as indicated in Figure 4, 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.

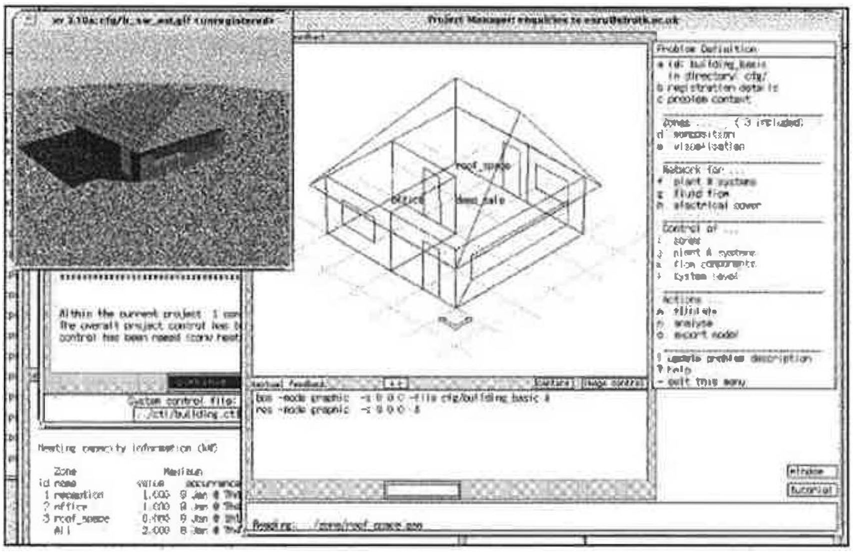

Figure 4 Graphical feedback of building model

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.

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

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.

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.

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 was 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 summarised in Table 3.

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

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 still 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.

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 artefacts being displayed and stored in the museum, some spaces need strict temperature and humidity control. A study (12) was carried out in order to predict the performance of a HVAC system as suggested by the client (see Figure 5).

Some results in terms of relative humidity control are shown in Figure 6. 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 6 compares relative humidity control possible with two HVAC system arrangements: the originally proposed system, and a modified system (bottom Figure 5) in which each storage space is independently serviced.

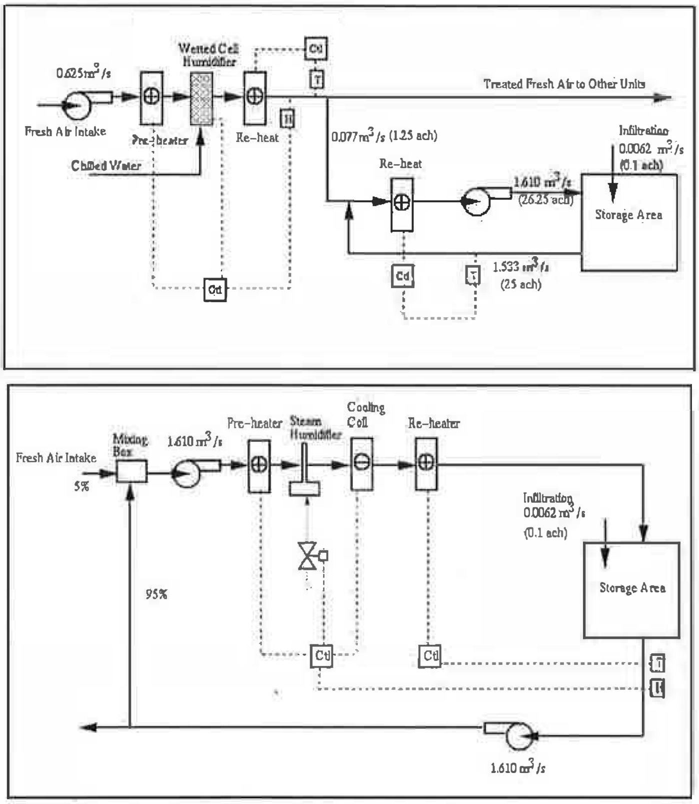

Figure 5. HVAC system / control as originally suggested (top), and an alternative arrangement (bottom)

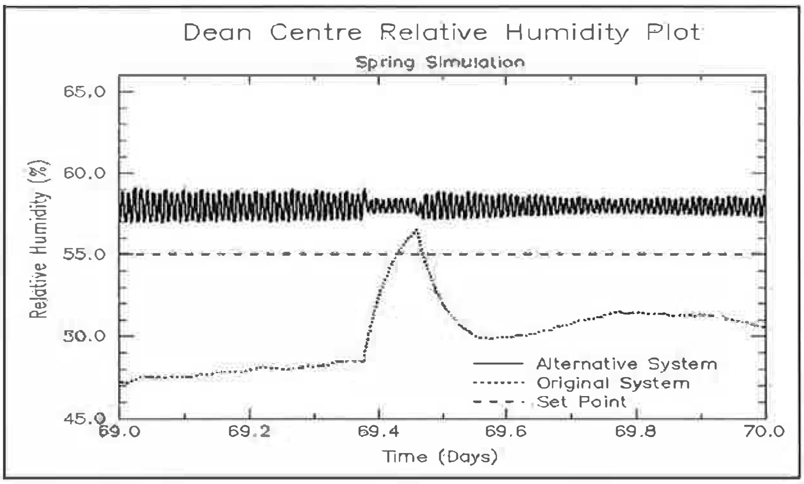

Figure 6. Relative humidity control performance predictions for both HVAC configurations

As implied by Figure 5, 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.

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 analysing 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 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 (14)) or in a more generic way by expressing models in NMF (21)), and towards enabling coupling of programs on the product model and results level (as in the COMBINE initiative (4)), 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.

Acknowledgements

The ESP-r system has evolved to its present form over 20 years. Throughout this period many individuals have made substantial contributions. In particular, we would like to acknowledge the contributions of some of our ESRU colleagues: Jon Hand, Milan Janak, Cameron Johnstone, Nick Kelly, Iain Macdonald, John McQueen, Abdul Nakhi, Cezar Negrao and Paul Strachan. Our hope is that the many other contributors, too numerous to mention, will be content with collective thanks.

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Author organisations of non-commercial simulation software mentioned in this paper:

BLAST	University of Illinois, Urbana-Champaign, IL, USA	**DOE-2**	National Lawrence Berkeley Laboratory, CA, USA
HVACSIM+	National Institute of Standards and Technology, Gaithersburg, MD, USA	**ESP-r**	University of Strathclyde, Glasgow, Scotland
TRNSYS	University of Wisconsin, Madison, WI, USA	**TUTSIM**	Twente University of Technology, Enschede, Netherlands