REPRESENTATION OF HVAC CONTROL IN COMMON SIMULATION PACKAGES

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ABSTRACT

The accurate representation of building operation is essential for building simulation to represent the consequence of design and operational controls correctly. This imperative is increasing with the use of calibrated simulations as a tool in the retrofit of buildings. Central to this is the representation of HVAC systems and controls, which have a major influence on building performance.

In this paper, the representation of common HVAC types and control strategies in DOE-2, Tas, Energy Plus and IES is reviewed and compared. HVAC types reviewed include variable air volume, active and passive chilled beams. Control strategies include a range of common terminal and AHU control approaches, demand controlled ventilation and central plant controls.

A number of significant shortcomings are identified. Key priorities for further simulation tool development are recommended.

INTRODUCTION

As the use of building simulation increases in industry, it is inevitable that the range of applications also increases. Thus while simulation may have been originally viewed as a tool for architectural optimisation, it is increasingly used for the optimisation of air-conditioning design and operation.

However, it is not clear that commonly available simulation models have sufficient functionality to meet these demands; indeed anecdotal evidence from a number of simulation practitioners indicates strongly to the contrary. In particular, limitations of HVAC representation have been noted as limiting the practical usefulness of calibrated simulation approaches, as the model cannot be fully calibrated if either justifiable, innovative or erroneous aspects of the building operation cannot be modelled.

In this paper, the results of a comparison of the HVAC representation capabilities of DOE-2 (v107 2000), Tas (1.8.5 2003), Energy Plus (v6.0.0) and IES (6.2.0.1) are presented, based on input from each of the authors' experience with particular packages. This approach is not as comprehensive as that adopted by Crawley et al (2005) but is more specifically focussed on HVAC and includes consideration of the users' perspectives on the packages. The framework of systems types and controls/operation requirements used in this paper is provided by Appendix B of the AIRAH Controls Guide [Aherne 2011]. This guide describes control algorithms for a wide range of common air-conditioning types, from which in excess of 100 HVAC plant and control configurations – of varying levels of quality – have been identified. These were distributed amongst the authors of this paper for assessment against the packages in which each author was most experienced.

It is noted that a more recent version of IES (6.4) exists at the time of writing which may have additional functionality relative to that reported in this paper.

It is also noted that EnergyPlus V6.0.0) introduces an Energy Management System (EMS) Module, with a built-in programming language (ERL) to specify control algorithms [Ellis et al, 2007, USDOE, 2010]. However, this paper focuses on standard configurations which are more accessible to the general user without specialist programming.

CAPABILITY OR COMPREHENSIBILITY?

It was originally the intent of this paper to review program capability against a range of plant and control configurations. However, the process of preparing this paper has highlighted that even quite experienced users struggle to understand the capabilities of the programs that they use regularly.

There appear to be four major underlying issues:

- There is a significant disjuncture between the language of simulation control and the language of building control. Simulation users have to consider how to translate from one language to another, and are not necessarily guided on how to do so by the package documentation.
- The documentation for simulations is often weak in this area, leaving users with significant uncertainty and discomfort around what their favoured package can actually do. In one case, a significant number of available control components

were not documented at all, leaving the nominated user unable to vouch for their function.

- The general understanding of HVAC controls in both the simulation community and the building design community is poor. This leads to weak understanding of the configuration and importance of controls both in simulation and in reality.
- There are significant differences in how controls are simulated as opposed to how they are operated in the real world. In the real world, controls provide an output in response to an error signal and progressively adjust this to obtain a stable final condition. By contrast, many simulation packages use a "solution inverter" control logic, which calculates the exact solution to the problem through reference to calculated variables, such as thermal load, which are not available in a real world situation.

As a result, the assessments in this paper should not be interpreted directly as being the capability of particular programs; it is more a representation of what four experienced users felt they could achieve with the programs. The necessarily subjective aspect of this is relevant as, if the capabilities of a simulation package are not obvious to a reasonably experienced user, then clearly there is an issue.

The authors apologise in advance for any resultant errors or omissions and refer readers to the developers of each individual package for advice with regards the representation of any individual issue or problem. The intent of this paper is to highlight general issues with the coverage of HVAC within simulation packages rather than scrutinise or criticise any individual package.

TERMINAL CONTROL

The control of space temperature at the terminal is fundamentally important to establishing the relationship between building loads and HVAC operation. In ***Table 1***, the coverage of common terminal control configurations is reviewed. A number of key issues can be identified:

- The simulation packages were mostly biased towards proportional terminal control; the exception was EnergyPlus which emulates PI/PID control via the “solution inverter” approach. Both proportional and PI/PID control are common in practice and optimisation of this selection is a significant energy efficiency issue.
- PI/PID control, where represented, is generally achieved through the use of proportional control with narrow proportional bands, rather than explicit PI representation. This can introduce stability issues.
- No package represents the commonly applied hysteresis of electric reheat control.

Aside from these issues, terminal control representation is reasonable.

SINGLE DUCT AIR HANDLER AND FAN COIL CONTROL

The majority of systems in buildings are single duct air handling systems servicing either constant or variable volume terminals. In Table 2, the coverage of common single duct AHU and FCU configurations is reviewed. The following issues can be seen:

- Programs vary widely in their ability to represent the industry standard approach of supply air temperature reset (where some selection of control zone conditions is used to directly modulate the supply air temperature according to a defined schedule). This is a critical issue as it is a key optimisation variable for the operation of such systems. Note that DOE-2’s poor performance in this area is because it adopts a solution inverter approach and does not allow the user any control over the zone temperature to supply air temperature relationship.
- No programs represent any form of incremental control. Such controls increment temperature up or down based on the relationship between the control zone temperature and the control zone set-point. While relatively uncommon, this type of approach has adherents in the industry.
- Most programs do not have an explicit representation of direct valve control, which is a control where the control zone temperature deviation drives the chilled water and hot water valves directly. This control is moderately common in industry and is often associated with unstable control due to the limited control of gain in the system.
- No programs have explicit representation of fan operation. This is because none of the programs have explicit representation of the air distribution systems within buildings. This means that the simulator is obliged to assume that whatever control methodology has been proposed is combined with a correctly operating control to achieve the required fan turndown outcome. The frequent failure of fan control systems in the field highlights the importance of improving the representation of fan operation and control; it is also one of the key areas where simulation programs can provide overly optimistic energy use results due to the idealised nature of program default assumptions.

- It is also noted that while IES provides the ability to achieve very flexible control of AHU supply air temperature, the complexity of doing so means that users are discouraged from doing so, and often revert to simpler, less representative approaches [Lowndes, 2011].

It is noted that representation of dual duct systems generally followed the same patterns as single duct systems and as a result is not presented separately.

ECONOMY CYCLE CONTROL

In temperate climates, economy cycle control is a critical energy efficiency strategy. In practice, a wide range of approaches is used to control economy cycles, some of which are significantly superior to others. ***Table 3*** reviews the representation of economy cycles in the selected simulation packages. The following issues can be seen:

- The majority of packages simulate most common methods of control. However, flexibility to simulate more unusual methods of control (such as dew-point control) is more limited.
- Representation of economy cycle operation in DX systems is significantly variable between packages.

Problems with the staging and precise control of the economy cycle in conjunction with supply air temperature control were also reported in relation to Tas.

GLOBAL AHU CONTROL

Global AHU controls such as optimum start and night purge are common to all AHU systems. The representation of these is reviewed in ***Table 4***. It can be seen that:

- The level of representation is variable, with no package having all the features associated with a complete representation of the nominated controls.
- Some packages could not represent optimum start, and most could not represent CO_2 control.

CHILLERS AND ASSOCIATED CONTROLS

Chiller technology has advanced significantly in the past 20 years; as a result, the range of common plant physical and control configurations has increased significantly. A range of common configurations and simulation issues is reviewed in ***Table 5***. A number of key factors can be seen:

- Overall the representation of chiller plant in most models is poor.
- Explicit modelling of chillers, that is to say the modelling of individual chillers based on parameters directly imported from chiller manufacturers, is uncommon. In most cases an intermediate translation phase is required which in some cases is difficult to use.
- In the programs with poor water-side models, simulators rely on aggregated two dimensional COP curves as direct inputs, typically combining multiple chillers into an assumed total plant operation curve. This limitation seriously undermines reliable prediction of chilled water or condenser water reset strategies that are important for improving plant energy efficiency in mild and warm climates. Similar problems arise with respect to the representation of chiller staging in these models.
- No model provides the ability to model the operation of cooling calls (which use a variety of criteria to delay the commencement of chiller plant operation to avoid nuisance chiller plant operation).
- Pump modelling is highly variable between models, with lack of transparency, difficulty of user control and overly optimistic controls being problems noted by users.

Anecdotally, many modellers appear to consider that the chiller modelling capabilities of packages are sufficiently weak that they prefer to export cooling loads and derive chiller energy modelling from a spreadsheet model that permits more complete, user-controllable and comprehensible modelling of the chiller plant.

COOLING TOWERS

Although the energy consumption of cooling towers is generally small, the impact that they may have on the efficiency of chiller systems is significant. For instance, the optimisation of chiller energy versus cooling tower fan energy via the variation of condenser water set-point is a significant issue for variable speed chillers. However, the representation of cooling towers in simulation packages is generally poor, as shown in ***Table 6***. In particular:

- Simulators are frequently required to make relatively broad assumptions about cooling tower performance, with few packages providing explicit modelling of cooling towers.
- Cooling tower fan control is not generally represented in adequate detail to permit confident modelling of options in this area.

BOILERS

The representation of boiler plant is generally similar in quality to that of chillers, as shown in ***Table 7***. Key issues include:

- Most models do not provide explicit representation of boilers – the simulator has to derive these and establish their own parameters.

- None of the models provides the ability to represent heating calls, which are used in practice to delay the commencement of plant operation to avoid nuisance operation.
- Modelling of pumping configurations is limited.
- Only one of the models represents thermal inertia, which can be a major issue for hot water systems with intermittent operation (Kenna 2009).

DISCUSSION

The conclusions that can be drawn from the above analyses are that:

- There is a significant gap between the HVAC systems that are being designed and operated in the field and the ability of simulation models to represent their operation at a level that enables relatively important design choices to be assessed. This gap appears to be narrowing with newer packages, but is still present.
- Chiller modelling and supply air temperature controls are arguably the areas of greatest weakness, along with the lack of explicit representation of fan and pump operation.
- These issues are exacerbated by language differences between the simulation and building control communities. In essence, simulation could be improved significantly by explicit guidance in how to represent common industry control approaches.

These issues perhaps reflect the reality that little industry consensus exists on matters of HVAC control, and that many design engineers – a key user group for simulation – have a weak understanding of this aspect of building operation. Although this could be argued as a case for avoiding further development in this area, the importance of control in determining efficiency means that it is imperative for simulation to take the lead by providing users the opportunity to learn from experimentation with a full range of realistic control configurations.

It is therefore a conclusion of this paper that explicit effort needs to be made in the improvement of HVAC simulation to better reflect current and future industry practice. There is potential for this activity to be promoted by IBPSA in collaboration with key industry players (such as controls companies) and organisations (such as ASHRAE).

CONCLUSIONS

In this paper, the representation of a common HVAC control and physical configurations in four leading simulation packages has been reviewed. It has been found that there are significant gaps in the representation of major systems, particularly:

- The representation of supply air temperature control in air handlers
- The representation of fan and pump control
- The representation of central plant components, their enablement and staging

Such gaps are exacerbated by differences in language between the simulation packages and the building design community, problems with simulation documentation, and the limited level of understanding of HVAC controls in general amongst both the simulation and building design communities.

Such deficiencies are of critical importance to the usefulness of simulation and to the ability of the industry to use simulation as a tool to advance, rather than follow, industry practice. There is a case for IBPSA in conjunction with other organisations to collaborate in the improvement of simulation package development in these areas.

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Table 1. Terminal representation. Dark cells indicate that the configuration is represented; light grey indicate partial representation and white cells indicate no representation. Partial representation of PI control is obtained by using proportional control with very small proportional bands and may be unstable in some cases.

	Tas	**DOE-2**	**IES**	**Energy Plus**
VAV Terminals				
Proportional control of heating/cooling	dark	dark	dark	
Deadband	dark	dark	dark	dark
PI control of heating/cooling	light grey	light grey	light grey	dark
Hysteresis control of electric reheat				
Pressure independent control	dark	dark	dark	dark
Pressure dependent control	light grey	light grey	light grey	light grey
Parallel fan operation		dark	dark	dark
Series fan operation		dark	dark	dark
Hot water reheat	dark	dark	dark	dark
Electric reheat	dark	dark	dark	dark
Global reheat lockout		light grey	dark	light grey
Schedulable minimum air flow		dark	dark	dark
Dual Duct Mixing Boxes				
One damper operation	dark	light grey	dark	dark
Two damper operation	dark	dark	dark	dark
Proportional damper control	dark	dark	dark	
PI damper control	light grey	light grey	light grey	dark
Multizone damper				
PI control		light grey	light grey	dark
Proportional control		dark	dark	
Induction unit/Active chilled beam				
Proportional control of chilled water valve	dark	dark	dark	
PI control of chilled water valve	light grey	light grey	light grey	dark
Proportional control of hot water valve	dark	dark	dark	
PI control of hot water valve	dark	light grey	light grey	dark
Variable airflow			dark	dark
Passive Chilled Beam				
Proportional control of chilled water valve	dark		dark	
PI control of Chilled water valve	light grey	dark	light grey	dark
Hot water heating	dark	dark	dark	dark
Global heating lockout		light grey	dark	light grey

Table 2. Representation of single duct air-handler and fan coil controls. Dark cells indicate that the configuration is represented; light grey indicate partial representation and white cells indicate no representation. Partial representation of fan speed control is obtained by using fan curves reflecting the energy/flow relationships associated with these different configurations.

	Tas	**DOE-2**	**IES**	**Energy Plus**
Supply air temperature control based on a reset schedule indexed to:				
>>High select		Light grey	Dark	Dark
>>low select			Dark	Dark
>>average			Dark	Light grey
>>return air temperature	Dark		Dark	Light grey
Other AHU/FCU heating/cooling controls:				
Open loop control of supply air temperature (incrementing of supply air temperature based on control zone set-point deviation)				
Direct valve control of chilled/hot water valves (Modulation of valves based on control zone setpoint deviation)			Dark	
Duct loss representation				
U-value	Dark		Dark	Dark
Percentage of current load				Dark
Fan speed control				
Constant fan speed operation with variable demand volume	Light grey	Light grey	Light grey	Light grey
Variable fan speed operation with variable demand volume at fixed static pressure	Light grey	Light grey	Light grey	Dark
Variable fan speed operation with variable demand volume at variable static pressure	Light grey	Light grey	Light grey	Light grey

Table 3. Economy cycle representation. Dark cells indicate that the configuration is represented; light grey indicate partial representation and white cells indicate no representation.

	Tas	**DOE-2**	**IES**	**Energy Plus**
Dry-bulb economy cycle operation (comparison of return temp to outside temp)	Dark	Dark	Dark	Dark
Enthalpy economy cycle operation (comparison of return enthalpy to outside enthalpy)	Dark	Dark	Dark	Dark
Enthalpy lockout (Maximum enthalpy limit)	Dark	Light grey	Dark	Dark
Dewpoint lockout (maximum dewpoint lockout)			Dark	Dark
Humidity lockout (maximum outside air humidity lockout)	Dark		Dark	Dark
Minimum outside air temperature lockout	Dark	Light grey	Dark	Dark
Independent temperature reset schedule operation controlling mixed air temperature	Dark		Dark	Dark
Two stage integrated operation with DX system based on PI control from zone temperature		Light grey		Dark
Two stage integrated operation with DX system based on proportional control from zone temperature		Dark		
Non-integrated operation with DX system based on zone temperature		Dark	Dark	Dark
Zone temperature lockout (for use with dual duct and multizone systems: economy cycle locked out when in conflict with the needs of the hot duct)			Dark	Dark

Table 4. Global AHU controls. Dark cells indicate that the configuration is represented; light grey indicate partial representation and white cells indicate no representation.

	Tas	**DOE-2**	**IES**	**Energy Plus**
AHU start/stop time scheduling	dark	dark	dark	dark
Optimum start		dark	light grey	light grey
Night purge	dark	dark	dark	dark
Early morning start up modes (full heating/full cooling)	dark		dark	light grey
CO_2 control of outside air provision			dark	dark

Table 5. Chiller plant representation. Dark cells indicate that the configuration is represented; light grey indicate partial representation and white cells indicate no representation.

	Tas	**DOE-2**	**IES**	**Energy Plus**
Explicit chiller modelling				dark
Cooling call thresholds				
Chiller staging based on return water temperature				light grey
Chiller staging based on chiller loading (electrical)				
Chiller staging based on chiller loading (cooling load)		dark	light grey	dark
Variable chilled water temperature control				dark
Variable condenser water temperature operation		light grey	light grey	dark
Variable primary chilled water pumping		light grey	light grey	dark
Primary/secondary chilled water pumping – fixed static pressure		light grey	dark	dark
Primary/secondary chilled water pumping – variable static pressure		light grey	dark	light grey
Outside air lockout on chiller operation			dark	dark
Staging at less than 100% load			dark	dark
Variable staging configurations based on schedule				light grey
Series chiller operation			light grey	dark
Series/counterflow chiller operation			light grey	dark
Chilled water system loss modelling				
U-value				dark
Percentage of current load	dark		dark	dark

Table 6. Cooling tower representation. Dark cells indicate that the configuration is represented; light grey indicate partial representation and white cells indicate no representation.

	Tas	**DOE-2**	**IES**	**Energy Plus**
Explicit cooling tower modelling				
Variable speed tower fan speed operation – proportional				
Variable speed tower fan speed operation – PI				
Two stage cooling tower fan speed operation – proportional				
Two-stage cooling tower fan speed operation – PI				
Multicell staged fan operation – proportional				
Multicell staged fan operation – PI				

Table 7. Boiler plant representation. Dark cells indicate that the configuration is represented; light grey indicate partial representation and white cells indicate no representation.

	Tas	**DOE-2**	**IES**	**Energy Plus**
Explicit boiler modelling				
Heating call thresholds				
Thermal inertia				
Staging based on return water temperature				
Staging based on boiler loading (thermal)				
Variable hot water temperature control				
Variable primary hot water pumping				
Primary/secondary hot water pumping - fixed static pressure				
Primary/secondary hot water pumping - variable static pressure				
Hot water system loss modelling				
U-value				
Percentage of current load				