THE APPLICATION OF SIMULATION IN THE PREDICTION AND ACHIEVEMENT OF ABSOLUTE BUILDING ENERGY PERFORMANCE

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ABSTRACT

Although simulation has traditionally been cast as a comparative tool, there is an increasing drive for simulation to provide information on absolute performance.

In this paper, key requirements are outlined for the credible prediction of absolute performance, including reporting, energy coverage, separation of behavioural and technical influences, modelling HVAC control, risk analysis and the use of simulation to generate energy targets for operation and commissioning.

It is identified that the best outcomes are likely to be achieved if changes are made to design process and the role of the simulator. Furthermore, the need for new functionality in simulation packages in order to facilitate more accurate modelling and testing of absolute performance predictions is identified.

INTRODUCTION

The use of energy simulation in design has traditionally been seen as a comparative process whereby design alternatives are assessed against each other. This comparative approach is enshrined in much of the current literature in relation to simulation. ASHRAE 90.1, for instance, specifically notes that an energy cost budget does not necessarily reflect actual energy use (ASHRAE, 2001). This is similar to many other regulatory applications where the simulation methodology is based around comparison of a design simulation against a nominal code compliant simulation (e.g. Seattle 2004, Standards New Zealand 1996). Where simulation requires reconciliation with reality, some form of calibration process is recognized as being necessary (e.g. FEMP 2000).

Such caution is supported by empirical studies. A recent study (New Buildings Institute 2003) found poor correlation between the theoretical and achieved performance of buildings across a large US data set. This study, however, noted that the simulations represent an upper asymptote for achievable performance, which can potentially be achieved if sufficient focus is placed on "tuning up" the building to optimum performance. However such focus is generally not present in average building projects, causing actual performance to fall short of potential.

In the context of the international concern regarding climate change, the need to achieve actual performance improvements in the built environment is imperative. This can only be delivered through a more holistic approach whereby a building's energy consumption achieves and maintains an actual target rather than merely doing better than a design alternative. This need is implicit from the development of performance-based energy rating systems such as Energy Star (US Department of Energy 2009) and the National Australian Built Environment Rating System (NABERS) (NSW Department of Environment and Climate Change 2009).

As a result, simulation faces new challenges to enable the prediction of absolute performance to be undertaken on a credible basis. Given the urgency of the climate change problem, it is arguable that the simulation packages which respond most quickly and effectively to these challenges will achieve greatest success over the next ten years.

In this paper, methods for the optimal use of simulation in projects targeting absolute energy/greenhouse performance targets are discussed. The framework for this discussion is based on the following key areas:

- Coverage – being the completeness of the simulation in representing actual metered energy consumption;
- Technical requirements – being the ability of the simulation model to accurately and usefully represent the building operation;
- Analysis and reporting – being the means by which the simulation is reported to, and utilized, by other members of the design team.

Much of the ensuing discussion is based on the author's exposure to simulation model production, reporting and use in Australia, where the author has a role as a reviewer of building design and simulation for projects that are aiming for pre-defined post-construction energy use/greenhouse production targets corresponding to particular ratings under NABERS; in particular, numerous simulations conducted by the consultancy community for office building projects. While it is reasonable to expect that practices may vary internationally, casual observation indicates that the observations in this paper appear relevant to commercial use of simulation internationally. The intent of this paper, therefore, is to highlight these challenges to enable key stakeholders to consider what changes are required in their practices to facilitate more accurate and useful predictions of absolute building performance.

COVERAGE

Thermal simulation packages provide good representation of HVAC energy and in most cases provide acceptable representations of lighting and lighting control, albeit often with the primary intent of representing the thermal load that the lighting creates.

However, there are numerous energy uses that fall outside common simulation parameters, including:

- Car park lighting and ventilation: Most commercial buildings have car parks which, depending upon circumstances may be included within the scope of the measured energy of a building. Representation of these items is generally not difficult with the exception of accurate modelling of pollutant based control for ventilation fans.
- Exterior lighting. Lighting for safety, architectural highlighting and building signage will commonly contribute to metered building energy. These items are easy to model but commonly forgotten.
- Ancillary tenant services. In many office buildings a range of additional services provided as facilities to the tenant may also be included within the building energy consumption. These include supplementary fresh air (which may also be pre-conditioned), condenser water circulation for tenant supplementary air-conditioning, kitchen exhausts, and similar. Poorly regulated, these can become major energy consumers as they are generally designed to handle a high level of capacity which is often only marginally utilized. Lack of effective control can result in excessive energy consumption.
- Lifts. As buildings reach higher levels of efficiency, lift consumption becomes a more important end-use and yet appears to be relatively immature in terms of energy efficiency. For high rise buildings, even modern technology high efficiency lift systems can use up to 15kWh/m², making it one of the largest end uses for such a building. Nipkow (2006) reports that stand-by energy use of lifts can comprise as much as 80% of total lift energy use, although this appears to depend on the level of usage and the height of the lift rise (Bannister 2009a). Prediction of lift energy consumption remains problematic due to lack of reliable data.
- Control equipment. HVAC and lighting controls and security systems all consume small but significant quantities of energy. This is rarely modelled.
- Stand-by generator overheads. Stand-by generators typically have electric jacket heaters of 1-4 kW capacity, with varying levels of control, operating all year. This is rarely modelled and data on actual loads is difficult to obtain.
- Chiller sump heaters. Similar issues apply to chiller sump heaters as for stand-by generator jacket heaters.
- Electrical losses. The reticulation of electricity within the building causes losses. The size of these is difficult to substantiate, but estimates appear to range in the region of 1-2%. Again, lack of data makes modelling of these losses problematic
- Domestic hot water. Domestic hot water is typically a small end-use in office buildings but may be somewhat larger in other building types. Irrespective it remains an identifiable end-use that requires representation in an absolute performance estimate.

Considered as a group, these end-uses can account for well over 50% of the actual energy use of a building. Failure to represent these when estimating total building energy use therefore would result in highly misleading results. Furthermore, failure to consider these items can result in significant inefficiency being present in a design in which the "traditional" areas of HVAC and lighting efficiency have been thoughtfully treated. In Australia, for instance, it is only in the past 2-3 years that designers have started regularly designing supplementary condenser water loops for efficient operation through the inclusion of motorized shut-off valves to terminate flow when the tenant air-conditioning unit compressor is not operating. This item by itself can save over 10% of total building energy consumption.

There is a consequent need to define standards that create a more consistent and comprehensive capture of end-uses in buildings. While individual standards may cover most of the above items, there does not appear to be a single comprehensive reference point for coverage. In practice, therefore, the key reference needs to be the full domain of services within the building being modelled.

TECHNICAL REQUIREMENTS

The estimation of actual energy use requires that the modelling of the energy use is not merely representative but realistic. This is particularly problematic in the HVAC area, where most commercially used simulation packages use significant approximations in the modelling of HVAC control and components. Key examples are discussed below.

HVAC Control Representation

The heritage of simulation tools is based around architectural optimization, rather than the detail of services control. As a result, most simulation packages are designed around the basic template style controls that offer only a first order approximation to actual control operation.

This also reflects how the design industry operates, in that most designers have at best a first order understanding of control, with the detail being left to the controls contractor.

As an example, consider the common control routines listed in Table 1. It can be seen from the table that each of the major control routines is typically modelled via some form of idealized approximation. Furthermore, in most cases, the idealized approximation is generally likely to be more efficient and more stable than the real-world alternative.

This is particularly troublesome given that these are common routines. If one wants to model a more esoteric routine, this becomes even more difficult. An example would be the control of a VAV system without reheats which needs to be controlled to roughly balance over and under heated zones. This control may be approximated in some cases based on return air reset modelling, but this is not available in all packages, and is not necessarily a true representation of the implementation of a real system.

The examples above are typical of similar problems throughout the whole topic of HVAC control. As a result, most simulation models provide heavily idealized, and generally optimistic, views of how the controls are likely to operate.

The representation of HVAC control is particularly important for accurate modelling in temperate climates, as these are the climates in which control dominates. For example, in temperate regions of Australia (which are similar to much of coastal western US and southern Europe), plant is designed for peak cooling temperatures in the 34-38°C region and peak heating in the region of 2-8°C, but spends the vast majority of the year in marginal heating or marginal cooling (ambient temperatures 15-25°C). Failure to turn down plant capacity – a key HVAC control function – can cause substantial waste of energy (Bloomfield and Bannister 2007, Bannister 2009b).

If the detail of control cannot be modelled then simulation models are likely to be routinely optimistic in predicting building performance. Furthermore, the inability to model HVAC controls means that designers and contractors alike are left making best-guess interpretations of optimum control.

HVAC Plant Representation

While it is true that most simulation packages can represent most types of plant, there are significant gaps in the detail of representation. Some key issues in this area are:

1. **Hot water plant representation.** A weak point of many of the commonly used simulation packages is the representation of hot water plant. Key weaknesses include: boiler efficiency representation; hot water loop loss representation; and the representation of thermal inertia effects in the hot water distribution system, as discussed in detail in Kenna (2009).

2. **Chiller/chilled water loop representation.** All of the issues identified above in relation to boilers apply to some extent with chillers and the chilled water loop.

3. **Specific versus notional pressure model representation.** One of the key issues facing the modelling of air and water distribution systems is the modelling of pressure. In practically all cases control of pressure is simulated through the use of generic plant curves that effectively assume the pressure flow relationship. Given that flawed commissioning of pressure is a leading cause of inefficiency in actual buildings, its absence from simulation models is a significant weakness.

These issues limit the ability of simulation models to provide useful input into the design process and in some cases generate significantly misleading results (Kenna 2009).

Table 1
Typical HVAC controls issues

Control item	**Typical real-world methods**	**Typical simulation methods**
Chiller staging	Stage up and down on return temperature; or Stage up on loss of supply temperature control, stage down on under-loading	Direct load calculation; aggregate load curves
Chiller load up	Chiller may be programmed not to fully load immediately.	Not simulated
Chilled water call	Call on based on individual valves exceeding 70-90% open. Call off based on all valves being less than 10-30% open. May include and outside air temperature lock-out	Chiller operates in presence of any chilled water requirement. Outside air lockouts typically difficult to represent.
Boiler operation	Similar to chillers	Similar to chillers
Variable air volume fan control	Fixed static pressure control	Direct modulation of fan volume to match demand; generally reliant on input fan curve.
Variable flow pumping	Fixed static pressure control	Direct modulation of pump speed to match demand; generally reliant on input pump curve.
Supply air temperature control	Hi-select zone control driving supply air temperature via a reset schedule	Ideal hi-select based on calculation of zone temperature required to meet calculated zone demand given zone airflow; or Reset schedule based on return air temperature or outdoor temperature; or Reset schedule based on fixed control zone temperature
Electric reheat control	Switching control with hysteresis	Proportional control, typically, or switched control without hysteresis
Economy cycle control	Sequenced with chilled water valve to achieve supply air set-point. May have temperature, humidity lockouts, and will have hysteresis between enablement and disablement to prevent cyclic operation.	Sequenced to achieve supply air temperature set-point. No hysteresis; typically only with temperature and enthalpy lockouts.
Minimum outside air control	Flow proportional; constant volumetric flow; CO_2 control	Generally constant volumetric, with some scheduling available. Occupant-responsive control difficult or impossible
Variable Air Volume Terminal	Proportional or Proportional/integral control	Typically only either proportional or proportional/integral, but not both.

Representation of Imperfection

It is well known that thorough commissioning of controls and plant is essential if efficient performance is to be achieved. Simulation models generally take this for granted as all plant and controls are generally configured to work as if perfectly commissioned. In practice, however, this is an unrealistic ideal as all buildings have some level of imperfection in actual operation. Such imperfection may arise due to faulty construction, commissioning or control, or may be a consequence of unexpected interactions between plant and occupants. The identification of the plant, controls, commissioning and operational items that have the greatest potential to detract from building performance is an essential step in ensuring that the energy performance of the design is risk-managed through system selection, design, construction, commissioning and operation. However, no simulation models provide any routine method of assessing the impact of imperfection. Indeed, in many cases, even the ad-hoc representation of imperfection is difficult due to the structure of the simulation programs.

Experience in Australia has demonstrated that the representation of imperfection is challenging, not only technically, but institutionally. This is highlighted by the response of the simulation community to the assessment of "off-axis" scenarios as required under the NABERS Validation Protocol for Computer Simulations (NSW Department of Environment and Climate Change 2009, Bannister 2005). Under this protocol, simulators are required to run a minimum of one scenario with at least four things "wrong". This is intended to gain some gauge of the degree to which the design is prone to underperformance through imperfect construction and commissioning. In practice, the effectiveness of this requirement is highly compromised by:

- Lack of knowledge as to which factors to realistically incorporate into such scenarios, due to the disconnect between building designers and building operators;
- A lack of desire to "challenge" a model too greatly, for fear that this might upset the design team and client, or show up issues in a design produced by the simulator's own company.
- The inability of simulation packages to represent common operational failure modes.

This type of sensitivity analysis is not only important for project testing. As Donn (1999, 2005) noted, one of the few ways we have to understand whether a model is right is by "playing" with it and seeing whether it responds in an explicable manner. Lack of the necessary skill and insights, the lack of tools within the simulation packages and, in some cases, excessively long run times, discourage this type of quality assurance.

Furthermore, when optimizing a design, the greatest question can be which variables to optimize. If the process of testing variables for sensitivity were automated, the focus of design optimization could be sharpened considerably.

Overall it is clear that the ability to undertake some form of assessment of building sensitivity to key parameters could significantly improve the usefulness of the building model in predicting absolute performance.

Realistic Input Data

Real buildings use real equipment and materials and are occupied by real people, none of which necessarily conform to the common means of representation. Thus, for instance, a real office building has tenant loads that run at high levels overnight, and have occupants in the building at semi-random hours. This cannot be represented by a simple on/all off schedule, and indeed is poorly represented by any fixed schedule.

Similarly, the information needed to appropriately characterise building materials and plant may not readily available, and the required inputs to the simulation may not be well adapted to the information that is available.

The development of improved methods of generating and representing input parameters to building simulation is essential if simulations are to become more realistic. Key items include:

- Development of realistic occupancy, operation and equipment schedules and densities for common space types. For individual projects with known tenants, for instance, this could be based on operation in their existing premises, while for unknown tenants a realistic default should be used;
- Development of improved methods of characterization of key plant items based on available data. This applies to all major plant items including boilers, chillers, fans and pumps.
- Development of coherent databases of properties for building materials.
- Development of common protocols for the realistic estimation of the items that typically lie outside the scope of the simulation, as discussed earlier in this paper.

REPORTING

The typical building construction process takes 2-3 years, plus at least one further year to stabilize and optimize building operation. During this process the stakeholders in the building change from the building designers, through to the builders and then the operators and occupants. In many projects, the simulator will have only a short term involvement in the design/construction process but the impacts of their work may have the potential to affect most of the other stakeholders. Given the identified issues of non-alignment between simulation and reality it is essential that the simulation is documented in a manner that reduces the risk of error in assumption and version control. These issues are discussed below.

Reporting to the Design Team

One of the key risks in simulation analysis is that the simulation incorrectly reflects the building design, or that the design changes after the simulation in a manner that invalidates the results. To minimize the risks of this it is important that the design assumptions of the simulation are reported back to the design team. This approach is reflected in the NABERS Validation Protocol for Computer Simulation (NSW Department of Environment and Climate Change, 2008) which requires reporting of many aspects of the simulation, including: building envelope constructions, glazing types, the basis of the area estimate used for the calculation of energy intensity indices, lighting and equipment energy densities, HVAC modelling parameters and assumptions, schedules for lighting, equipment loads, occupancy and HVAC operation, calculations for non-simulated items such as those discussed earlier in this report, and a listing of energy use by end-use category. In presenting this level of detail, it becomes significantly more possible for the design team to peer review the simulation model when produced and check ongoing validity after a design change.

Setting Targets

If the hypothesis that simulation represents an upper asymptote to real-world performance is accepted then it follows that it provides an excellent basis for the generation of targets for building performance. However for this to occur, a number of steps are required:

1. The simulation must be updated progressively through the design and construction so that the targets developed are representative of the building as-built.
2. The simulation must include all the energy end-uses within the building or, at least, within the monitored component of the building.
3. The building must be equipped with metering that is able to differentiate energy end-uses in a logical manner so that it is possible to compare against the simulation results on other than a gross level;
4. The simulation results must be processed in a manner that provides targets for the implemented metering points. These should typically include monthly targets and daily profiles. It is also possible to generate climate-correlated benchmarks for climate-affected factors such as boiler and chiller operation.
5. The metered energy use and the simulated energy use need to be compared and interpreted to facilitate problem identification and resolution to tune the building closer to its simulated performance.

These steps may have the effect of significantly prolonging the simulator's involvement in the project. Experience also suggests that obtaining a satisfactory outcome on the metering requires considerable effort in design and commissioning.

Efficiency or Behaviour?

A further important issue in the reconciliation of simulation against actual performance is the separation of technically-driven variables, such as HVAC operation, from behaviourally driven variables such as equipment operation.

The importance of this separation is highlighted by examples such as Jiang et al. (2008), where the simulated energy use for an apartment block was found to be far higher than actual energy use. The cause of this was that the actual occupant loads in terms of lighting and equipment were far lower than simulated. While the authors proceeded to calibrate the model successfully, the critical task of evaluating plant efficiency was heavily clouded by the impact of occupant behaviour.

Although there are linkages between the behavioural and technical components of a building's operation, it is often possible to separate these into semi-independent groups. Thus for office buildings, for instance, HVAC, common area lighting and supplementary services are first-order technically driven variables while tenant lighting and equipment use can be driven in the first order by behavioural issues. This is recognized in the metering and billing arrangements for such buildings in some counties (notably Australia, New Zealand and Hong Kong) where the HVAC, common area lighting and lifts are considered to be "landlord energy" and the tenant light and power "tenant energy". Although far from absolute, such divisions enable the performance of the building to be assessed against the simulation prediction in a more useful manner, as differences can be separately tracked to technical issues, such as control, commissioning or plant failure, or behavioural issues, such as tenant equipment and lighting switching habits. This then enables a rationalization of whether it is the building's systems or the occupants that are efficient or inefficient relative to the simulation, or indeed whether the simulation's assumptions about tenant behaviour were fundamentally incorrect and in need of revision.

CONCLUSIONS

This paper has presented a discussion of the factors that need to be considered when using simulation for the prediction of absolute performance. Key issues include:

- Ensuring that the coverage of the simulation matches all the energy uses being assessed within the building;
- Ensuring that the simulation correctly represents the technical detail of the building operation;
- Ensuring that the simulation results are reported and used in a manner that enables the design team and building operators to

make use of the model to optimize the building both in design and operation.

While many of the issues raised are in themselves relatively obvious, collectively they represent a significant challenge for many key stakeholders in the building design and construction process. In particular:

- Simulators need to improve the depth, accuracy and reporting of simulations to ensure that they are meaningful and usable by the design team;
- Designers need to ensure that metering systems are designed and installed such that they can be compared against the simulation results once the building is operational;
- Simulators need to be retained for longer term involvement in the project to update the model as the design changes;
- Simulation developers need to consider the importance of developing better representations of control operation and key plant items to ensure that the models provide a credible basis for absolute energy estimation.

These challenges will need to be met over the next 2-4 years to enable the simulation industry as a whole to keep pace with the demand for in-operation building performance that is a necessary response to concerns about global climate change.

REFERENCES

ASHRAE 2001, See Section ASHRAE 90.1 – 2001, Section 11

Bannister, P. 2009b Why Good Building Go Bad While Some Are Just Born That Way, Ecolibrium, (Australian Institute of Air-Conditioning, Refrigeration and Heating), P24-32, February 2009

Bannister. P. 2009a. This comment is based on data recently gathered by the author for a 35-storey building with 3 lift rises.

Bannister, P, 2005. The ABGR Validation Protocol For Computer Simulations, Building Simulation 2005, Montreal.

Bloomfield, C., and Bannister, P. 2007. Energy Efficiency Opportunities in Existing Commercial Office Buildings in Australia, Sustainable Buildings 2007, Hong Kong, 4-5 December 2007.

Donn, M. 1999, Quality Assurance – Simulation and the Real World, Proceedings, International Building Performance Simulation Association Conference, Kyoto, Japan September 1999.

FEMP 2000, Federal Energy Management Program Monitoring and Verification Guidelines Edition 2.2, Chapter 25. US Department of Energy Report DOE/GO-102000-0960 September 2000.

Jiang, W., Lui, B., Snell, J., and Helmes, D. Calibration and Collaboration: Important Tools to Design High-Performance Affordable Housing Buildings. 2008 ACEEE Summer Study on Energy Efficiency in Buildings. pp3-169 to 3-180.

Kenna, E., Bannister, P. 2009. Simple, Fully Featured Boiler Modelling. Building Simulation 2009, Glasgow, 2009.

New Buildings Institute 2003, Is What They Want What They Get? Examining Field Evidence for links between Design Intent and As-built Energy Performance of Commercial Buildings. Final Report EPA Cooperative Agreement Number X – 82905201-0 Vol 1 Revised January 15 2003. Available from: US Environmental Protection Agency 1200 Pennsylvania Avenue NW, MS 6202J Washington DC 20460 also at www.newbuildings.org/downloads/papers/EPA_Volume1(r1).pdf

Nipkow, J., and Schalcher, M (2006). Energy Consumption and Efficiency Potentials of Lifts. International Energy Efficiency in Domestic Appliances & Lighting Conference' 06, available at http://mail.mtprog.com/eedal.html

NSW Department of Environment and Climate Change. NABERS Energy Guide to Building Energy Estimation 2008. Available at www.nabers.com.au.

NSW Department of Environment and Climate Change 2009. National Australian Built Environment Rating System (NABERS) see www.nabers.com.au.

Seattle 2004, Reference Standard-29 Non Residential Building Design by Systems Analysis. City of Seattle Department of Planning and Development.

Standards New Zealand 1996, NZS4243 – 1996 Energy Efficiency: Large Buildings

US Environment Protection Agency 2009: Energy Star. See www.energystar.gov.