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Computational Tools for Low Energy Building Design: Capabilities and Requirements

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Abstract

Integrated building performance simulation (IBPS) is an established technology, with the ability to model the heat, mass, light, electricity and control signal flows within complex building/plant systems. The technology is used in practice to support the design of low energy solutions and, in Europe at least, such use is set to expand with the advent of the Energy Performance of Buildings Directive, which mandates a modelling approach to legislation compliance. This paper summarises IBPS capabilities and identifies developments that aim to further improving integrity vis-à-vis the reality.

Introduction

Optimising building performance is a multi-variate problem made complex by the presence of interacting technical domains, diverse performance expectations and pervasive uncertainties. IBPS provides a means to accommodate this complexity while allowing exploration of the impact of design parameters on solutions that offer acceptable overall performance and cost.

IBPS programs have historically been simplified to a level that preserves the essence of the domain while excluding superfluous features. Mahdavi (2003) has pointed out that such simplifications are necessary to facilitate more effective performance explorations and inter-person communication. Where complexity dominates it is possible to decompose the problem into a hierarchy of sub-problems each of which may have an associated performance target and be constrained by the requirements of another sub-problem. The sub-problems may then be solved by appropriate means under supervisory control to ensure that all constraints are met. Several researchers have successfully applied the approach to simplified design problems (Klemm *et a*l 2000, Choudhary *et al* 2003) and thereby demonstrated that it is possible to make explicit the trade-offs that exist in building design.

At the present time, the development trend is towards *enhanced functionality*, *domain conflation* and *design process integration*.

Enhanced functionality

Here, the aim is to enable better physical representations ─ for example, of the swirl imparted to room air flow by a supply nozzle. While contemporary IBPS programs are highly functional, substantial deficiencies remain vis-à-vis designs that embody non-trivial phenomena such as thermal bridges, linked heat and moisture flow, geometrically complex shading devices, embedded renewable energy systems, stochastic occupant interactions, phase change materials, non-traditional control and so on. Addressing inadequacies exposed through use is driving the current phase of program refinements and it is apparent that this responsive development approach is leading to 'over-engineered' programs whereby particular phenomena may be modelled in different ways, with arbitrary selections left to the user. Air flow, for example, can often be represented by prescribed schedules and/or modelled via distributed leakage descriptions (network air flow) and/or room discretisation (zonal methods and computational fluid dynamics), with the user left to ponder the required mix. Such alternative abstractions will typically exist for all modelled constructs relating to form, fabric, systems, occupants and control. This theoretical pluralism stems from a perceived need to accommodate different user viewpoints while integrating state-of-the-art modelling techniques – a kind of theoretical backward compatibility. Work is underway to assist users to make appropriate selections (e.g. Djunaedy *et al* 2003 in the case of air flow modelling).

Domain conflation

Here, the aim is to make explicit the trade-offs that underlie acceptable design solutions ─ for example, between improved overall energy efficiency and increased local air pollution in the case of micro combined heat and power. There is a distinct trend in IBPS program evolution: new domain models are initially simplified (presumably to provide a quick response to user need or reflecting author understanding of the domain being addressed) and subsequently refined (presumably to remove limitations exposed through use). This has led to the situation where most simulators are hybrid, with detailed models of construction heat transfer, inter- and intra-zone air flow and radiation exchange co-existing with simplified models of conventional and renewable supply-side components, emissions and human comfort. It may be expected that the latter models will be refined over time and new domain models added (e.g. for life cycle impact assessment; Citherlet 2001) in order to explicitly address performance trade-offs in the context of designs that aim to reduce/reshape energy demand, mitigate environmental impact, improve indoor conditions and accommodate low carbon supply solutions, all at acceptable cost. As more energy-related performance domains are added so the need for output constructs that support cross-domain views of performance will grow (Mahdavi *et al* 2006). Figure 1, for example, shows an Integrated Performance View (Prazeres and Clarke 2005), which supports the collation of disparate performance aspects such as seasonal fuel use, gaseous emissions, thermal/visual comfort, daylight utilisation, renewable energy contribution and so on.

Design integration

Here, the aim is to accommodate the different skill levels and conceptual outlooks of the disciplines collaborating in the design process. Part of the solution is to ensure that IBPS programs are able to interoperate with the disparate industry applications such as CAD and software for structural analysis, regulation compliance, cost estimating, pipe/wiring layout and work flow scheduling. Much of the required data model could then be automatically generated and the power of simulation embedded within the design process. To this end, Bazjanac *et al* (2002) are developing a comprehensive data model based on the concept of *Industry Foundation Classes* (IFC), which cover aspects such as building geometry, structure, plant, electrical services and facilities management. Along complementary lines, Augenbroe (1995) developed a prototype data exchange environment by which applications may share data under the control of a formally declared process model. This work has recently been extended within a 'Design Analysis Integration Initiative' (DAI 2008) that includes work flow management while recognising that much available information is loosely structured and available in incompatible forms. Notwithstanding such efforts, application interoperability in the context of the multi-actor, temporally evolving, semantically diverse building design process remains an elusive goal. True performance optimisation must recognise the complex and multi-criteria nature of the building design activity. This requires the inclusion of non-traditional aspects such as problem decomposition, the adoption of formal performance assessment methods and the development of standard approaches to the judging of designs in terms of diverse considerations.

Specific developments

The following summaries are restricted to the principal developments being pursued at present.

Air flow

The network air flow modelling approach (Walton 1989) is now widely implemented and the present need is to extend the scope and robustness of component models defining fluid flow as a function of pressure difference.

Work has been undertaken to embed the computational fluid dynamics technique within building simulation. Beausoleil-Morrison (2000), for example, implemented a conflation controller whereby the turbulence model may be reconfigured at each time-step to accommodate changing flow regimes resulting from occupant and control actions.

There exists between the techniques of CFD and network air flow modelling, a technique of intermediate complexity termed zonal modelling ((Inard *et al* 1996). The advantage of the approach is its ability to represent intra-zone air movement without the need to solve the Navier-Stokes equations as is done in CFD. The problem with the approach is the need to partition rooms in a manner that represents the possible flow regimes (plumes, jets and boundary layers). Gagneau and Allard (2001) and Guernouti *et al* (2003) have devised empirical rules to automate this partitioning.

Lighting

In the context of daylight simulation, researchers have explored alternative ways to model the rapidly changing sky brightness distribution while eliminating the need to reinitiate an entire daylight simulation at each time step. Typical approaches to the calculation of indoor illuminance distribution are to categorise daylight conditions as a function of sun position (Herkel and Pasquay 1997) or to treat real skies as blends of clear and fully overcast states (Erhorn *et a*l 1998). Such approaches are computationally efficient but accuracy constrained. To overcome the latter deficiency, numerical models have been pursued (Reinhart and Herkel 2000); the issue then is how best to reduce the computational burden. One approach is to operate in terms of pre-computed daylight coefficients based on sky patch pre-processing (Tregenza and Waters 1983). To process a year at hourly time steps would then require 'n' sky patch simulations rather than 8760, where 'n' is typically 145. Geebelen and Neuckermans (2003) demonstrated that further reductions in the computational time are possible by increasing the discretisation mesh size within a radiosity algorithm: for rooms with common office proportions, a mesh dimension of one third to a half of the smallest room dimension performed well in terms of acceptable accuracy and practical computation time. Of course, the computational burden will rise in cases where the model itself is time varying due, for example, to the operation of window shading devices.

Occupant representation

Most interactions between buildings and occupants are two-way processes. A poorly designed building may give rise to overheating, resulting in occupant responses that worsen the indoor conditions. The incorporation of such considerations within IBPS requires an explicit model of occupant behaviour.

Rijal *et al* (2007) used results from field surveys to formulate an adaptive model of occupant window opening behaviour in response to indoor/outdoor conditions in the context of offices.

Fiala *et al* (2003) developed an explicit model of occupant geometry and thermo-regulatory response. Tanabe *et al* (2000) added to this approach by developing a method to predict the effective radiation area of the human body for any posture thus allowing determination of the apparent mean radiant temperature.

Given that human perception is difficult to model mathematically because of its subjective nature (different individuals will respond differently to the same environmental stimuli), some researchers have applied the fuzzy logic technique, which allows imprecise concepts (sets) such as ‘cold’, ‘cool’, ‘neutral’, ‘hot’, and ‘warm’ (or low, neutral, high) to be represented. The values of the set members range, inclusively, between 0 and 1 with the possibility of these members being shared between sets. In relation to thermal comfort, set members will include principal environmental stimuli such as dry bulb and mean radiant temperatures, relative humidity and local air speed and personal parameters such as metabolic rate and clothing level. Thus, a 21°C dry bulb temperature, for example, may have a member value of 0.6 when associated with the neutral category but 0.0, 0.3, 0.1 and 0.0 when associated with cold, cool, warm and hot, i.e. a 21°C stimulus can give rise to one of three perceived responses. Fuzzy rules are then applied to all environmental stimuli (ES) and personal factors (PF) to obtain an overall fuzzy prediction, for example:

if <dry bulb temp.> is neutral;
and <mean radiant temp.> is neutral;
and <relative humidity> is high;
and <air speed) is low;
and <metabolic rate> is high;
and <clothing level) is low;
then HOT

Because each ES or PF can simultaneously be a member of more than one class, all possible if-then rules must be evaluated to give the distribution of possible outcomes.

Exergy analysis
This technique allows the quality (usefulness) of energy to be assessed in addition to the quantity consumed. The objective is to attain a design solution in which the lowest quality energy (i.e. low exergy) is harnessed, e.g. a low temperature water source being used for space heating rather than electricity. The transformation of conventional (first law) building simulation theory to a (second law) exergy theory requires that the individual sources within the building’s energy balance be referred to a reference state that defines an acceptable datum. Deciding on these reference states and interpreting the results from exergy simulations of real systems can be challenging (Asada and Boelman 2003).

Micro-grids
The future is likely to be characterised by a significant utilisation of renewable energy delivered through the public electricity network (distributed generation) and by local schemes serving to complement the grid (embedded generation). In the latter case, it will prove beneficial to group building types so that the aggregate load profile is favourable in relation to the power variations associated with the renewable energy supplies. Modelling such micro-grids requires the development of demand management algorithms that can switch certain loads within the context of renewable power trading. Such a facility will primarily interact with the building heat and electrical domains by acting to reschedule heating/cooling system set-point temperatures, and restricting power consuming appliances where acceptable.

Uncertainty
Uncertainties abound in the real world and it is important to allow for these at the design stage. There are essentially two ways to do this: by undertaking multiple simulations while perturbing model parameters to reflect expected variations; or by embedding a model of uncertainty within a program’s algorithms. The former approach has been widely applied within program validation and applicability

studies, in the form of differential, factorial or Monte Carlo methods (Lomas and Eppel 1992) depending on whether the aim is to determine overall uncertainty, the contribution of individual parameters, or both. With this approach, the IBPS program remains unaltered but the computational burden rises because of the need to undertake multiple simulations. The latter approach is a new entrant to the building simulation field. Program modification efforts aside, its attractiveness lies in its ability to identify individual and overall uncertainties on the basis of a single simulation. Macdonald (2002), for example, replaced uncertain parameters within the energy conservation equations for room air, surfaces and intra-construction energy balances with affine representations (Figueiredo and Stolfi 2004) whereby single parameter values are replaced with a first order polynomial comprising the mean value of the parameter and individual uncertainties represented by interval numbers (Neumaier 1990). Solution of the conservation equations on the basis of affine operations then leads to an affine number representation of state variable uncertainties (as opposed to a single, definite value). In addition to computational efficiency, the approach facilitates simulation-time control on the basis of uncertainty considerations: for example, a simulation might be terminated or the imposed control modified if the ability to maintain thermal comfort becomes ambiguous.

Supply systems

Typically, models of the systems that supply heat and power are developed from pre-constructed component models and therefore a major issue is how these models are generated in the first place. Chow (1995) has developed a 'Primitive Parts' approach whereby component models may be synthesised from pre-constructed models representing individual heat and mass transfer processed. The merit of the approach is that arbitrary complex models may be rapidly configured for particular problems.

Work is ongoing to develop dynamic models of new and renewable energy systems suitable for building integration. Grant and Kelly (2003), for example, have developed a model of a ducted wind turbine, which may be deployed around roof edges to convert the local wind energy to AC power. In one implementation of the technology (McElroy and Kane 1998), an air spoiler was incorporated to increase the air speed through the turbine. By covering the spoiler with photovoltaic cells, the device was able to convert solar energy to DC power thus making the electrical output uniform across the year.

Many other supply-side developments are ongoing, including the development of models for ground and air source heat pumps in anticipation of a possible return all-electric heating as a means to facilitate the future embedding of renewable energy systems.

Computation time

Despite advances in computational power, state-of-the-art simulation stubbornly defies real-time design application. The main reason for this situation is that domain integration (e.g. the embedding of CFD within the building thermal model) is computationally demanding, typically exceeding processing power capacity enhancement by several orders of magnitude. In an effort to address this problem, attempts have been made to reduce the computational demand by introducing equation solver refinements targeted on the sparse system of equations that characterise parts of the building simulation problem domain. Clarke (2001), for example, implemented a matrix partitioning technique whereby the sparsity of the multi-zone building thermal heat balance matrix equation is eliminated and individual matrix partitions may be processed at different frequency depending on the time constant of the related building part. This results in a substantial reduction in computational requirements, relative to sparse matrix processing techniques. Another approach is to apply a model reduction technique to construct a lower order model via a projection on a state space of lower dimension (Van Dooren 1999). Berthomieu and Boyer (2003), for example, have applied a technique from control theory to a building thermal model (Boyer 1999). The approach balances so-called controllability and observability Gramian matrices (Moore 1981), which embody information on the input–output behaviour of the system and characterise system stability. In this way, they obtain a model of smaller size than the original. When applied to a typical dwelling, computing time was reduced by a factor of 3, while the error associated with the model reduction was constrained to less than 0.2°C.

Simulation application

At the present time, the growth in IBPS application is exponential, driven largely by the complexity of the problems being addressed and the performance expectations of new legislation Such applications tend to explore new concepts and systems for which empirical performance evidence is sparse or nonexistent. An example is hybrid ventilation modelling (Delsante *et al* 2002) whereby natural and mechanical ventilation systems co-exist, with the operation of the former perhaps assisted by a passive device such as a chimney to utilise the natural stack effect. Cron and Inard 2003, for example, demonstrated that, for schools located in French cities, fan-assisted natural ventilation with control based on temperature and CO_2 concentration outperformed a mechanical system in terms of overall energy use and indoor air quality.

Conclusions

Present government policy is incentivising the deployment of renewable energy systems, and this portends a future where heterogeneous supply systems of disparate scale will be expected to co-operate in the context of built environment energy demands that are the subject of reduction and profile reshaping initiatives. To compound a complex problem, issues relating to user health, comfort and safety as well as energy system security and economics are likely to become more prominent in design codes and government policy.

It is against this background of profound change that IBPS tools are emerging to provide the means to pursue robust solutions. They do this by offering a means to simulate arbitrarily complex systems when operating under conditions that typify their likely use in practice. Any identified performance shortcomings, across a range of relevant performance indicators, may then be explored and rectified at the design stage. This paper have summarises the program refinements that are underway at the present time.

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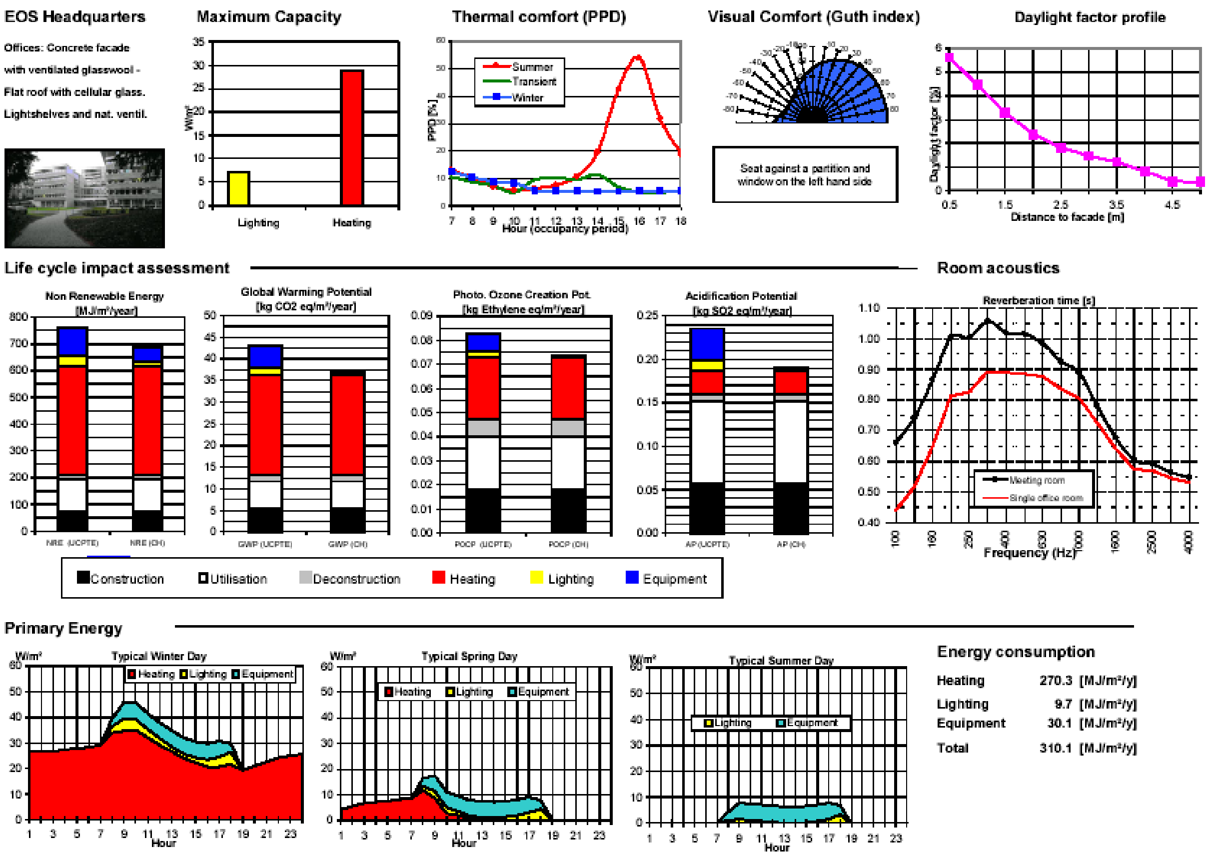

Figure 1: An integrated view of performance.