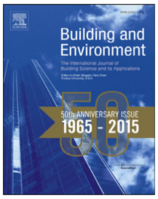
Building and Environment 91 (2015) 294–306

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



Integrated building performance simulation: Progress, prospects and requirements

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ARTICLE INFO

Article history:
Received 15 March 2015
Received in revised form
1 April 2015
Accepted 2 April 2015
Available online 11 April 2015

Keywords:
Building performance simulation
State-of-the-art
Future requirements
Scope extension

ABSTRACT

This paper is concerned with the role of Building Performance Simulation (BPS) in assisting with the creation of energy efficient habitats. It characterises achievements to date in a non-program-specific manner and in relation to the ultimate goal of providing practitioners with the means to appraise, accurately and rapidly, the multi-variate performance of built environments of arbitrary complexity. The shortcomings of the state-of-the-art, when assessed against this goal, are used to identify future development priorities.

1. Introduction

The drive towards a sustainable built environment raises challenges for practitioners. These stem from the need to reduce energy consumption, integrate clean energy supplies and mitigate environmental impacts, all while meeting expectations for human wellbeing and economic growth.

Spitler [1] has described the evolution of BPS to date: “The simulation of building thermal performance using digital computers has been an active area of investigation since the 1960s, with much of the early work (see e.g. Kusuda 1999 [2]) focusing on load calculations and energy analysis. Over time, the simulation domain has grown richer and more integrated, with available tools integrating simulation of heat and mass transfer in the building fabric, airflow in and through the building, daylighting, and a vast array of system types and components. At the same time, graphical user interfaces that facilitate use of these complex tools have become more and more powerful and more and more widely used”. Hong et al. [3] provide a summary of BPS as it existed at the start of the present millennium, concluding presciently that “with the growing trend towards environmental protection and achieving sustainable development, the design of ‘green’ buildings will surely gain attention. Building simulation serves not only to reveal the interactions between the building and its occupants, HVAC systems, and the outdoor climate, but also to make possible environmentally-friendly design options”.

While the power of simulation is widely recognised, it is not generally appreciated that the approach does not generate design solutions, optimum or otherwise. Instead, it supports user understanding of complex systems by providing (relatively) rapid feedback on the performance implications of proffered designs. This essential attribute of simulation – learning support – is well summarised by Bellinger [4]: “After having been involved in numerous modeling and simulation efforts, which produced far less than the desired results, the nagging question becomes; Why? The answer lies in two areas. First, we must admit that we simply don't understand. And, second, we must pursue understanding. Not answers but understanding”.

Designing the built environment is a task made complex by the presence of interacting technical domains, diverse performance expectations and pervasive uncertainties. BPS provides a means to accommodate such complexity whilst allowing exploration of the impact of design parameters on solutions that provide the required life cycle performance at acceptable cost. The technology portends a future in which practitioners can routinely model the interacting heat,

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http://dx.doi.org/10.1016/j.buildenv.2015.04.002
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air, moisture, light, sound, electricity, pollutant and control signal flows and thereby nurture performance improvement by design.

The approach can be used to ensure requisite levels of comfort and indoor air quality, to devise energy efficiency and demand management solutions, to embed new and renewable energy technologies, to lessen environmental impact, to ensure conformance with legislative requirements, and to formulate energy action plans at any scale. Such functionality defines a best practice approach to design and planning because it respects temporal and spatial interactions, integrates all performance domains, supports co-operative working, and links life cycle performance to health and environmental impact. The approach is also rational from a practical viewpoint because it enables the gradual evolution of the problem description, with incremental performance outputs informing the actions to be taken at progressive design stages.

In many regions throughout the world, clean and sustainable energy solutions are being driven by legislation that mandates the BPS approach, e.g. the European Performance of Buildings Directive [5] and ASHRAE Standard 189 [6] both of which aim to bring about high performance buildings through a holistic approach to design. In addition, the collaboration activities of the International Energy Agency have accelerated developments in key areas such as energy technologies (www.iea.org/techinitiatives/end-use-buildings/buildingsandcommunities/) and solar cooling and heating (http://www.iea-shc.org/). Other organisations, such as CIBSE in the UK (www.cibse.org) and the Department of Energy in the US (www.energy.gov) are supporting BPS take-up through the development of application manuals and educational materials.

Although a large number of BPS tools exist (www.buildingenergysoftwaretools.com), there is a significant overlap in functionality [7], and while most tools aspire to encapsulate the interactions between a building's constructions, systems, user behaviour and weather, not all do this in a fully dynamic manner. Through iterative evaluation of design variants, simulation supports strategic decisions that recognise new potential directions in the development process. What-if analyses may also be performed to evaluate the robustness of a new technology under different usage scenarios and operating conditions. Moreover, BPS can act as a virtual test bed to assess the potential of hypothesized (as yet non-existing) materials, components and systems intended to create competitive advantage by improving performance in a cost-effective way.

Moving beyond the design phase, there is the potential to apply simulation to building commissioning and operation. There are two reasons why growth in these regards may be expected: first, it will address the present discrepancy between predicted and actual performance; second, new business models are emerging that are driven by whole life performance.

In common with other technology fields, BPS is subject to the so-called ‘hype cycle’ [8]: while BPS has in general supported an upward slope of productivity improvement over the last two decades, specific aspects such as systems simulation, building information modelling and life cycle assessment are often the subject of hyperbole.

The present challenge is to ensure that BPS tools evolve to adequately represent the built environment and its myriad supply technologies in terms of their performance, impact and cost. Attaining multi-functional tools, and embedding these within the design process, is a non-trivial task. This challenge is being addressed by the International Building Performance Simulation Association (IBPSA; www.ibpsa.org), which provides a forum for researchers, tool developers and practitioners to review modelling methods, share evaluation outcomes, influence technical developments, address standardisation needs, and share application best practice. A major activity of IBPSA is the delivery of bi-annual international conferences – Vancouver, Canada (1989), Nice, France (1991), Adelaide, Australia (1993), Madison, USA (1995), Prague, Czech Republic (1997), Kyoto, Japan (1999), Rio de Janeiro, Brazil (2001), Eindhoven, Netherlands (2003), Montreal, Canada (2005), Beijing, China (2007), Glasgow, Scotland (2009), Sydney, Australia (2011), Chambéry, France (2013) and Hyderabad, India (2015) – with all proceedings open-access. The existence of two peer-reviewed journals – *Building Performance Simulation* (ISSN: 1940-1507) and *Building Simulation* (ISSN: 1996-8744) – is a clear indication of maturity within the field.

2. BPS aims and achievements

A need for innovation is at the heart of many technology roadmaps for sustainable buildings and cities, such as those recently issued by the International Energy Agency [9] and the European Commission [10]. To cite but one example here, it is expected that breakthrough developments in new facade constructions [11] will make substantial contributions in the transition towards cost-effective, nearly-zero energy buildings with high indoor environmental quality.

The ultimate aim of BPS is to support such innovation by providing a high integrity representation of the dynamic, connected and non-linear physical processes that govern the disparate performance aspects that dictate the overall acceptability of buildings and their related energy supply systems. While there has been good progress with fundamental process representation, this has been achieved with much duplication of effort and significant deficiencies remain. No formal research has yet been undertaken into acceptable levels of problem abstraction to service the myriad possible performance appraisal tasks. Indeed, there remains confusion about the difference between modelling and simulation. Becker and Parker [12] have stated that it is “common to see the words *simulation* and *modeling* used as synonyms, but they are not really the same thing; at least, not to those in the field bearing those words in its name. To be precise in terminology, a simulation enacts, or implements, or instantiates, a model. A model is a description of some system that is to be simulated, and that model is often a mathematical one. A system contains objects of some sort that interact with each other. A model describes the system in such a way that it can be understood by anyone who can read the description and it describes a system at a particular level of abstraction to be used”.

BPS must also couple different domain models in order to represent the interactions and conflicts that occur between problem parts and give rise to the need for designers and clients to accept performance trade-offs. While there has been some progress with principal coupled domains (e.g. thermal and lighting), many domains are still missing or inadequately represented (e.g. occupant behaviour and integrated renewable energy systems). There is therefore a need for formal research into domain impacts and interactions.

Finally, design process integration is required to embed high fidelity tools within design practice in a manner that adds value and, in the long term, supports virtual design through the interactive manipulation of a design hypothesis against performance feedback given in real time. While some promising integrative mechanisms have emerging, in the form of data and process models, these offer only partial solutions at the present time. Further research is required to significantly extend these models and to understand the business process adaptations necessary to accommodate a fully computational approach to design.

These three issues – high integrity representation, domain coupling, and design process integration – are now considered in turn.

2.1. Physical integrity

BPS tools have traditionally been simplified to a level that preserves the essence, however defined, of some domains while excluding others. Mahdavi [13] has pointed out that such simplifications are often necessary to facilitate more effective performance explorations and inter-person communication. While contemporary BPS is highly functional, substantial deficiencies remain vis-à-vis designs that embody non-trivial phenomena such as thermal bridges, conjugate heat and moisture flow, geometrically complex shading devices, embedded renewable energy systems, stochastic occupant interactions, changing thermo-physical properties, smart control and the like.

Addressing inadequacies exposed through use appears to be the main driver for tool refinement and it is likely that this responsive development approach is leading to over-engineered programs whereby particular phenomena may be modelled in different ways. Air flow, for example, can be represented by prescribed schedules, distributed leakage descriptions (network air flow), or highly resolved room discretisation (zonal method and computational fluid dynamics), with the user left to ponder suitable approaches or blends. 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. Some work is underway to assist users to make appropriate selections (e.g. Ref. [14] in the case of air flow modelling) although, given the non-trivial nature of the problem, progress may be expected to be slow. The situation is exacerbated by an inappropriate emphasis on the software engineering aspects of BPS development at the expense of evolution of the underlying physical model. However achieved, the ultimate aim is to support model building that, while parsimonious, is nevertheless fit for purpose.

In summary, much independent (often duplicated) work has been undertaken to evolve mathematical models for particular processes:

- air flow models to represent the low Reynolds Number, non-steady flow regimes observed in buildings;
- light flow models to assess visual comfort and the contribution of daylight;
- moisture flow models to assess impacts on materials and air quality;
- occupant models to represent human presence and adaptive building interaction;
- fuzzy logic models to accommodate subjective human perception by representing imprecise concepts;
- exergy models to assess the quality of energy sources in addition to energy quantity;
- uncertainty models to determine the impact of variations in design parameter values;
- supply models to represent new and renewable energy systems;
- advanced control models to regulate energy systems/components and co-ordinate hybrid schemes;
- micro-grid models to enable load switching within the context of local renewable power trading;
- material models to support adaptive behaviour (e.g. phase change materials, photovoltaics and switchable glazing);
- efficient equation solvers to reduce simulation times and facilitate real-time design support; and
- enhanced geometry models to represent complex shading devices, solar tracking, thermal bridges and the like.

Because such developments are pursued in the absence of an overarching framework for BPS, it has proven difficult to systematically integrate the resulting models within all BPS tools.

2.2. Conflating performance domains

The aim here is to make explicit the trade-offs that underlie most design solutions, e.g. between improved energy efficiency and increased local air pollution in the case of micro combined heat and power, or between daylight capture (to displace electricity use for lighting) and its exclusion in the case of a photovoltaic façade used to generate electricity locally. Such solutions require that different domain models be able to interact at appropriate spatial and temporal resolution.

While some principal domain couplings have been established – e.g. between the thermal and lighting domains and between the heat and air flow domains – progress is slow and no approaches to integrative modelling have yet been formally researched and justified. Because of this, the impact of domain interactions on problem parameters is poorly understood and essentially excluded from performance appraisals. There is, however, a distinct trend in BPS program evolution: new domain models are initially simplified (presumably to provide a rapid response to user need or reflecting limited understanding of the domain being addressed) and subsequently refined to remove limitations exposed through use. For example, a three dimensional construction heat flow model might typically be blended with a one dimensional moisture flow model, or a dynamic building model might operate alongside a steady-state plant representation. 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/behaviour. It may be expected that the latter models will be refined over time and new domain models added (e.g. Ref. [15] for life cycle impact assessment) 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.

Whether it is best to integrate domain models within a single program or within separate, cooperating programs is a moot point. The former approach supports high integrity, multi-domain modelling because all domain models have access to the same data model and can therefore interact at the solver level. The latter approach implies that a problem can be decomposed into a hierarchy of sub-problems, each represented by a different tool – for comfort, HVAC, air flow, lighting *etc.* – with an overarching coordination mechanism to ensure that domain interactions are translated to appropriate tool reconfigurations as a simulation progresses. While a decoupled model might prove useful when the coupling is one-way (e.g. the calculation of surface pressure coefficients by an urban canyon CFD program for use by a building air flow algorithm), for many problems (e.g. urban heat island impact) domain interaction is bi-directional and full coupling will be required. Cóstola et al. [16], for example, have demonstrated the de-coupled approach using programs for building energy simulation and construction heat and mass transfer, while other researchers have applied the approach to simplified design problems [17,18]. The de-coupled approach is presently favoured by CAD vendors because it readily adds appraisal functionality to their existing offering. The barriers resulting from the absence of a tool coordination mechanism (i.e. weak tool interoperability) are expected to be mitigated by adherence to a common data exchange schema that allows a shared model semantic.

2.3. Design process integration

The aim here is to accommodate the different skill levels and conceptual outlooks of those who collaborate in the design process. Part of the solution is to ensure that BPS programs are able to interoperate with other 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 may then be automatically generated and the power of simulation embedded within the design process.

There exists a plethora of building information models (BIM) and their related construction sector platforms, e.g. Revit® [19], with some work to extend the data model to include work flow management. The core issue is how to transfer information between tools without the need to access different BIMs. There are several initiatives in this regard. For example, Bazjanec [20] and co-workers are developing a 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 [21] and co-workers developed a prototype data exchange environment by which applications may share data under the control of a formally declared process model. This work has been extended within a 'Design Analysis Integration Initiative' [22] that includes work flow management while recognising that much available information is loosely structured and available in incompatible forms. Green Building XML, or gbXML [23], is made available as an open schema covering the geometrical and some energy-related aspects of a building. The schema partially supports the transfer of information between CAD models and a variety of engineering analysis tools.

At the present time, all BIMs are partial, many are proprietary, and there is scant support for core activities such as problem decomposition, model quality assurance, tool application coordination and interoperability, user conceptual outlook and skill level, the temporal aspects of design, semantic diversity in the construction industry, scenario-based design appraisal, performance representation and presentation, judging designs in terms of diverse considerations, and mapping of simulation outcomes to design intervention. Application interoperability in the context of the multi-actor, temporally evolving, semantically diverse building design process remains an elusive goal. True performance simulation must recognise the complex and multi-criteria nature of the building design activity and will require the inclusion within BPS of support constructs such as problem decomposition, automatic performance assessment, and standard approaches to the judging of designs in terms of diverse criteria. Until BIM matures, all that can be done to avoid an unnecessary burden on BPS tool users is to encourage vendors to adhere to common input formats and provide support for inter-tool data exchange in specific cases.

Another vexed issue is user interface: why does each BPS tool offer a unique interface to its peculiar and partial model of performance? What is needed is a way to tackle the two fundamental problems that underlie the use of all design tools: the quantity and nature of the data being manipulated, and the expertise and conceptual outlook of users. By constructing a user interface that incorporates a significant level of knowledge in relation to the user, the domain, and the BPS tools, a more co-operative dialogue can be enabled. This, in turn, allows designers to more easily abstract a design hypothesis into a form suitable for computer manipulation and then initiate the required assessments. While there have been attempts at creating front-end authoring environments that may be used to tailor interfaces to the different conceptual outlooks, technical capabilities and computer aptitudes of users, e.g. Ref. [24], these have not been taken up for two principal reasons: the absence of a shared vision of user requirements, and the market positioning of tool vendors that downplays ease of use problems.

3. BPS future requirements

In the early days of building performance simulation, users were likely to be building physicists or building services engineers concerned to evaluate the impact of a limited number of energy efficiency measures and/or size HVAC equipment. Contemporary BPS application is driven by concerns such as energy demand reduction, climate change mitigation, environmental protection, fossil fuel replacement, security of supply and improved living standards. This situation has given rise to several distinct needs: support for diverse user types and applications; upward and downward extension of the application scale; the linking of energy, environment, wellbeing and productivity; the imposition of uncertainty and risk; consideration of life cycle performance; support for both design and policy objectives; and the addition of new technical domains such as micro-generation, micro-grids and demand management/response. In short, BPS has become much more than a building design support tool: the following sections illustrate emerging application areas.

3.1. Building performance

The remit of BPS is set to expand to meet the challenges posed by increased user expectations and legislation. Good indoor air quality, for example, is a fundamental prerequisite of a health-promoting building. Numerous issues can be addressed through the application of macroscopic and microscopic air flow modelling or a combination of the two. In a domestic context, for example, air flow modelling will contribute to the prediction of condensation, dampness, mould growth and the spread of spores. In commercial and industrial contexts, air flow modelling can address some of the issues underlying sick building syndrome and low occupant productivity, such as the removal of volatile organic compounds and the maintenance of a low mean age of age. While the application of computational fluid dynamic (CFD) techniques to the above issues is not new, the embedding of CFD within BPS to enable the reconfiguration of turbulence models and boundary conditions as a simulation proceeds is likely to become a routine requirement.

The prediction of surface condensation and mould growth is an area where the CFD and fabric moisture domains can be applied jointly. Both models can co-operate with the building thermal model to assess wall surface and near-wall conditions. The information required for mould growth prediction is then available: the time evolution of the free moisture and temperature conditions at internal surfaces. Using the same combined model, it would be possible to track the diffusion path of mould spores.

At a lesser level of granularity, a network air flow model supports the analysis of contaminant dispersal throughout a building. An example of this approach is the modelling of the diffusion of combustion-derived contaminants through a naturally ventilated building close to a busy road. If more detail is required with regards to specific localised concentrations, the predictions of the network air flow model can be used as boundary conditions for the CFD domain. This demonstrates an advantage of the modular solution approach in that the same phenomena can be examined at different levels of detail depending on the application requirement.

The ability to couple an HVAC domain to other domains enables it to be used in the modelling of low carbon energy systems. For example, ventilated photovoltaic (PV) façades can be modelled using a combination of an air flow network linked to a 3D façade representation thus allowing the PV cells to reduce the solar radiation absorbed by the fabric (to account for that portion converted to electricity) while adding an intra-construction heat flux as a function of cell operating temperature. Further, the air flow network may be connected to an HVAC model representing a heat recovery system linked to the façade cavity (adjacent to the PV components) and/or to an electrical network model to link the PV output to local loads (lighting, water heating, heat pump space heating *etc.*) or to the low voltage electricity grid.

3.2. *Micro-grid design*

Renewable energy (RE) systems are typically pursued at the strategic level, with distributed hydro stations, bio-gas plant and wind farms being connected to electricity networks at the transmission or distribution levels. To avoid problems with fault clearance, network balancing and power quality, it has been estimated that the deployment of systems with limited control possibilities should be restricted to around 25% of the total installed capacity [25], while MacKay [26] has highlighted the difficulties of resource capture at a scale required to match national demand. These limitations are due to the distributed, intermittent nature of RE sources, requiring controllable, fast responding reserve capacity to compensate for fluctuations in output, and energy storage to compensate for non-availability.

To achieve a greater penetration level, RE systems can also be embedded within the built environment where they serve as a demand reduction device. Such embedded generation, featuring low carbon technologies (RE or otherwise), requires the temporal matching of local supply to local demand, often after the application of demand reduction measures. For example, passive solar devices, adaptive materials, heat recovery and/or smart control may be used to reduce energy requirements, and low carbon systems – realised as appropriate mixes of technologies such as combined heat and power plant, heat pumps, gas turbines, photovoltaic components, fuel cells and wind turbines – used to meet a significant portion of the residual demand. Any energy deficit is then met from the public electricity/gas supply operating in co-operative mode. The significant point is that, for the embedded approach to be successful, the energy reduction and management measures must be deployed alongside the low carbon systems. This requires application of BPS to identify appropriate technology matches when assessed in terms of relevant criteria relating to air quality, human comfort, energy use, environmental impact and capital/operating/maintenance cost.

A potential paradigm for future energy systems is the concept of the micro-grid, where several heat and electricity generators co-operate in a local network. BPS tools equipped with appropriate domain models are well-suited to the analysis of such systems where the production of heat and electricity is inherently linked to the time varying building loads. Further, the approach may be extended from the modelling of individual dwellings to communities. In this regard, some challenges remain to be resolved, not least the development of smart control algorithms that switch flexible loads within the context of power dispatching and trading. Such a facility would primarily interact with the building thermal, HVAC and electrical domains by rescheduling heating/cooling system set-point temperatures, and withholding/releasing power consuming appliances when possible.

3.3. *Urban energy management and action planning*

At present, databases of energy use and supply are being established for geographical area of interest (e.g. institution, region or city) and to high temporal and spatial resolution (e.g. 15 minute and per property respectively). These data may then be analysed in order to provide information on fuel use and emissions to a range of stakeholders, from policy makers, through planners and designers, to citizens. To assist with interpretation, a Geographical Information System (GIS) is often employed to overlay the energy and environment data on conventional types of information such as street layouts or low voltage power cable routings. To assist with policy formulation, BPS may be used to appraise options for change, e.g.Ref. [7], to support the policy-making process. Where an option proves beneficial, its associated fuel use prediction may be returned to the database to be held alongside the present (actual) fuel use data. This enables the side-by-side display of GIS information layers relating to the present and future in support of rational action plan formulation. One emerging prospect is the combination of BPS outputs with policy criteria to generate opportunity maps for cities that depict the spatial distribution of technical opportunity and policy constraint for any given technology, e.g. Ref. [27].

3.4. *Internet energy services*

The Internet has now attained a level of resilience and capacity that enables it to support a wide range of energy-related services, with real-time delivery to those that might best act on the information. The challenge is to develop products that represent a value proposition to stakeholders and to establish service providers to deliver these products. Insofar as these challenges can be met, services can be tailored to assist the process of good governance and sustainable development by providing information on issues such as:

- fuel use by time, type and sector in support of energy efficiency and RE systems deployments;
- emissions monitoring in support of air quality and climate change targets attainment;
- city performance profiling in support of energy/environment action planning;
- large scale, synchronised home appliance control in support of electricity base load management and city-scale performance evaluation; and
- energy trading between future micro-grids.

Services may also be established to provide direct links to citizens in order to support their greater participation in sustainable development. Examples include indoor environment monitoring and control in support of responsive care provision for vulnerable members of society; and smart metering with the provision of personalised energy use data and advice in order to encourage desirable changes in usage patterns. Typically, a service provider will add value by interpreting estate data and providing the actual energy/environment service – e.g. by raising an alarm, instigating a control action or by updating a secondary Web site. BPS is useful here because it allows the rapid appraisal of options for estate intervention before enactment.

In summary, future BPS tools must offer user interfaces that cater for the needs of different user types and target applications while facilitating access to multi-domain performance modelling functionality. This non-trivial objective is best pursued through developer and user community buy-in to a shared vision of the future, and task sharing development of the new features required. Encouraging such collaboration is the intention of the future vision statement as published by IBPSA [28].

4. BPS state-of-the-art

Since its emergence in the 1970s, BPS has been the subject of a sustained research effort pursued by researchers acting both independently and within concerted actions. These efforts are extensively reported in the literature, most notably within the proceedings of IBPSA's bi-annual conference, BPS-related journals and the outcomes of IEA Annex activities. Notwithstanding this effort, several observations may be made on the limitation of the state-of-the-art, which implies aspects that require attention.

Most tool features remain program-specific, with little progress on interface harmonisation and application standardisation in order to facilitate feature sharing and allow users to access multiple tools. For example, databases relating to material properties, weather data, modelling entities (plant components, control systems, construction types *etc.*) and previously established models are *ad hoc*, held in proprietary format, have no central repository and offer no accompanying evidential basis or provenance. Interfaces are likewise *ad hoc*, adhere to disparate human–computer interface principles, and show little sign of evolution based on any formal requirements analysis and industry buy-in. Approaches to model making populate a wide spectrum, employ dissimilar syntax and require procedures that imply a radically different semantic, while program outputs relate to different subsets of overall performance, with interpretation confounded by the use of disparate performance criteria expressed in a variety of styles.

The time cycle of BPS application also remains unacceptable in relation to the requirements of practice. Attempts to address this by simplification of the theoretical basis and/or reduction in domain representation are ill-founded and unlikely to evolve the state-of-the-art in the direction required.

Progress with the conflation of existing domain models – thermal, air/light/moisture flow, plant *etc.* – is slow and, where attempted, there is often an inappropriate balance of model resolution with, for example, transient 3D construction heat flow models blended with one dimensional moisture flow models, or dynamic building models blended with steady-state plant models. This situation is often the result of an inappropriate emphasis on the software engineering aspects of the problem at the expense of evolution of the underlying physical model.

Further, while specialist tools exist for significant non-thermal domains such as acoustic comfort, indoor air quality, embodied energy, renewables, economics, life cycle assessment and the like, slow progress is being made on BPS integration. The principal barrier here is perhaps the absence of an overarching data model, which necessitates inelegant adaptations to specific tools.

Despite its core importance, support for the mapping of simulation outcomes to design intervention is nebulous. Likewise, there is little acceptance of, and agreement on, the procedures required to quality-assure models, coordinate BPS-based performance appraisals and train/support/accredit users.

As they evolve, BPS tools will become applicable to a widening range of problems; the real issue is whether the underlying modelling approach can accommodate future requirements. Sometimes a new feature will require only a minor code change, e.g. the modelling of phase change materials can be implemented in a numerical code via a modified conservation equation source term or coefficient. In other cases the required change will be non-trivial. The following summaries relate to some principal developments that will bridge the gap between current BPS capabilities and future needs: many of these developments are presently being pursued.

4.1. Air flow

BPS is routinely applied to develop effective ventilation strategies, e.g. Refs. [29,30]. A principal method, network air flow modelling [31,32] and its derivatives [33], is 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. Other possible improvements include the introduction of a pressure capacity term into the mass balance equations to facilitate the modelling of compressible flows, and the introduction of transport delay terms to the network connections – where the fluid velocity and geometrical characteristics of a particular connection are known then a transport delay can be calculated automatically.

Because buildings define a low Reynolds Number, non-steady flow problem, work has been undertaken to embed the computational fluid dynamics technique within BPS. Beausoleil-Morrison [34], for example, developed a conflation controller whereby the turbulence model parameters are automatically reconfigured at each time-step to accommodate changing flow regimes resulting from occupant behaviour and control system action.

Further, and in the context of health and comfort, it is not appropriate to couple a detailed surface model to a lumped air volume as the detail of the former model's predictions would be lost. Rather, adequate representation of surface and air/vapour distribution dictates that a CFD domain couples to a 2D surface model. Such an extension impacts upon the treatment of surface (de)absorption in the presence of an active CFD domain. This will require extensions to the linkages between the building thermal/moisture and CFD domains to handle the possible grid coupling cases: 1D/3D, 2D/3D and 3D/3D.

The modelling of fire/smoke requires that extra equations be added to handle combustion reactions and the transport of combustion products (e.g. via the implementation of mixture fraction or grey gas radiation transport models). Such adjustments can be readily implemented within existing numerical codes since the governing equations are of diffusive type and so can be treated in the same way as the energy and species diffusion equations. In conjunction with the network flow model, the transient distribution of fire and smoke may then be applied as a boundary condition for the prediction of the movement of occupants during a fire.

A further CFD refinement is to enable modelling of small solid particulates that have appreciable mass within the main air stream. Two particle dispersion/deposition modelling methods are appropriate here: treating the particles as a continuum, or particle tracing using Lagrange coordinates. A prototype continuum-based model has been established to enable the modelling of very small particles in flows with Stoke's number significantly less than 1 [35].

There exists between the techniques of CFD and network air flow modelling, a technique of intermediate complexity termed zonal modelling [36]. The advantage of the approach is its ability to represent intra-zone air movement without the need to solve for turbulence effects 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). Several researchers have devised empirical rules to automate such a partitioning [37,38].

4.2. Lighting

In the context of daylight simulation, there is a need 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 [39] or to treat real skies as blends of clear and fully overcast states [40]. Such approaches are computationally efficient but accuracy constrained. To overcome the latter deficiency, numerical models have been pursued [41]; 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 [42]. 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 [43] 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.

4.3. *HVAC systems*

While component models exist to represent most HVAC systems, many of these relate to steady-state operation with no account of dynamic response. Work is therefore required to introduce dynamic considerations into these models.

The extensibility of the approach is then essentially unlimited with new component models implemented as new products emerge. The major issue confronting BPS is the generation of the component models in the first place and the combination of the selected components to form a supply system. To this end, two issues need to be addressed: the synthesis of component models from basic heat transfer/flow elements and the automatic linking of the resulting models. The former issue has been addressed by a ‘Primitive Parts’ technique [44] whereby a new component model may be synthesised from pre-constructed models representing individual heat and mass transfer processes. The merit of the approach is that arbitrary complex models may be rapidly configured for particular problems. The latter issue might build upon previous and current research into object-oriented, equation-based approaches to complex physical systems modelling [45,46].

4.4. *Control*

Early examples of stochastic control include the pioneering algorithm by Hunt [47], who developed a relationship between the lighting conditions in offices and the probability that occupants would switch on lights on arrival, and a model for the simulation of occupant presence by Page et al. [48]. Since then there has been an explosion of activity in the field resulting in algorithms for occupant presence and behaviour as summarised in the next section.

Simulation-assisted control has also received growing attention because of the ability of the approach to enact trade-offs between different sub-systems, e.g. between HVAC and lighting systems. Clarke et al. [49], for example, established a prototype simulation-assisted controller, in which a BPS tool was embedded in a real-time control system; results from experiments demonstrated the feasibility of the approach. More recently, Wetter [50] has developed a ‘Building Controls Virtual Test Bed’ to link BPS-based building automation systems, while Mahdavi et al. [51] have demonstrated the use of embedded simulation to rank alternative control options.

Given that human perception is difficult to model mathematically because of its subjective nature (different individuals will respond differently to the same environmental stimuli), researchers have applied the fuzzy logic control 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 temperature> is neutral;
and <mean radiant temperature> 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 are evaluated to give the distribution of possible outcomes and therefore the required control action.

4.5. *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 condition.

No matter how well the technical domains of the building are modelled, the behaviour of occupants can vastly alter the physical behaviour and ultimately the predicted performance. These effects arise from two avenues: behaviour (e.g. window opening) and attitude (e.g. the rejection of facilities on other than performance grounds). Two approaches to occupant modelling are possible: typical interactions may be included within a controller that has authority to adapt the parameters of the affected domain models prior to solution at a given time; or, more realistically, an explicit model of occupant behaviour may be introduced by which the physiological and psychological responses to stimuli are explicitly represented. In both cases the aim is to address the distributed impacts of occupant actions (e.g. the impact on the network flow, CFD, thermal and lighting domains in the case of the previously cited window opening case).

Mahdavi and Pröglhöf [52] reviewed developments in the field and concluded that control-related behavioural trends and patterns for groups of building occupants can be extracted from long-term observational data. To this end, Rijal et al. [53] 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. [54] developed an explicit model of occupant geometry and thermo-regulatory response. Tanabe et al. [55] 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. Other researchers have developed algorithms for occupant presence [79], manual/automatic luminaire control [80], and high resolution occupant behaviour modelling [81].

At the present time IEA Annex 66 (*www.annex66.org*) is attempting to rationalise existing occupant-related models and present these in a form that may be readily accessed by all BPS tools.

4.6. Model quality assurance

The quality of results depends, of course, on the physical correctness of the model. It is a widely held view that it is not possible to validate results but only to increase the level of confidence that is placed in them. The BESTEST initiative [56,57] represents a major international effort to increase the confidence in BPS outcomes. Its progress is reflected in its first footholds in professional standards such ASHRAE Standard Method of Test 140 [58].

It is also possible to automate sensitivity analyses as a means to handle uncertainty and, albeit in a limited way at present, undertake multi-objective optimisations involving the systematic evaluation of design alternatives within a (partial) solution space. With the likely deployment of demand management/response techniques in future, buildings will be expected to react to imposed disturbances. BPS can then be used for robustness analysis or to support local optimisation under uncertainty.

4.7. Uncertainty considerations

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 [59] depending on whether the aim is to determine overall uncertainty, the contribution of individual parameters, or both respectively. With this approach, the BPS program remains unaltered but the computational burden rises because of the need to undertake multiple simulations.

The latter approach is a nascent 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 [60], for example, replaced uncertain parameters within the energy conservation equations for room air, surfaces and intra-construction energy balances with affine representations [61] 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 [62]. 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.

It is worth noting that it is common practice to not report confidence levels for simulation results. This omission is unacceptable in most cases because it is well known that building performance is entirely dependent on parameters that are highly uncertain such as occupant behaviour.

4.8. Exergy analysis

This technique allows the quality (usefulness) of energy to be assessed in addition to the quantity consumed: a likely important attribute of future BPS tools when applied to the issues relating to the electrification of heating. The objective is to attain a design solution in which the lowest quality energy (i.e. low exergy) is harnessed, such as 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 will likely prove challenging [63].

4.9. Computation time

Despite continuing advances in computational power following Moore's Law, 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 problem domain. Clarke [64], for example, implemented a matrix partitioning technique whereby the sparsity of the multi-zone building energy balance matrix equation is eliminated and individual matrix partitions may be processed at different frequency depending on the time constant of the related physical part. This results in a substantial reduction in computational requirements, even 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 [65]. Berthomieu and Boyer [66], for example, have applied a technique from control theory to a building thermal model [67]. The approach balances so-called controllability and observability Gramian matrices [68] that 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 claimed to be less than 0.2 °C.

In future, solver developments may be implemented to bring about computational efficiencies and thereby assist with the translation of simulation to the early design stage. For example, context-aware solution accelerators may be embedded, parallelism may be introduced, network computing might be exploited, and/or computations moved from the CPU to the GPU. Such developments might build upon new methods such as ‘intelligent matrix patching’ whereby the coupling information between domain models are stored in a ‘patch’ matrix allowing the numerical model of the coupling components to be activated only when the actual coupling takes place. Further, a greater level of coefficients management may be introduced to ensure that these are only updated when required and otherwise never reprocessed. Such devices, along with hardware improvement, would lead to significant further reductions in computing times.

4.10. New and renewable energy systems

The future is likely to be characterised by a significant utilisation of new and renewable energy technologies. Where these are deployed at the local level, it will be beneficial to group buildings and implement load control strategies so that the aggregate load profile can be adapted to the uncertain heat and power variations associated with renewable energy supplies.

Modelling such schemes will require the development of demand management algorithms that can switch 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 this is acceptable.

Another major requirement will be to extend current HVAC simulation capabilities by adding models for new and renewable energy technologies – heat pumps, combined heat and power, solar thermal/electric, fuel cells, wind turbines, district heating *etc*. BPS has already proven itself amenable to the modelling of passive and active renewable energy systems. Grant and Kelly [69], 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 electrical power. In one implementation of the technology [70], 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 electrical power thus increasing the electrical output throughout the year. Other development examples relate to ground and air source heat pumps and Stirling engines for combined heat and power [71].

A core issue to be addressed derives from the fact that such models can span several modelling domains. For example, a photovoltaic façade has thermal, air flow, electrical and control constituents: the model is essentially the linkage point between the domains, interchanging key coupling variables as the simulation progresses. This issue is further exemplified by a dynamic fuel cell model [72] where control volumes represent the fuel cell plates, gas channels and balance of plant such as the gas desulphuriser and reformer. The equation-set describing the fuel cell covers 3-D heat conduction in the stack, gas dynamics and electrochemical reactions, while the boundary condition for these equations is supplied from other domains: environment temperature, relative humidity, electrical demand *etc*.

Developments are also required in relation to the modelling of micro-generation systems, which will often be subjected to control actions based on electrical as opposed to thermal criteria. Examples include voltage regulation, network stability and phase balancing. Control of this type requires the iterative coupling of all domains that impact on the electrical domain and will need to be intelligent enough to balance the conflicting demands of local comfort and community benefit. This type of control will likely include some form of financial decision making.

4.11. Intelligent front- and back-ends

Result interpretation is the element which usually differentiates most between the requirements of the novice and the expert. The expert will be trying to detect patterns in, and relationships between, the different design parameters, in an attempt to isolate the dominant causal factors and aid problem understanding. To do this, all the data generated by the program has to be available and capable of being displayed in juxtaposition with any other data. The novice, on the other hand, merely requires a concise summary of performance, preferably in terms of parameters which are most meaningful to the design team and client. Abstracting application returns into these terms is difficult and will require the development of BPS front- and back-ends, which intelligently manage users [23].

4.12. Economic considerations

An accurate estimate of the cost of low carbon solutions within new builds and retrofits is characterised by many uncertainties involving interrelated factors that are difficult to assess. Most simulation models therefore exclude cost considerations, thereby enabling design inter-comparisons on performance grounds alone. What is required is the development of rule-based expert systems that address the complex cost estimation problem in a manner that overcomes the inaccuracy of a simply rate times quantity approach.

5. The future

At the present time some mega-trends are discernible that are likely to bring about extension of the scope of BPS application.

5.1. Internet of things

The so-called ‘big data’ revolution implies a future of connected devices relaying data to servers that act to delivery information services that represent value to different stakeholders. Nowhere is the potential greater than when the approach is applied to services such as built environment performance tracking, appliance remote control and timely citizen advice. BPS has a significant role to play in helping to map observations to suggested action as part of the analytics applied to collected data. It might do this through the *a priori* generation of ideal performance benchmarks to allow rapid identification of areas for improvement, or through exploratory simulations that prioritise possible design changes and control action. Enabling such innovation will require new methods for automated model calibration, data-driven inverse model generation, or hybrid approaches that mix empirical data and physics-based models.

Significantly, the ‘internet of things’ approach will allow the utilisation of non-traditional information sources as a means to bridge the gap between prediction and observation, e.g. the imposition of HVAC system operational states or occupant behaviour data on models representing existing buildings.

5.2. High performance computing

There exists a spectrum of energy modelling approaches typified by BPS at one pole and general energy-economy-environment models at the other, and there is a palpable need to make appropriate linkages.

From a BPS perspective this linkage can best be achieved by utilising high performance computing to radically increase the scale of the problem that can be processed. While it is likely that many aspects of a building simulation problem will not be amenable to parallel computing because of the intrinsic connectedness of the underlying mathematical model, many computationally intensive aspects will be: e.g. inter-building shading, multiple domain CFD simulation and simulation results recovery. As the scale of the problem increases – from single building, through community energy schemes to regional options appraisal – it will be important to ensure that BPS programs are capable of being operated in scripted mode where no user is present to drive the application process. It will also be necessary to ensure that present modelling capability relating to air flow, plant and electricity networks may be applied across multiple buildings; and, of course, to add in transport considerations (such as building-connected electric vehicles).

5.3. Cloud computing

The present push being given to so-called cloud computing and the reason underlying this push have the potential to drive BPS in diametrically opposite directions. On the one hand, the formidable resources available on a cloud server will support enhanced simulations and facilitate model sharing, with local computers relegated to the preparation of models and the viewing of simulation results. On the other hand, and given that the communication industry will seek to make profit from bandwidth as opposed to compute power or data storage (both with rising capacity and falling cost), it makes sense to retain local simulation capability and thereby avoid data transmission charges. The inherent message is probably that it is best to retain both options at the present time.

5.4. *Virtual reality*

While BPS portends a future that can deliver a virtual reality to its users, this will require the replacement of present-day output constructs with features that support experiential appraisals. This will require that time evolving indoor environmental conditions, for example, be included as an integral part of fully rendered building images much in the same way that present tools might animate shading patterns. Likewise, it will require that all aspects of a problem (building, plant and systems, lighting fittings, occupants, electricity networks, renewable components *etc.*) be included in a single image with imposed information relating to energy use and its variation over time. Occupant models might even serve to judge the acceptability of performance as part of the simulation process in contrast to the present situation where the tool user is the judge: a deeper form of virtual reality where models of occupants react to the virtual reality represented by simulation outcomes.

5.5. *Computational approach to design*

At some point BPS will reach a stage where performance prediction (i.e. user reward) follows problem description (i.e. user effort) with an imperceptible time delay: as the level of descriptive detail is increased so the underlying simulation engine is able to provide additional layers of performance detail. There are however formidable barriers to the attainment of such functionality within a resource constrained design process. Many modelling features are tool specific, with little commonality of approach across tools. Tool outputs invariably relate to different performance aspects or, worse still, different flavours of the same performance aspect, with interpretation confounded by the use of different criteria expressed in a variety of styles. Unhelpfully, user interfaces are tailored to each tool's particular and partial targets and approaches to problem definition employ dissimilar syntax and imply a radically different semantic.

As more performance domain models are added to BPS, so the need for output constructs that support cross-domain views of performance will grow [73]. Only then can designs be adequately assessed in terms of diverse considerations. The concept of Integrated Performance Views (IPV) are helpful here [74] whereby performance criteria addressing energy use, occupant comfort and environmental emissions are brought together and represented in a manner that is deemed suitable for the intended user type. Clearly, different IPV flavours are possible with alternative levels of detail made available using multi-media techniques.

A proper debate on the role of models in design is long overdue, with the aim of agreeing how BPS tools can best be used in practice in order to establish standardised Performance Assessment Methods (PAM) as specific instances of a generic procedure such as that which follows (required action underlined, required knowledge in *italics*):

establish initial model for an *unconstrained base case design*;

calibrate model using *reliable techniques*;

assign boundary condition of *appropriate severity*;

undertake integrated simulations using *suitable BPS applications*;

express multi-domain performance in terms of *suitable criteria*;

identify problem areas as a function of *criteria acceptability*;

analyse results to identify *cause of problems*;

postulate remedies by relating parameters to problem causes;

establish reference model to *required resolution* for each postulate;

iterate from step 4 until overall *performance is satisfactory*;

repeat from step 3 to establish *design replicability.*

BPS tools are typically used by in-house or external specialists to appraise design solutions proposed by others. Such a situation is ultimately unsatisfactory because the inherent delay in performance feedback cannot readily accommodate the decision-making requirement of practitioners. Further, it is difficult at present to ensure that different BPS tools provide similar output when applied to the same problem. While this can be achieved by subjecting each tool to formal validation procedures, the effort required to ensure conformance is formidable. A more desirable situation is to build tools from the same set of validated models encapsulated within objects representing the physical (e.g. constructions, plant component *etc.*) and virtual (e.g. turbulence models, equation solvers *etc.*) entities comprising a building or community. These objects would be intelligent enough to understand their context so that the experience would be similar to a flight simulator in that objects defining a problem are the controls being manipulated and the performance outcomes the resulting flight path. Mazzarella and Pasini [75], for example, have reflected on the achievements of, and future prospects for, such an object-oriented approach to BPS tool development. Ultimately, the approach will open the way for participatory democracy in that all stakeholders, including end users, could contribute to a design at an early stage. Attaining such a state will require collaborative approaches to software engineering. The benefits of adopting a common BPS tool construction environment are many as summarised below.

Developers need not be expert in all areas in order to formulate a BPS tool. Conversely, limited scope, special purpose programs can be developed as appropriate.
New methods can be established and added once approved to enhance the scope or depth of future tools.
Alternative abstractions of each method, detailed and simplified, micro and macro, can be made available, with blends selected at tool construction time.
New domain models may be readily introduced or, alternatively, domain decoupling implemented to facilitate model reduction.
Tool construction can be dependent on problem composition, with methods added as the problem state evolves to support new appraisals.
Different methods for the same modelling function can be attached to different problem parts. For example, the majority of constructions might be represented by a one dimensional transient conduction scheme and the remainder by a three dimensional scheme to facilitate a local condensation study.
Tools can be constructed ‘on the fly’ that have variable scope, from a single zone, through whole building to entire community.

6. Barriers to collaborative development

The international BPS development community comprises diverse technical and business interests and has not yet evolved effective mechanisms by which long term development goals can be agreed and collectively pursued. This situation has nurtured the *Seven Deadly Sins*, as previously identified by Maver [76] in the context of Computer-Aided Architectural Design, and here recast for BPS.

Macro-myopia:	The claim that a specific tool is all-singing, all-dancing and easy to use but with no acknowledgement of the contributions of the collective and the deficiencies of the tool relative to the long term aspirations of the community.
Déjà vu:	The re-emergence of ideas that have striking similarity to earlier work but with no attempt to openly acknowledge or build upon what went before.
Xenophilia:	The importing of concepts from other disciplines (engineering, architecture, computing *etc.*) that diverts intellectual effort from researching what lies at the heart of BPS. The absence of BPS as a core discipline makes it difficult to justify R&D funding.
Non-sustainability:	Where the greater proportion of R&D effort is devoted to tool development, with correspondingly less attention given to researching design solutions that yield improved quality to the building clients and users.
Failure to validate:	Where a plethora of exotic claims are not substantiated by independent validation. In many other disciplines this would be unacceptable.
Failure to evaluate:	Where there is no independent investigation of tool usability and functionality in practice. The absence of credible user feedback means that further R&D is undirected and vulnerable to academic drift.
Failure to criticise:	A community conspiracy that condones, even encourages, self-indulgent speculation and solipsism: a bad example to set for the next generation of researchers.

In summary, BPS tool developers are forced to address disparate requirements relating to user interfaces, data model manipulation, mathematical models, numerical methods, database management, software engineering, validation, documentation and the like. Because there is limited development sharing, and since no single organisation will possess the necessary expertise in all areas, contemporary tools have substantial deficiencies vis-à-vis the reality. To compound the problem, tools are promoted in a manner that hides these deficiencies and implicitly undermines the development effort expended on contemporaries. This is clearly an unacceptable situation and serves only to fragment the development effort. The consequence of such behaviours is a slow pace of change, lack of standards, unnecessary duplication of effort, tension between developers, and a plethora of applications all with substantial shortcomings.

To address the above issues, IBPSA has published a futures vision for BPS as a means to direct developments toward new functionality [27]. The intention is to convey the message that BPS is potentially better, quicker and cheaper than traditional approaches to design and policy formulation and provide an international framework to:

- define and coordinate developments relating to domain abstraction, domain conflation and design process integration;
- bring about task sharing approaches to the improvement of models and to resolve the theoretical pluralism that threatens to widen the gap between developers and users;
- define the interactions between domains and the semantic schema to allow the level of tool interoperability required;
- develop interface requirements specifications based on formal consultations with practitioners and tool developers and a shared understanding of ultimate BPS functionality;
- clarify the BPS target applications and the features and facilities required by the different user types;
- establish problem decomposition/abstraction rules and remove semantic ambiguities;
- define the semantic of performance entities and the criteria to be used to express overall performance in a manner that facilitates design inter-comparison;
- define performance assessment methods and approaches to train/support users; and
- explore and promote future BPS tool construction and performance standards.

At the same time professional bodies such as ASHRAE and CIBSE are establishing mechanisms to support use in practice – such as their Energy Modeller Accreditation Programme [77] and Building Simulation & Energy Modelling Portal [78] respectively. However, these have not yet evolved to a stage where key business questions, such as the examples that follow, may be readily answered.

What are the costs and benefits of simulation?
How do I identify the correct program for my needs?
Who provides independent program validation and accreditation?
How do I embed modelling tools in my business?
What are the different roles in a simulation team?
What training will my staff require and who can provide this?
In what ways will I need to change my company's work practices?
What are the procedures for making models and undertaking performance assessments?
How is a model quality-assured?
How is a model documented and archived?
How is a model calibrated before use?
What performance criteria should I adopt when appraising performance?
What are the risks to my business?
Where will I find approved databases for use in model definition?

7. Conclusions

Many government policies aim at incentivising the deployment of low carbon systems and this portends a future where heterogeneous energy 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 an already complex problem, issues relating to user health, comfort and safety as well as energy system security and economics are set to become more prominent in design codes and government policy.

It is against this background of profound change that BPS 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 earliest possible stage, with relevant messages fed back to the policy-making process. This paper has characterised the program refinements that are underway at the present time and highlighted the need for closer collaboration in the field.

The question is: can a truly integrated BPS platform be constructed that is able to represent real world complexity in a manner that supports user understanding? Or will the problems derived from partial, over-simplified tools continue to be pushed on to unsuspecting users? Only time will tell.

Acknowledgements

The authors are indebted to the many individuals worldwide who contribute to the evolution of building performance simulation capability and application and thereby ensure that the field remains essential and stimulating. Our apologies to those individuals whose work, due to space constraint, has not been here referenced.

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