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Closing the Performance Gap through better Building Physics

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Abstract

More than thirty years of development of building energy simulation have seen the implementation of sophisticated tools that are now well integrated in the design process. However, a good deal of frustration remains over the discrepancies often found between predicted and measured performance—the so called 'performance gap'. In this editorial, the possible reasons underlying these discrepancies are discussed and attention is drawn to some of the underlying assumptions and simplifications that are still embodied in common models of building physical processes. Is it not time to revisit some of these assumptions and see if better models can be employed—models of higher fidelity certainly exist? It is suggested that the encapsulation of modelling data using Building Information Modelling (BIM) components and the prospect of Graphics Processing Unit (GPU) parallel processing power may be able to bring about the next step in modelling realism that is needed.

Keywords
Editorial, Building Simulation, Energy, Building Physics

The last decade has seen the use of building simulation methods in evaluation of building designs with respect to energy performance and carbon emissions come into common practice. At the same time, awareness of real building energy performance has grown as more data has been made public. In the EU, for example, promoting the awareness of building energy performance has been one of the aims of the Energy Performance of Buildings Directive. This has resulted in both building carbon emissions performance calculated at the design stage and measured during operation being expressed as performance bands (A-G) and illustrated much as they are in certifying consumer white goods. In the UK, for example, these types of certification are known as the Energy Performance Certificate (EPC) and Display Energy Certificate (DEC) schemes—the former applying to all buildings at design/construction stages and the latter applying to public buildings in operation.

In light of these significant efforts to improve energy awareness it is probably not unreasonable for clients, designers and operators as well as the public to expect buildings proclaimed to be 'A-rated' at the design stage, to transpire to be 'A-rated' during operation. However, whether one compares rating bands or absolute emission rates, this is often not the case. This broad realization has generated a good

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deal of discussion about what has been termed the 'performance gap'.

The performance gap

Discussion of the performance gap revolves broadly around the issues of modelled verses actual performance (primarily with respect to energy/emissions but also overheating and air quality) and has been highlighted by recent articles in this journal[6;12]. These issues are also a significant concern to the Chartered Institution of Buildings Services Engineers as it plays a role in providing benchmark data, modelling guidelines and the training and certification of assessors[3;4].

I suggest that there are a number of factors that play a role in the performance gap, some of which are concerned with the way ratings are calculated, but more generally with factors influencing the differences between modelled and real performance. These include:

1. the differing types of emissions data used in the production of rating values;
2. uncertainties in building design parameters used in modelling;
3. uncertainties in operational data used in modelling;
4. unintended errors in the calculations;
5. limitations in the underlying models.

It is the last of these that has received least comment and that I want to address later in this article, but I will firstly comment on issues 1–4. Climatic conditions (simulated as opposed to actual) are another source of uncertainty. However, these uncertainties are relatively easy to quantify and make allowances for. More could also be said about modelling systems and building commissioning but I will focus on room thermal and fluid flow processes. Before discussing possible reasons for the 'performance gap' it is worth clarifying the definition of the different ratings of concern as these turn out to be rather different in nature.

The carbon emission rate calculations that are used in the UK and other EU countries to evaluate design and construction stage compliance, are based on the emissions related to the building's services alone i.e. mechanical systems and lighting. These are calculated using standard assumptions about internal heat gains, ventilation rates, lighting levels, room temperatures, occupancy levels and hot water demands according to broad classifications of building type. This is very reasonable if the intent is to make side-by-side comparisons of building design and specification alternatives. What is often not realized, is that the carbon emissions stated in the final results and presented in the certificate data do not include the emissions from equipment such as computers (although emissions relating to any cooling of the equipment are accounted for). This may seem strange to some but, as these are not under the control of the building designer it is arguably reasonable to exclude them from the comparison. Furthermore these emissions may, if included, desensitize the calculations when seeking to compare building design alternatives and reward good building services design.

In contrast, most evaluations of real buildings are based quite simply on the utility meter data (or possibly sub-meter data when available). Accordingly, it is energy meter data that is used to derive the annual carbon emissions used to calculate the ratings in many schemes e.g. Display Energy Certificate operational ratings in the UK. This data is naturally 'all encompassing' and reflects many other sources of building energy demands besides those of the primary building services.

There are many sources of electrical demand related to building services besides those included in the design rating calculations (e.g. EPC asset ratings). Commonly occurring demands include those of lifts and escalators, external lighting, emergency lighting, fire alarm systems, data and communications equipment, control systems, signage etc. (The CIBSE has recently published, in Technical Memorandum 54[4], methodologies for taking some of these into account in other types of building simulation.) The sum of these other emissions can be significant in some buildings and, taken along with the uncertainty in many of demands related to occupant/management behaviour in real buildings, the rating methodologies can be seen to have significant differences and so some systematic variations between published ratings should be unsurprising.

With regard to parameter uncertainties (point 2), if one attempts even the simplest form of room heating load calculation, one is faced with having to take some time to collect together a large set of parameter values relating to dimensions, fabric properties and climate conditions. When it comes to dynamic thermal modelling of multi-zone buildings, the number of parameters grows significantly so that software users are only too thankful for the libraries of default values their particular software provides. Elementary fabric thermal properties such as specific heat capacity, density and thermal conductivity are known to be uncertain—not only due to variability in the source of products but also variations in moisture content. Consequential uncertainty in modelling results is inevitable.

Many of the different heat gains that are represented in building energy simulations are dependent not only on intensity or peak output, but highly dependent on the temporal variations (reflected in model schedules or profiles) and so subject, in reality, to variations in occupant behaviour and operating practices. Consequently, given that the current generation of simulation software has to have predetermined input parameters to define heat gains, this data must be regarded as having a high degree of uncertainty associated with it—probably more so than those who fund modelling exercises realize. As I noted earlier, if one is simply aiming at making side-by-side comparisons of designs, some of this uncertainty is insignificant and one is mostly interested in getting good guidance in design decisions. However, when it comes to predicting performance in absolute terms, these uncertainties loom large.

Given that we know the inputs to simulations are in all honesty highly uncertain, one might ask; can we not quantify their significance and arrive at more meaningful results? Indeed there has been a good deal of effort in academic spheres at developing methodologies for analyzing such uncertainties, the sensitivity of the model predictions and, how this can be taken account of in design methods. Introducing some of these approaches into practice in my view requires two things, however. Firstly, quantifying uncertainties requires multiple annual calculations and so more computing power and data processing capacity. This may have been an issue that limited such approaches in the past, but can now be regarded as in the realm of feasible with conventional desktop computers. Secondly, dealing with uncertainties more openly would require something of a paradigm shift in the way we evaluate performance and how it is communicated and accepted by clients or users of model outputs. In many cases, the question asked of the modelling exercise may come down to: will the building overheat—yes or no? Or, will the building meet the emissions target or not? A more mature approach to design risk is called for.

To illustrate this point I will refer to an analogous situation in which model outputs are regularly compared with reality: weather forecasting. In many countries the public is presented with forecasts that suggest it will rain or not in a particular location at a particular time (in this approach reliance is placed on the meteorologist making a complete interpretation of the climate model results). In other countries, the public is presented with the percentage probability of rain occurring at a particular location and time. In this case, the user of the forecast can make their own decision whether to take their umbrella with them when a 50% chance of rain is forecast. In terms of modelling buildings, wouldn't it be more useful to know that a building had a certain percentage probability of overheating rather than be presented with an unreliable yes/no answer? I am suggesting then, that to move to an approach to modelling that deals with uncertainty in a quantifiable way, we also need to change the way outputs are treated and communicated to others.

The state of building energy simulation

Having acknowledged that model parameter uncertainties play a large role in the differences between simulated and measured building performance, we must also ask: are the simulation methods and software reliable? Although this sort of question may have been asked afresh recently, it is a natural question that has been both asked and studied in the past by scientists and model developers. Serious efforts at simulation tool verification and validation were made following the development of the first generation of building simulation software starting in the 1980s. Methodologies for testing simulation tools were developed that can be classified as: (i) analytical verification methods, (ii) empirical validation testing, and (iii) inter-model comparisons[1]. Some of this collaborative research effort has been reported in this Journal[2;11].

Getting reliable results from simulation tools requires skilled users. Given the large quantity of parameter data that the user has to select in building a model, the process is somewhat error prone. At the same time, it has to be acknowledged that design information does not always correspond one-to-one with the data inputs of a particular simulation tool. Users therefore have to make some interpretation of the design data. Consequently, differences in interpretation between users and simple errors can be expected to introduce some uncertainty to the modelling process. Acknowledging this, it is then revealing to examine the results of inter-model comparisons that have been published. (In published studies we can assume the errors have been eliminated and the users are highly skilled.) The question of model reliability then becomes a question of bugs in the software (rare but not unknown) and systematic differences because of limitations in the underlying physical models and their data.

The most notable study of this type was initiated by the International Energy Agency (IEA) in the BESTEST project[9], the results of which were taken up in the formulation of the ASHRAE Standard 140[1]. In the series of tests specified in this standard, very simple cuboid geometries with single windows are defined i.e. the model complexity is very limited and tightly defined. Even a browse through the informative data that is provided in the standard document shows that the agreement between the different commonly used software that has been tested is not particularly reassuring. In many test cases the range of differences is little better than 25% in terms of annual energy demand. In some cases the differences are much larger. This is partly explained by the annual heating and cooling energy in some cases nearly balancing so that the net value is due to the difference between two relatively large numbers: the net value predicted between different software appearing highly variable. Why should there be so much difference between simulation tools even in relatively simple test cases? The systematic differences between programmes in such tests are then primarily due to the differences in the underlying models of the physical processes that determine building behaviour.

Although the first generation of whole-building annual energy simulation tools came on the scene in the 1980s, it is not until the last decade that significant investment in producing commercial software has been apparent. This recent development has come as mandatory design requirements have moved to focus on energy and carbon emissions performance rather than simply insulation standards. With more than thirty years of development a greater degree of convergence and increased sophistication in the development of the models employed in such software might be expected. However, if one delves into the technical documentation or coding of such software and compares the basic underlying models with those reported thirty years ago, I suggest there is little difference to be found and some significant simplifications to the building physics models persist.

What is it about simulation software that has improved then? As building energy simulation tools have developed from academic research tools to commercial analysis and design software the most obvious developments are: (i) vastly improved user interfaces, (ii) many more variations in systems and fabric features can be represented, and (iii) integration with BIM enabled tools and CAD systems have been implemented. This has made the software vastly more usable. However, my main point would be that development of some of the underlying models and their related assumptions and simplifications, has been neglected.

Some of the key assumptions that are commonly employed in modelling building heat transfer and air movement in current building energy simulation tools are:

1. conduction heat transfer is assumed to be one-dimensional;
2. the air in room is assumed to be fully mixed;
3. moisture transport and its effect on thermal conditions is ignored.

Some of these assumptions had to be made in the early days of software development because computing power and memory were very limited (indeed many modelling approaches can be traced back to the realm of punched cards and mainframe computers being required for building simulation calculations). These assumptions were also more reasonable in the era where the prime interest was evaluating the energy used in fully air-conditioned buildings. Now that we are in the era of highly insulated, low leakage buildings with more advanced features, some of these simplifications should be questioned again.

The assumption that conduction heat transfer is one-dimensional is made almost universally in building energy simulation. This is the same assumption as modelling a building surface as isothermal and represented by a single surface temperature. However, what we have learnt from low-energy architecture and detailed investigations of heat transfer conditions (including detailed 3D modelling exercises) is that features like corners and junctions between fabrics can perform very different from plane walls. With generally better insulated fabrics, features that by virtue of their geometry make very different conduction paths (or make thermal bridges), become highly significant.

Related to this, it has been known for many years that the degree of framing in a wall construction changes its dynamic and steady-state behaviour. Although it has always been possible to make corrections for steady-state losses in framed structures, the effect on dynamic behaviour has generally been neglected. The assumption of one-dimensionality is particularly grievous when it comes to ground-coupled surfaces. Follow-on exercises to supplement the BESTEST efforts[14] have shown that building energy simulation tools still do a poor job at predicting ground heat transfer unless they are coupled to computationally expensive fully three-dimensional numerical models.

A further consequence of using one-dimensional models of fabric heat transfer is that, in addition to there being no representation of corners and junctions in the fabric, models assume the surface areas are the same inside and out. Accordingly, the user must make a decision, when inputing the building geometry, whether to use the inside or outside faces of the building fabric (recommended practices differ). Since they generally do not have the same area (in small buildings the difference can be very noticeable) either the inside or outside convective and radiant heat transfer calculations have to be compromised.

The assumption that the air in rooms is well mixed is equivalent to assuming a single temperature represents the state of the room air. This may be quite reasonable in the case of mechanically ventilated rooms with conventional air distribution systems. However, in naturally ventilated and displacement ventilated rooms this is a poor assumption. The limitations of this assumption were demonstrated by Howarth[7] for the simple case of a room with a radiator heat emitter in this Journal some time ago. In deep-plan spaces and taller spaces this assumption also becomes questionable. This assumption is furthermore linked to the manner in which convective heat transfer between surfaces and the room air is modelled. Although there has been progress in deriving correlations of convection heat transfer for a wide range of conditions, their application is still restricted by the assumptions of isothermal walls and fully-mixed room air. Likewise, the manner in which both longwave and shortwave radiation in modelled is necessarily limited in is sophistication by the isothermal wall assumption.

The limitations on modelling convective heat transfer using isothermal surfaces that represent whole walls and other surfaces, must also be questioned in the era of highly insulated buildings. As insulation levels improve, the convective component of the overall wall resistance becomes relatively large. Consequently simplifications and uncertainties in modelling convection, both inside and outside, become more significant. It can also be said that using wind data averaged over one hour in calculating external convection and making gross assumptions about the local wind environment, must also introduce a high degree of uncertainty compared to real conditions in complex urban environments—again more so with well insulated buildings.

Most building fabrics are even less consistent with a one-dimensional model of conduction when one recognizes that many materials are distinctly porous and that nearly all allow the transmission and storage of moisture. The physics of combined heat and mass transfer in porous materials has been well understood for many years[5]. The effect on the modification of heat transfer and consequently on both air-conditioning loads and overheating temperatures have been clearly demonstrated. However, although there has been advancement in the modelling of these effects[13], in simulation practice they are very often ignored and in many tools can not be represented. Surely, as there is increasing interest in the benefits of breathable fabrics and in the application of constructions such as straw bale panels, the question of modelling dynamic moisture transport deserves further examination?

Forthcoming opportunities

I have highlighted a number of types of uncertainties that can be expected in comparison of building simulation results and measured building performance. The limitations of the underlying physical models has received little comment in recent discussions of the ’performance gap’. In response to the inherent simplifications I have pointed out, I think it is reasonable to ask: can’t we do better? Before we despair of the models that are available, it should be recognized that there are ways forward both in terms of the fidelity of the models and the related issues of computing power and parameter data.

If one considers firstly the issue of modelling conduction processes and the room air, a natural approach to suggest would be to increase the dimensionality of the models (i.e. move to 2D or 3D) and increase the level of discretization: in other words, subdivide the surface and room volume into many more polygons and polyhedra. There are certainly numerical models that allow this to be done[15;17]. However, the issues of required computing power in the case of methods such as Finite Elements or Finite Volumes remain—not least because we wish to simulate every hour of the year.

Reliance is often placed in modelling conduction in building simulation applications on the use of what can be collectively called weighting factor methods. Although these are efficient in simulating long time series, these methods have always assumed one-dimensionality. Wentzel has recently demonstrated that this does not have to be the case and that it is feasible to derive weighting factors from fully three-dimensional models of building components[18]. This ‘Dynamic Thermal Network’ method can address the complexities of corners, junctions and ground-coupled constructions with high accuracy along with the required efficiency of other weighting factor methods[16].

Moving away from the assumption of fully mixed room air would require discretising the air and solving fluid transport equations in one form or another—either a simplified zonal modelling approach or some form of computational fluid dynamics. These approaches have always been hindered by the heavy computing demands and the complexities of mesh generation. Although computing power continues on an upward trend this is not likely to be sufficient to enable conventional CFD methods to be applied in transient building simulations.

A rather different approach to modelling room airflow has emerged from academic work recently. This uses both a different form of fluid equations and a different mode of computing. The approach in question combines the Lattice Boltzmann Method for solving the fluid flow equations and making use of the massive parallel processing power of modern Graphics Processing Units (GPU programming). This approach also has the advantage of requiring very simple meshing proceedures[10]. The ability to simulate fluid flow in real time with very little set-up effort has already been demonstrated. The advances in parallel processing using GPUs has clearly been driven by the computer games market but could be highly advantageous in engineering applications. The prospect of highly efficient physically accurate daylighting and radiant exchange modelling using GPU programming methods is also a real prospect[8].

An issue with all models that involve greater discretization (i.e. involve some form of computational mesh) is that much more geometric detail needs to be input and that some manual intervention in the meshing process is sometimes required. To enable practical application in building simulation software would require any meshing to be highly automated and robust.

Where physical models are more sophisticated (e.g. include moisture transport) then more physical property parameters are required. This then raises the question as to where the user of the software gets these values from? If the data is not widely available it is quite possible that the models are executed with highly uncertain parameter values, in which case the advantage of the more sophisticated model is reduced.

One of the innovations in CAD technology that has seen widespread uptake and commercial investment in recent years, is Building Information Modelling (BIM). In this approach to managing design data, geometric representations of building components are encapsulated with a range of attribute data that can include those necessary for modelling. I suggest that taking advantage of this capability can remove some of the information burden from the tool user. Combining the detailed BIM geometric data with innovative meshing methods could address the challenges of automated mesh generation noted above. Consequently, BIM could be a key enabler to making more sophisticated models of physical processes usable.

A certain amount of frustration regarding the size of the differences between predicted and real performance is understandable. Given that nearly all buildings are unique and occupants behaviours are very variable, we will always have to face up to significant uncertainties in trying to predict performance. However, I have sought to point out some possible reasons why we are not capturing the effects of physical processes in buildings as realistically as we could. As we place increasing reliance on simulation outputs and invest more in software research and development, it is important that modelling of building physical processes does not get neglected. There are now opportunities to take up improved modelling methods with the advent of BIM and GPU programming. I am therefore hopeful that the next decade will be one in which building physics receives renewed attention as simulation methods become more embedded in design and operating practice.

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