Building Performance Simulation
From Research to Professional Practice

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Abstract

This paper explores the challenges and opportunities in integrating Building Performance Simulation (BPS) in the the design of the built environment. While the complexity of building performance and the challenging sustainability target would benefit from a more systematic adoption of BPS, some limitations are still evident. Process-based changes and new business approaches should complement BPS tools technical innovation to better equip practitioners to contribute to addressing future challenges. The paper addresses the barriers to integrating BPS into professional practice, such as the complexity of simulation tools, the need for specialist knowledge and education, and the lack of a shared participative approach to design and building. The potential of BPS to support integrated performance analysis and its role in transforming design practices to meet national and international carbon reduction targets are examined. Recommendations are suggested for overcoming these barriers and promoting a wider adoption of BPS in professional practice.

1. Introduction

It is well recognised that in order to address the environmental, social and economic goals of sustainable development, efficient energy utilisation and the mitigation of environmental impact are important factors. The role of the built environment in both contributing to the environmental impacts and providing huge opportunity to reduce emissions is also recognized, to the point that many government initiatives worldwide over the last 40 years have focused on this sector (Gao *et al*., 2017). However, building energy systems are complex, their performance depending on the interaction of multiple factors and on the occupants' activities and behavior. In the absence of a means by which the performance benefit of proposed measures can be predicted reliably, such initiatives will fail.

Studies in the UK by the Building Research Establishment (BRE) as long ago as the late 1980s indicated that energy consumption in buildings could be reduced by 30 % with low and no-cost interventions that have negligible impact on users in terms of the way in which they perceive and use buildings (Building, 2024). However, in order to improve the likelihood that governments achieve internationally agreed emission reduction targets related to the built environment by their target date (Scottish Government, 2023), a raft of new building regulations and associated legislation has been introduced (EU, 2023). Building designers have a key role to play in delivery, and while the systems required to deliver such targets exist in large measure, there is no universally available decision support mechanism.

It is generally accepted that human activity is a key contributor to climate change and that our profligacy in the use of finite resources, from building materials to fossil fuels, necessitates behavioural change. If nothing else, in order to achieve national and international Carbon reduction targets, design professionals will be required to transform their existing design practices.

2. Overcoming Barriers to Integrated Working

Although dynamic simulation tools have existed since the 1970s, and despite their ability to accurately simulate buildings and their systems, their

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use has been restricted to specialist modellers who apply the tools on users' behalf. The principal reason for this is that in order to use such tools in earnest, users require in-depth knowledge of a range of thermodynamic processes, environmental systems and controls issues.

Further, for over 30 years there has been talk of integrated design team working but little evidence of buildings that exemplify this process has emerged. In order to bring the professions together, each discipline needs to be aware of the unilateral effects of any design decision on the performance of the building as a whole, and not just the aesthetics, the cost or the thermal behaviour for example. Bioclimatic issues and a more holistic approach to sustainability mean that buildings can no longer be seen in isolation whereby myriad building components, interactions with users and overall performance are intrinsically linked both internally and with the external surroundings.

In order to accommodate such thinking, the professions need to recognise the need for an overhaul of current work practices and to make significant improvements in design team interaction, in order to equip the professions with better insights and the right tools for the job. Attempts have been made to tackle this at a number of levels in the past: research, educational and professional, and although in-roads have been made, some design practice and process-based barriers are more difficult to tackle than others. However, fortunately, alleviation methods for some issues exist already.

3. BPS: Integrated Performance Analysis

In the context of the development of tools to support integrated working, building simulation tools have long been the preserve of a few specialist consultancies rather than being used where they can have the greatest impact – within construction design practices. This has resulted in additional costs for designers (time and financial) in terms of buying-in specialist services. In addition, the designer is not able to fully explore the design potential: being restricted by what the specialist reports back.

There are well-documented reasons for this situation: most notably the perceived difficulty of using simulation tools; the associated cost (hardware, software licenses, staff training); and liability issues. Also, the construction industry is traditionally a poor investor in research and development, preferring to operate core business activities on proven ground.

However, for design practice to gain maximum benefit from the potential of simulation, simulation must be embedded within the design process (McElroy *et al.*, 2007). The most problematic issues are that members of the design team will require access to models at different stages as the design progresses and that the problems surrounding the exporting and retrieval of models by multiple users are non-trivial.

This is further complicated by the fact that over the last two decades the construction industry, in attempting to become more streamlined, has moved increasingly away from the notion of integrated working towards a risk averse culture – despite the best of intentions. Instead of traditional design teams with architect and client overseeing the process, we are now faced with disruptive factors such as: value engineering, nominated subcontractors, diminishing direct labour resources and skills shortages, thus the delivery mechanism is now one step away from design team control. All of this makes it more difficult to know exactly what is going to be delivered at the end of the day – so, is there any real point in undertaking simulations to predict performance when for many all that matters is 'on time, on budget'?

The problem for BPS in terms of taking the next steps may have at one time related to lack of information, but this is no longer the case. There is no shortage of knowledge and a plethora of design guidelines exist for both designers and clients, but the problem is a lack of a procedure for integration of the emerging sustainability issues into the design process. And in the absence of a framework within which to work, those designers who wish to pursue a low carbon philosophy face significant barriers within a process that tends to be piecemeal and ridden with gaps. To tackle the problems, and to make the required degree of progress, a paradigm shift is required, involving a complete change of mind-set in terms of the design process.

While the shift to a more participative design process should have been fostered by the fast uptake of BIM, this has not yet led to a widespread adoption of paradigms such as the Integrated Design Process. Even when those are applied, it seems the role of simulation specialists is more that of providing off-line estimation of the requested performance metrics.

4. BPS: Design Tools

BPS has rapidly gained a wide popularity within the scientific community, particularly among the researchers responsible for its introduction and development. Not only has it been recognised as a valuable method of virtualizing the in-depth analysis of the multifaceted aspects of building performance, but it has become established as one of the most significant contributions of science to professional practice.

Integrated performance simulation offers building designers a spectrum of new analysis possibilities. Prior to the advent of simulation, computer-based design tools traditionally relied on simplifying reality in order that calculations could be undertaken manually. Dynamic, integrated simulation on the other hand uses complex mathematical models to represent energy flow paths and their interactions as they vary over time, thus allowing an in-depth analysis of the factors that influence the energy and environmental performance of buildings. This provides users with:

- the ability to handle a level of complexity hitherto not possible;
- the ability to address all relevant environmental issues; and
- the ability to explore all energy flow paths simultaneously.

By employing detailed building input data and using realistic weather data, dynamic simulation allows designers to understand the relationships between thermodynamic interchanges as they actually occur in buildings. This allows designers to explore the complex relationships between form, fabric and systems (conventional and renewable) in terms of the underlying dynamic transfers of heat, mass and momentum. In this way simulation allows the exploration of design issues in a holistic manner and in a way that respects the integrity of the actual physical system.

However, while the potential of BPS in supporting the investigation of the complex behaviour of buildings cannot be disputed, the actual impact (should this exist), on everyday practice, and the subsequent diffusion into professional practice does not match up to the potential or the expectations of the experts. At the same time, more and more BPS tools and players have emerged and/or entered the market, indicating that there should be a real interest. A deep analysis and constant monitoring of market trends and the diffusion of BPS tools would allow a better understanding of the direction of travel, highlighting opportunities as well as constraints and limitations, which would enable IBPSA to be more effective in promoting and supporting the use of BPS in practice.

The challenges to using BPS in practice have been documented by over time by various users and researchers: ranging from the need for specialist computing equipment, through a steep learning curve, to fear of unrecognised data input errors and lack of credibility of predictions Howrie (1995). Despite progress, (Clarke & Hensen, 2015), there also remains a perception that simulation is costly and slow, that users lack trust in outputs and in their ability to interpret results, and progress is also hampered by a lack of recognised quality assurance procedures, poor interoperability between tools and an ongoing problem in relation to the jargon associated with the technology (Hand, 1999; Donn, 1997).

How fast the existing tools are moving towards the exploitation of the full potential of BPS, and how this can be connected to the integration with other design or project management tools, including BIM, remains to be understood, and possibly promoted.

5. BPS: Constraints and Drivers

In the interim, the following outlines the main constraints and drivers that have had an impact on the development and use of BPS (in chronological order). Many of these are well known and have been covered in previous IBPSA papers, notably Clarke (2015) and PhD research (McElroy, 2009) Despite the passage of time and the overcoming of some of these limitations there has been no measurable corresponding boost for the diffusion of simulation. The reasons for this are varied and in order to resolve these we need to better understand the drivers and challenges.

5.1 Calculation Power

If the complexity of the simulation algorithms has been a key factor in preventing the spread of simulation, it could be argued that the increasing availability and calculation capacity of personal computers should have supported the resolution of this as an obstacle to the diffusion of simulation in professional practice. From a research perspective, the increased capacity has indeed permitted the development of more and more complex and accurate algorithms and models: extending the areas (thermal, visual, acoustic, air quality, moisture migration and fire safety, etc.); moving the boundaries (e.g. from the envelope to the climatic surrounding); increasing the detail (envelope/ system/ control components, users, and so on) and time discretization (control), enabling the integration and comprehensiveness (co-simulation), and upscaling the size and scale of the analysis (multizone, urban and regional areas). On the other hand, increased complexity and capability of models does not always lead to better models or improved output with the margins for error increasing with additional functionality. Perhaps as a direct result of this, the diffusion and successful implementation of simulation in practice from a professional perspective does not appear to feature a corresponding trend and yet, the potential benefits are well documented (Clark & Hensen, 2015).

5.2 User Interfaces

Simulation programs allow users to explore in detail the multi-variate performance (temperature, energy, comfort, environmental impact, etc.) that arises when occupants interact with buildings as they respond, in turn, to weather and control system influences. Compared with simplified tools, which derive from many in-built assumptions, simulation requires users to input large amounts of data, much of which is unfamiliar and expressed in an unfamiliar language. This results in a steep learning curve for new users and can create confusion and a lack of trust in the programs, causing novice users to doubt themselves and so reverting to simplified alternatives due to a perception that simulation tools are difficult to use in routine design work.

As the power of integrated BPS has increased, the need to develop interfaces that support a structured approach to design hypothesis specification and evolution has emerged as a non-trivial issue. Increasing the user-friendliness of a program is often done in a manner that belies the true complexity of the issues to be analysed, there thus a balance to be struck between protecting the user from the vagaries of the program and allowing access to the complete functionality of a powerful, multi-domain simulation environment. The problem is compounded by the fact that users' needs continue to evolve with experience, suggesting a need for an evolving interface – i.e. one that would support the transition from novice to experienced user, providing early stage support and offering insights as to more novel approaches as the users' understanding evolved.

As integrated BPS tools emerged, there existed a perception that as soon as users had access to better interfaces, the barriers to using integrated simulation in practice would evaporate. The reality is often the opposite, with the user-interface giving rise to as many problems as it solves. There is no easy answer to this dilemma and attempts to develop user interfaces over the years have been fraught with problems despite the substantial increase in the available computer power. A lack of support for program use in practice and the absence of quality assurance procedures relating to model evolution and performance appraisal procedures was seen by designers as a major barrier to the routine use of simulation modelling in practice.

5.3 Problem Definition

Because simulation specialists are not building designers, and building designers are not proficient in use of BPS, the mapping of design questions to simulation intent is a particularly challenging activity. Furthermore, an appreciation of the level of detail required to answer the design questions to be addressed is a skill that comes with experience. This gives rise to an additional barrier imposed by the fear of user error in inputting data and an associated concern of a potential discontinuity between program capabilities and the scale and complexity of real buildings.

The creation of appropriate models that are suited to exploring the key issues is an art. It is equally as possible to create an overly complex model, as it is to over-simplify the model to the detriment of addressing the critical aspects of the design. Thus, the use of simulation can be seen as costly and slow, with no guarantee of useful results.

5.4 Performance Assessment

Underlying model construction is the question of appropriateness: the model may be accurately constructed but is it the right model to answer the questions? What analysis does the profession need to undertake and at what level of detail? Is one model enough to explore all pertinent aspects? Can the same model be used to explore contaminant dispersal, lighting distribution, summertime overheating risk and annual energy consumption? If not, what level of detail is required in each separate model? The answer to this is not straightforward. The time required to extract and understand simulation outputs and results in terms of design performance predictions should not be underestimated. Insufficient time invested in analysis can contribute to misinterpretation of results and a failure to spot significant issues.

5.5 Expertise and Training

Kaplan (1992) suggested that, *"models are to error as sponges are to water"*. In the past, users were easily frustrated by systems that did not support model creation, documentation, archiving and retrieval systems, designed to trap errors, but the degree of training required to access BPS tools has been progressively reducing thanks to the development of user more user-friendly graphical interfaces, simulation suites and environments, optimization tools, reporting tools, etc. These have reduced the informatics skills requested to access simulation and have simplified the use of simulation tools for professionals with no specific training in building science. But there are risks: while it is easier to use tools, it is also easier to make mistakes due to input errors, misinterpretation of results, etc. (McElroy, 2009; Clarke, 2015; Beausoleil-Morrison, 2021). Thus, increasing the number of possible users, has also contributed to raised concerns about the reliability and trust users can place in simulation results. This has fuelled scepticism, with some presumable impact on the actual diffusion of simulation.

5.6 Results Analysis

Even when a user is confident with a program's inputs, can the user trust the outputs? And if so, results interpretation can present significant problems. In the absence in fully integrated models, how can a designer transform simulated predictions into design action? How can a designer be sure which design parameter is driving the results? Ultimately, the only way to assess the accuracy of a simulation program is to construct the building, monitor its performance and compare the actual and predicted data. While tool developers may have reason to be confident in program outputs, there existed at the outset of the research no mechanism whereby this confidence could be passed to users. The main reasons for this are twofold:

- the multi-variate nature of the problem makes it difficult to identify the design parameters that give rise to performance outputs; and
- each design has unique characteristics that make it difficult to compare outputs across designs or with benchmarks.

This poses questions around whether or not design professionals are well enough equipped to build models that are robust and no more complex than required to answer the design question being investigated, and if so, can they interpret and translate the simulation outputs into useful design action.

5.7 Regulation and Requisites

Research progress on both the theoretical and modelling side has extended the potential areas of analysis, allowing the evaluation of a range of different aspects and the introduction and the calculation of new performance metrics. To a certain extent this has supported the introduction of more detailed and more demanding performance requisites, the evaluation of which require the adoption of more and more detailed calculation methods and more and more frequently requiring the use of simulation. Nevertheless, this activity has been generally limited to larger buildings, with special relevance in terms of consumption and/or impact on users either by number or by requisites. In addition, the application of simulation has been considered as the elective solution to evaluate and optimize the performance of new or deeply renovated buildings. Finally, while the introduction of new metrics and requisites has undoubtedly promoted the development or upgrade of existing calculation tools or suites, it might be disputed that this has equally supported better awareness in the appropriate use of simulation or in the realization of its real potential in terms of optimization of the design and operation of buildings generally.

5.8 Extremization of Performance, Emersion of Competing/Overlapping Areas, and Necessity for MOO

The increase in the number and thresholds for performance targets has led to an escalation in complexity of the analysis required due to the growth in emphasis on the conflicts and interactions between different objectives and to a more unstable balance among them. An extremization of the relevance of energy or resource efficiency has highlighted critical impacts on the occupants' comfort and satisfaction, also because of a higher level of expectation associated with higher performance design standards. In such cases, the use of advanced simulation approaches has proved to be irreplaceable, while still limited to larger or more crucial applications.

5.9 Information Availability and BIM

This final trend seems to be an outlier, in that unlike the others it has reached the wider audience of professionals, following long term discussion within the research community. Building Information Modelling (BIM) comprises information collection and exchange in a structured form, allowed by the introduction of the building information models. One of the perceived limitations of BPS has been the availability and reliability of large quantities of data, and the expectations are high that BIM, as an information organizational and sharing platform, can bring new life to BPS. For this to come to fruition, the focus would have to shift to the interoperability of tools, which in turn would contribute significantly to an increase in the efficiency of the entire process, including the simulation. However, difficulties in achieving such a complete seamless interoperability seems to occupy the ongoing discussion. Notwithstanding the fact that while information and its quality tend to increase with the development of the project, and ignoring all concerns about accuracy and reliability of BPS in the earlier design phases, a question remains about the efficacy and more generally, the point or purpose of BPS.

5.10 Business Integration

Adopting a computational approach to design could make a valuable contribution to the mitigation of climate change impacts and the wider goals of sustainable development. In order for this to happen, the tools need to be fully assimilated into the design process. Such integration would require a paradigm shift in the way designers do business, in short a complete change of mindset. From clients to designers, and project managers to contractors to manufacturers, those responsible for the design and delivery of buildings face many pressures and are often reluctant to tackle the challenges associated with adopting new methods into an already complex process; in spite of the fact that new and impending legislation now requires that these issues be addressed. In addition, the costs associated with staff training and maintaining up to date equipment and applications in a fast-evolving technology area, places an additional burden on those practices that want to develop and maintain an in-house simulation capability, and so it is not always straightforward to adopt new methods, despite the apparent potential benefits. But the BIM experience indicates that this is possible.

6. And so?

So, what is still lacking or what can contribute to a larger diffusion of BPS in professional practice? Rather than a conclusive and comprehensive identification, it might be worth suggesting ideas and areas for further investigation by the IBPSA community. Here are some:

- Costs vs benefits: Would a reduction in cost make the use of BPS more intrinsic in design practice? Being simulation a time intensive activity, how could its costs be reduced? Are there other cost items in the desing and building process that could be saved and reinvested in simulation? To what extent the revenues from the simulation results or the model itself could compensate for these higher costs?
- Is there scope to improve the relationship between tool vendors and tool users through CPD, in-house support workshops and summer schools, for example? And could this be extended to educational institutions?
- Integration and adaptation of simulation tools with/during the design and operation phase: it is a priority to address the detail/accuracy paradox and to use only the level of detail strictly necessary, as increasing the number of uncertain parameters does not necessarily improve accuracy, rather it may do the increase uncertainty. That said, performance evaluation to conduct comparative assessments in the early design phase does not require accuracy in absolute terms. Synthetic/lumped parameters may be used instead of more detailed description, yielding useful results. However, it should be remembered that lower-level models may need to be easy to scale up or refined in a seamless way.
- Different business models/Innovation of building design and operation processes: is it enough to move from a linear to an iterative model, or is it necessary to proceed further towards a multi-directional/integrated approach? Based on this perspective, all design team professionals may be called upon to contribute to the definition of the optimal design or to the revision of it. Efficient data interchange is key to enabling the iterative approaches that require to be implemented. Nevertheless, even through multiple iterations, the whole process remains mostly linear if the decision-making is not open to a more shared approach to participation. This begs the question, to what extent can BIM promote a change of paradigm in which professional competences are contributing in a multi-directional/integrated way? How could the synergy between BIM and BPS reduce the scale or the complexity of the projects to which BPS is actually contributing? And, finally, will the inclusion of BPS in the loop change how buildings are designed or will it still remain an accurate and sophisticated way to calculate some performance metrics and inform the final decision?
- Different interpretations/understanding of the value of simulation: is the objective to produce simulation results only, or is there additional value in the model itself? In other words, once the process is over, the model is among the outcomes, and if we recognise the value in this, could the building model be used to make the overall effort more profitable? Is there a way to maximize the benefits from this?
- Extension of the number of beneficiary users: not only can BIM aggregate the contributions from different professionals but also provide contributions to multiple users/uses. Extending the horizon of BPS to wider use of resources, including information models, may increase the convenience and therefore the attraction of investing in the development of BPS models. The current trend from BIM to Digital Twins may suggest that a circularity is possible for information models as well as for physical resources.
- Education: simulation as virtual Problem Based Learning (PBL) environment. An over-

looked value of simulation is the role it can play in educating new generations of professionals. If PBL is gaining the limelight in the discussion about effective educational approaches, there are areas like Building Physics in which the temporal and spatial scale of the object of interest cannot fully be explored and experienced directly. Providing a deeper understanding of the inner processes occurring within the different subsystems and components of a building, offering a tangible way to check the effects of design choices or configurations will drastically enhance the competence of the professionals who are called to develop and manage more and more challenging solutions to trade-off between extreme performance requisites in the context of complex and contrasting objectives (Beausoleil-Morrison, 2021).

7. Conclusion

The adoption of Building Performance Simulation (BPS) in professional practice presents significant opportunities for improving the design and performance of the built environment. However, several barriers must be addressed to realize its full potential. These include the complexity of simulation tools, the need for specialist knowledge, the lack of a consolidated design integration approach and possibly the business model and value chain in the construction sector. To overcome these challenges, it is essential to integrate further BPS into the design process, provide adequate training and support for practitioners, and develop user-friendly interfaces that facilitate the use of simulation tools. However, fostering a collaborative approach among design professionals also by promoting the use of BPS in educational institutions, and changing the rules of the game are needet to fill the gap between BPS popularity in research and starvation in practice. By addressing these issues from a cultural perspective, BPS can play a crucial role in achieving sustainable development goals and reducing the environmental impact of the built environment.

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