The concept of building performance in building performance simulation – a critical review

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Abstract

Building performance is a concept that receives significant interest through efforts in the fields of High Performance Buildings in the USA, the Energy Performance of Building Directive in Europe and many others, and which is at the core of the work of the International Building Performance Simulation Association (IBPSA). Yet the concept remains evasive and mostly left undefined. This paper presents findings from an in-depth literature review on the topic and suggests a working definition for discussion within the community. This definition relates to further efforts needed to correlate various performance quantification approaches. The paper also reflects on the position of the field of building performance in relation to other adjacent disciplines.

Introduction

This paper discusses an important missing link in the knowledge base of building performance simulation: the absence of a working definition of "building performance". This seems to be a common issue with other disciplines; as noted by Rahim (2005), '*technical articles of research tend to use the term "performance" but rarely define its meaning*'.

Thus far, the notion of building performance has mainly been developed from inside the building discipline, chiefly from a background of building science and simulation. However, a generally accepted theory that can underpin the efforts to further building performance simulation is still missing. There also is a mismatch between the needs of the building community, experimental measurement, and simulation approaches, leading to a range of work that addresses what is known as "the performance gap"; yet in reality, there are many such gaps.

Seminal works on the topic of building performance were the book by Markus *et al* (1972) and Report 64 by the CIB (1982). However, most recent work fails to connect to that early basis, with many contributions either focussing only on single aspects (e.g. energy efficiency) or being overly broad (such as many of the sustainability studies). Arguably, the most recent contribution of note is the chapter by Augenbroe (2011) on the role of simulation in performance based building. This addresses some fundamental issues, however it is limited to simulation (thus excluding other methods of building performance analysis) and design (thus excluding other parts of the building life cycle); moreover it is rooted in a pure normative view of decision making.

A common definition of building performance will help to strengthen the position of both scholars and practitioners in the field of building performance simulation, and can go some way in bridging the performance gap between predicted/simulated and measured performance by providing a common understanding.

Methodology

This paper summarizes key findings from an extensive review and in-depth thinking on the subject of building performance analysis, conducted by the author while writing a book on this subject that is to be published by Wiley in 2017, which cites well over 1000 different sources from literature in both our field as well as adjacent disciplines.

Findings

The concept of building performance is not new; it is an integral part of the history of building and architecture in general. Performance concerns clearly already played a role in the shelters built by early humans, and some Neolithic monuments like Stonehenge (3000-2000 BC) have a number of fascinating performance attributes like durability and alignment with the solar path. Building performance is mentioned in the famous work by Vitrivius, and is implied in his famous notion of *firmitas*, *utilitas* and *venustas* (strength, utility and beauty). The industrial revolution led to the emergence of new disciplines, such as structural engineering and building services engineering, which separated from architecture and brought in their own perspectives and notions of performance. In 1896 Louis Sullivan, an American architect, wrote the famous line 'form follows function', which led to deep rethink of architectural design and an increased emphasis on building function and performance. Around the 1960, the field of building science (or building physics in continental Europe) emerged, hand in hand with the development of personal computers. Interest in building performance, and especially energy efficiency, was spurred on by the energy crisis of the 1970s, leading to the works by Markus *et al* (1972) and Report 64 by the CIB (1982) as mentioned in the introduction. IBPSA, the International

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Building Performance Simulation Association, was founded only in 1987, after the use of personal computers had been well established. In the late 1990s, the Probe studies in the UK (Post-occupancy Review of Buildings and their Engineering) raised questions about the actual performance of state-of-the-art facilities through a range of deep user satisfaction surveys, combined with extensive measurements. Towards the end of the 2nd millennium, concerns about sustainability and climate change maintained momentum, while the ICT revolution led to rapid development of measurement as well as simulation techniques.

The field of building performance is complex due to a number of characteristics of the built environment. These include the long life span of buildings, with its many phases, the many different stakeholders in buildings (which even change over time), the many systems and components that are used in buildings, the wide range of challenges in the environmental, economic, health and wellbeing that buildings have to respond to, the organisational structure of the construction industry, underlying tensions between the fields of architecture and engineering, and others.

A large body of literature has been produced that deals with various aspects of building performance, with journals like *Building Research & Information*, *Building and Environment*, *Energy and Buildings*, *Advanced Engineering Informatics*, *Automation in Construction*, *Applied Energy*, *Energy Policy*, the *Journal of Building Performance Simulation*, *Building Simulation: an International Journal*, *Architectural Science Review*, *Design Studies*, *Architectural Engineering Design and Management*, the *Fire Safety Journal*, the *Journal of Cleaner Production*, *Construction Management and Economics*, *Construction and Building Materials* and others all having published hundreds of journal papers on relatedwork. A full review of all these contributions is beyond the scope of this paper and, indeed, any work of writing. Instead, a few selected key contributions are briefly discussed here to give a flavour of the field:

- Markus *et al* (1972) contributed the first book on the specific subject of building performance. This work highlights the importance of understanding the role of humans in the assessment of building performance, as well as the interaction of various systems. It also presents design as a special kind of decision making. Chapters discuss designing for people, design as decision making, the use of resources, spatial elements, the bounding of spatial elements, the grouping of spatial elements, the computer as a design tool, appraisal during and after design, and the organisation of inter-disciplinary design in an educational setting.
- Report 64 by the CIB (1982) provides a deep discussion of building performance, based on the work of various CIB working groups. This publication takes a wide view on performance aspects, including areas such as acoustics, moisture ingress and fire. It covers both physical measurement as well as prediction, and introduces the notion of a Performance Test Method (PTM). Sections discuss the performance approach in buildings, the necessary knowledge base, determination of performance requirements, prediction of the performance of design solutions, evaluation of suitability for use, and application of the performance concept at various scales and life cycle stages. Report 64 is famous for the often quoted phrase that '*the performance approach is, first and foremost, the practice of thinking and working in terms of ends rather than means*'.
- Hartkopf *et al.* (1986a, 1986b) launched the idea of Total Building Performance, which relates various predominantly building physics domains (spatial performance, thermal performance, indoor air quality, acoustical performance, visual performance and building integrity) with physiological, psychological, sociological and economic issues. This structure leads to a matrix where the domains span a number of rows, whereas the physiological, psychological, sociological and economic aspects span columns; each field in the matrix list a number of relevant building performance requirements. This work also furthers the thinking about diagnostic tools for existing buildings.
- IEA Annex 21 (2016) developed the concept of a performance assessment method (PAM). A PAM is a roadmap for assessing building performance through building energy simulation, which requires the establishment of a representation of a base case design, model calibration, the evaluation of boundary conditions, integrated simulation, an expression of multivariate building performance, identification of problem areas, generation and testing of solutions to any problems, and a testing of the robustness of the performance analysis by running different weather files. For a deeper discussion see for instance Clarke (2001: 285-298).
- Kalay (1999) gives an insightful contribution on tensions between building form, function, context and behaviour. He explores the famous architectural notion that '*form follows function*' and relates this to views of building design as problem solving or as puzzle making, noting that performance evaluation is needed to give direction to the design process.
- Foliente (2000) is an important paper that draws a clear distinction between prescriptive and performance based building legislation, discussing the advantages as well as disadvantages of each approach. Prescriptive

legislation, which describes solutions that are deemed to comply, may be a barrier to innovation, may hinder cost-optimization, and may inhibit international trade; performance based legislation gives more freedom for alternative solutions and products provided that performance is demonstrated. Foliente points out that in practice there often is a mix between prescriptive and performance based specification.

- Preiser and Vischer (2005) have contributed a seminal book on Post Occupancy Evaluation (POE) in the wider sense, which they label Building Performance Evaluation (BPE). The book includes an introduction and overview of building performance, which positions performance at the interface between criteria and design solutions; it also discusses various stakeholders in performance and the role of performance in various building life cycle stages and emphasizes the importance of performance feedback. Interestingly the book does not really connect to building performance simulation approaches. Further sections explore performance during strategic planning, briefing, design, construction, occupancy, reuse and recycling, and case studies. The work contains an excellent appendix for those wishing to set up their own user satisfaction survey.
- Kolarevic and Malkawi (2005) offer a rare view of building performance from a wider perspective, including architectural design and theory. This edited book covers, amongst others, discussions about unscripted performance, performance form, performativity, direction of performance and performers, as well as more technical views on building simulation and building performance dialogues; it also includes the transcript of a deep panel discussion that contrasts various viewpoints. Later work that extends the architectural view is the book by Hensel (2013), with chapters that explore the notion of performance in general as well as specifically in architecture, non-discrete architectures, anthropogenic architectures, performance-oriented architecture, and which explores the road ahead.
- Becker (2008) is an often-cited paper on performance-based building design. Much of the content stems from the CIB work in Report 64, as well as the later EU dissemination and networking project PeBBu (Performance Based Building). The paper includes a process that develops user needs (UNs) into performance requirements (PRs) which can be used to study how well design proposals meet the required performance.
- Blyth and Worthington (2010) discuss the briefing process (known as architectural programming in the USA), which is a core activity in establishing the user needs and expectations where it comes to the future building performance. This work explores the nature of briefing, the briefing process, identification of needs, accommodation of growth and change in briefs, communication, learning from experience, and management of the briefing process; the book also includes case studies and a range of model briefs (at the urban, strategic, functional, fit-out and operational level).
- Augenbroe (2011) provides a deep discussion of the role of building performance simulation in building design. This text treats building simulation as a virtual experiment that is needed to quantify how well a technological solution meets user requirements. It emphasizes the need for a stakeholder dialogue about performance requirements, and about how the building meets these requirements. Augenbroe offers some deep observations that include comments on the need to balance the complexity of simulations with the information needed to make an informed choice, the need to account for the uncertainties that underlie simulations, especially in early design stages, and the importance of the fact that simulation is based on a range of assumptions and thus never fully matches reality, leading to the issue of the ‘performance gap’. The chapter also offers a critical discussion of data mapping between BIM environments and simulation tools.

While the above contributions provide a rich discussion of various aspects of building performance, most of the discussion is framed within the building discipline and is introspective. The key notion of performance that stems from the existent literature is that performance is a concept that lives on the interface of user requirements and the behaviour of technical solutions, and which captures how well the “solutions” meet the “demands”. However this notion is rather restricted and technical, and seems disconnected from other world views.

At this point it becomes important to note that there is a significant body of knowledge about the concept of performance in other fields, notably the areas of requirement engineering and systems engineering, which has been developed on the basis of thinking, experimentation and refinement by a large community of authors, both in science and industry. An example is the contribution by Gilb (2005) on competitive engineering, which contains a deep discussion of the concept of performance of a broad range of systems that is directly applicable to buildings and which helps to identify a wider view of different types of user requirements. The work by the International Council on Systems Engineering on technical measurement gives an advanced view on how to capture and quantify performance in a range of specific measures and parameters (INCOSE, 2005). This can be used to refine the relatively crude concept of 'performance indicators' as used in the building literature into dedicated measures that capture the need of the client, the performance of a system, as well as the working of subsystems that are of interest in the context of the system but not necessarily of prime importance to the client. Elements of normative decision theory also help to structure thinking about performance; see for instance Hazelrigg (2012) where the discussion about definition of objective functions and optimization offers an important context for making choices in the building design process. Pohl and Rupp (2015) discuss requirement engineering, as a wider view to briefing and architectural programming that may help the work in this area.

Typically, these works give a wider reflection on the concept of performance, which is helpful to review and develop the specific notion of building performance in the context of architecture, building science, and building simulation. This leads to a position that refutes the notion of xenophilia as a 'deadly sin of simulation' as described by Clarke and Hensen (2015); we hold that xenophobia is just as dangerous and that much can be learned from other fields. However, the field of building simulation does have a lot of particularities that require deep expertise and that should be taken into account when moving forwards, and that makes it a distinct field of its own. Concepts from other fields should be examined carefully for applicability before being embraced by building science and building simulation.

The Concept of Building Performance

A proper definition of 'building performance' should account for the fact that there are various viewpoints of the concept: (1) an engineering view, which focuses on how well a building performs a task or function, (2) a process view, which recognizes building as a construction process rather than an object, and (3) an arts and humanities view that sees performance as presentation and communication. Further exploration of these views leads to the following:

- Within the engineering perspective, performance relates to how well a building fulfils its functions. This can be further specified in terms of distinguishing quality (how good a building is at carrying out functions), workload capacity (how much a building can do), and resource saving (how much resource is needed or can be saved). The engineering view, especially the resource saving aspect, is currently dominant with IBPSA and most papers presented at the Building Simulation conferences. Workload capacity, such as in the number of persons that a building can serve over a certain amount of time, is seldom discussed.
- Performance from a construction perspective typically concerns the management of cost, time, quality, safety, waste reduction and customer satisfaction. This view of performance seems to be discussed mainly in the construction management context, which at present is somewhat disconnected from the IBPSA community.
- The arts and humanities perspective of performance is more difficult to pin down, but concerns aspects such as creativity, interpretation, communication, embodiment, enchantment and movement. This view of performance is deeply connected with some of the architectural approaches towards building performance. An interesting exercise is to review building performance using a questionnaire designed to review an arts performance as designed by Pavis (Counsell and Wolf, 2001: p 229).

Further detail can be added from a range of sources that deal with requirements in each of the performance viewpoints, notably Gilb (2005: 37-38) and INCOSE (2015: 264).

This view of performance is summarized in Figure 1.

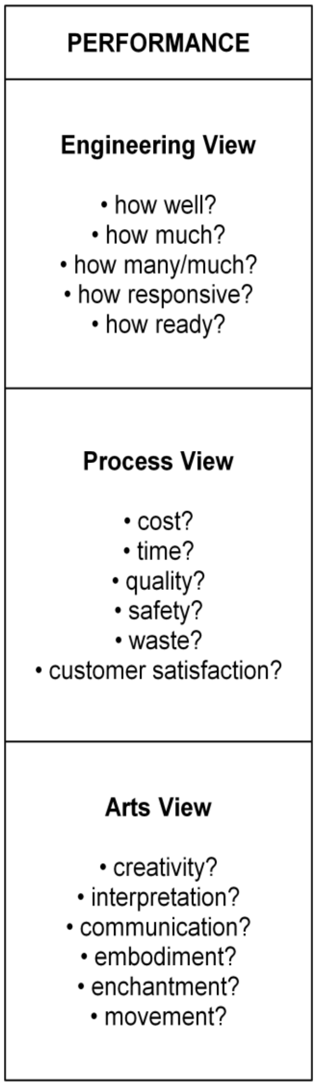

Figure 1: Main performance views and attributes.

Definition of Building Performance

Based on the previous discussion, the following definition of building performance is offered to the building science community as part of an emergent theory of building performance analysis (for further detail, see de Wilde, 2017):

Building performance is a concept that describes, in a quantifiable way, how well a building and its systems provide the tasks and functions expected of that building. Requirements may stem from three main views: an engineering view of buildings as an object, a process view of building as a construction activity, and an arts view where performance involves the notions of form and appreciation. Important performance requirements in the engineering view pertain to building quality, resource savings, workload capacity, timeliness and readiness.

Quantifying Building Performance

In order to work with performance, one not only needs a definition of the concept, but also methods for quantification – as phrased by Lord Kelvin: "*when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be*".

In general, there are four methods to quantify building performance: classical physical measurement, building simulation, expert judgment, and user assessment.

Some of the physical measurement approaches include the use of climate chambers, co-heating tests, durability tests, evacuation experiments, façade test rigs, fan pressurization (blower door) tests, burn hall measurements, hot-box experiments, acoustic measurement, thermography, wind tunnel testing, and a broad range of monitoring of parameters related to temperature, indoor air quality, lighting, and resource consumption. Different categories of building performance simulation cover acoustics, air flow, heat and moisture transfer, lighting, occupant movement and evacuation, thermal and structural behaviour. Expert judgment is often used in court, where expert witnesses may be asked to comment on relevant cases; this is also an underlying method for the judgment of architectural performance in the artistic sense of the definition. User evaluation is the main driving factor for Post Occupancy Evaluation (POE), although POE can also be interpreted as a wider process that incorporates both monitoring and user satisfaction surveys. A more in-depth discussion of these methods is provided in de Wilde (2017).

Scientific quantification imposes a certain rigor on each of these approaches. There is a close interaction between designing purposeful changes to a system, and observing the effects of these changes on measured behaviour; this requires one to capture initial states, changed changes, input and output, and a range of controllable as well as uncontrollable control factors. General principles for the design and analysis of experiments are discussed by various authors such as Montgomery (2013). Current definitions that aim to structure this process for building performance analysis appear relatively limited, with the concepts of performance test methods (PTMs), Performance Assessment Methods (PAMs) and Analysis Function (AF) representing the state of the art. However, these have not been developed to a level that allows a clear mapping between the different analysis modes that are in use. This is one of the contributing factors that makes it hard to compare physical measurement with prediction through building performance simulation, and thus contributes to the 'performance gap' problem.

Conclusions

The discipline of building performance simulation is currently operating without a definition of a key concept. This paper has critically reviewed this situation and presents recent work that addresses this issue, suggesting a definition that combines an engineering, process and arts view while clarifying the performance attributes that need to be quantified to work with this definition. The definition is offered to the community as a working concept; the author welcomes suggestions for improvement.

In terms of approaches to quantify building performance, the dominant methods are physical measurement and building performance simulation; however user evaluation is becoming more important. Expert judgment also has a role to play but is less prominent than the other approaches.

At present, the field of building performance analysis has only limited performance quantification approaches that are applicable across measurement, simulation, expert judgment and user evaluation; further work in this area is needed to allow for a better comparison of quantifications in each of this four areas.

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