Automation in Construction 41 (2014) 40–49

Contents lists available at ScienceDirect

Automation in Construction

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

The gap between predicted and measured energy performance of buildings: A framework for investigation

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ARTICLE INFO

Article history:
Accepted 8 February 2014
Available online 2 March 2014

Keywords:
Energy performance gap
Prediction
Measurement
Building design and engineering

ABSTRACT

There often is a significant difference between predicted (computed) energy performance of buildings and actual measured energy use once buildings are operational. This article reviews literature on this 'performance gap'. It discerns three main types of gap: (1) between first-principle predictions and measurements, (2) between machine learning and measurements, and (3) between predictions and display certificates in legislation. It presents a pilot study that attempts an initial probabilistic probe into the performance gap. Findings from this pilot study are used to identify a number of key issues that need to be addressed within future investigations of the performance gap in general, especially the fact that the performance gap is a function of time and external conditions. The paper concludes that the performance gap can only be bridged by a broad, coordinated approach that combines model validation and verification, improved data collection for predictions, better forecasting, and change of industry practice.

1. Introduction

Within the building industry, there is an increasing concern about a mismatch between the predicted energy performance of buildings and actual measured performance, typically addressed as 'the performance gap' [1–4]. Rapid deployment of automated meter reading (AMR) technology, typically now harvesting data at hourly or even half-hourly intervals, is making the performance gap more and more visible. The magnitude of this gap is significant, with reports suggesting that the measured energy use can be as much as 2.5 times the predicted energy use [4]. Increased pressure on the industry to address the challenges of environmental issues and rising energy prices makes it important to address this performance gap, with clients and the general public expecting new high performance buildings to meet increasingly stringent energy efficiency targets. While it seems reasonable to allow for some variation in both predictions and measurements due to the realities of uncertainties (inherent in predictions) and data scatter (inherent in measurements), the evidence seems to point to the gap presently being too wide to be acceptable.

Bridging the gap between predicted and measured performance is crucial if the design and engineering stage is to provide serious input to the delivery of buildings that meet their (quantified) ambitions, such as High Performance Buildings, Zero Carbon and Net Zero Energy Buildings. Bridging the gap is also crucial if the industry wants to deliver buildings that are robust towards change, that maintain a good performance throughout their lifetime, and that are engineered to adapt to changing use conditions in terms of 'occupant proofing' or 'climate change proofing'. Furthermore, it is a key prerequisite to novel modes of building delivery and facility management, enabling concepts such as performance based building, or performance-contracting, where occupants purchase a working environment with specified comfort boundaries rather than hardware (building and systems) that might – or might not – deliver such an environment [5,6]. In a wider context, the performance gap erodes the credibility of the design and engineering sectors of the building industry, and leads to general public scepticism of new High Performance Building concepts.

Energy efficiency is only one of the various performance aspects of buildings; it is highly likely that similar performance gaps exist between predicted and measured indoor air quality, thermal comfort, acoustic performance, daylighting levels and others. However, building industry and research presently focus on the energy performance gap; this might be due to the fact that energy metering is more prevalent and easier to implement than measurement of the other aspects. This paper aligns itself with this general focus on energy.

Energy performance of buildings can be studied at various levels of resolution. The primary view used in most studies is annual energy use of the whole building for heating and cooling purposes. However, one needs to be very careful in terms of including or excluding additional energy use for appliances, lighting, hot water and others. Energy efficiency can also be studied at higher temporal resolution using monthly, weekly, daily or even hourly data. A further differentiation relates to the

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http://dx.doi.org/10.1016/j.autcon.2014.02.009
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object of study in energy performance analysis; at the design stage (prediction) this is linked to design intent, whereas post construction the measurement only applies to a building as actually constructed (instantiation). The energy performance gap typically concerns predicted performance of the design intent with observed performance of the realized building over the year.

Some discrepancy between prediction and measurement is inevitable due to numerical errors in simulation, and experimental variation in any observation [7], but getting reasonable agreement has been a key aim of tool developers ever since the inception of energy performance prediction methods, which started in the 1960s [8]. A good historical overview of various efforts in this direction is provided by Strachan et al. which although focussed on the development of the ESP-r simulation program is also applicable to many other similar efforts [9]. Their paper describes the validation of ESP-r in the context of a series of IEA Annexes (BESTEST) and related validation projects starting from the late 1970s. The key approaches used in much of this work are analytical validation, inter-program comparison and empirical validation, with the latter mostly based on results obtained from dedicated test cells; see for instance [10]. Yet these validation approaches are not without criticism. For instance Williamson [11] has pointed out that the analytical approach requires strong constraints and thus often does not reflect the real world, while inter-program comparison does not guarantee that any of the tools studied reflects what happens in the real world. But typically empirical validation is only possible for simple situations, not for full building complexity. In general, the field of verification, validation and testing (sometimes abbreviated as VVT) is still under development [12–14]. Interest is now also showing at the measurement side, most notably through the International Performance Measurement and Verification Protocol (IPMVP) [15,16]. Rapid developments in monitoring techniques and data mining techniques, including cheap sensors, radio-frequency identification (RFID) tags, and ubiquitous positioning, provide an increasingly high resolution map of reality and hence set higher benchmarks for performance predictions [17].

Indications of the ‘performance gap’ as addressed in this work started to appear from the mid-1990s [18], with a continuous coverage to the present day [1,19–22]. It must be noted that this performance gap is positioned in a different context than the above validation efforts: it addresses the differences between prediction and measurement of the energy performance of a complete building, including the full complexities of sub-systems, control settings, occupant behaviour, climate conditions, and others. Also, it is important to emphasize that in true prediction, made when the project still is in the design stage, there is typically only a description of a building, but no actual object—apart from a case where the design involves the renovation of an existing building; see for instance Sanguinetti [23].

This article develops a framework for further investigation of the magnitude of the performance gap, and for R&D, efforts towards narrowing or bridging the gap. It first provides a critical review of current literature on the subject, both in terms of root causes and solutions, and then continues to develop a fundamental position that distinguishes three different views of the energy performance gap. From this perspective the discussion then focuses on a pilot study that attempts an initial probabilistic probe into the performance gap. Finally, findings from the pilot study are used to identify a number of key issues that need to be addressed within future investigations of the performance gap in general.

2. Root causes

Literature on the energy performance gap suggests various causes for the mismatch between prediction and measurements. These causes can be grouped in three main categories: causes that pertain to the design stage, causes rooted in the construction stage (including handover), and causes that relate to the operational stage. Note that the specific issues which cause a performance gap will vary from one building to another; in many cases there will be a combination of several issues.

Within the design stage, a first cause towards later performance discrepancies is frequently within the design itself. Issues can start from mis-communication about performance targets for the future building between client and design team, or between the members of the design team [2,24,25]. A further key problem is that design teams often cannot fully predict the future use (functions) of the buildings; operational requirements and conditions might thus be subject to significant change [4,25–28]. It is also possible that, in terms of energy performance, the building design itself is inadequate through poor thermal concept, overspecification (oversizing of HVAC components), or lack of appropriate detail. Even if the design itself is energy efficient, lack of attention to buildability, simplicity, sequencing of the construction process, or of appropriate detail might be a built-in source for later underperformance [3].

It has been suggested that there might be issues with energy saving technology for buildings, especially in those buildings that aim to be more efficient, ‘green’, or ‘high performance’ than the average design. Equipment might simply not perform as well as specified by the manufacturer, either by nature or by over-optimism on system acceptance by the intended users [1,24]. Novel and advanced systems might be specifically prone to underperformance and ‘teething problems’ [28]. Many energy saving systems appear to be overly complex, as are the controls for these systems [3]. Additionally, many systems in general are becoming increasingly dependent on software for their operation, requiring updating (evolving) of this software to keep pace with changes to the environment, thus adding an extra layer of complexity [29].

Obviously, the second cause of a performance gap within the design stage relates to modelling and simulation as they are the key components of any prediction. Any use of incorrect methods, tools or component models will result in unreliable predictions and a gap later down the line [2,4,25]. The correct use of tools alone is insufficient; the tool user/analyst/modeller also needs to have the right knowledge and skills and the ability to apply these in the right manner [30]. This includes a good overview of the application area of models and methods, and correct data input definition. Note that within a generally well-performing method there might be component models that still have issues [31]. Even with a correct model applied by a well-trained analyst, all predictions remain subject to fundamental uncertainties, especially with regards to variation in aspects such as actual weather conditions, occupancy schedule, internal heat gains, and plug loads [1,4].

Linking back to the design context, it is also suggested that there can be a mis-alignment between design and prediction. Quoting the Zero Carbon Hub report [3], “*Calculations and modelling are often divorced from design and the mechanisms for ensuring that modelling is an accurate reflection of what is built are weak*”. The same source suggests that there is an unfortunate lack of formal error and accuracy testing of detailed design calculations, and that typically there is no modelling/calculation audit trail [ibid]. The Carbon Trust points out that it would be beneficial to test designs for robustness, ensuring that these designs can accommodate change of use and occupancy. This does not seem to be the case in current modelling practice [2]. Finally, Williamson [11] points out that present approaches do not take system performance deterioration into account, which again will lead to a mismatch between prediction and measurement.

A different group of causes for the performance gap arises from the actual construction process and the handover to the client. Many authors point out that the quality of building is often not in accordance with the specification, with insufficient attention to both insulation and airthightness [4,24,25]. Often, details are left unspecified and for the contractor to define, with potential risks for the creation of thermal bridges; or on-the-job solutions leading to unexpected extra wood in timber-frame walls that can change the overall performance [32]. Further discrepancy between design and actual building is introduced by