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Strategies for minimizing building energy performance gaps between the design intend and the reality

Patrick X.W. Zou*, Dipika Wagle, Morshed Alam

Department of Civil and Construction Engineering and Centre for Sustainable Infrastructure, Swinburne University of Technology, Melbourne Australia

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ABSTRACT

The disparity found between the predicted energy consumption in the design stage of buildings and the energy use during operation is known as energy performance gap. According to recent studies, the actual energy consumption can be twice to five times higher than predicted by the model. Building energy performance gap can have significant financial and environmental impact. This study aims to address this issue by interacting with professionals in the industry to identify the factors that contribute to the building energy performance gap, and to explore strategies that can help minimise the gap in major office buildings. Semi-structured interviews with 13 building energy professionals were conducted to gather and analyse the relevant design factors that contribute to the gap. Possible strategies of managing the factors were also identified through the semi-structured interviews. The interview responses were analysed qualitatively using Nvivo software, and as a result, 8 factors of energy performance gap were identified, as follows: (i) Inaccurate design parameters, (ii) Failure to account for uncertainties, (iii) Lack of accountability, (iv) Poor communication, (v) Lack of knowledge and experience, (vi) Inefficient and over-complicated design, (vii) Lack of post-construction testing, and (viii) Lack of feedback. Recommendations were drawn from the strategies identified from the study, and a framework on how to address the energy performance gap in the design process was proposed. The framework has three categories, namely strategies for better regulation and better accountability, strategies for project team for accurate energy models, better communication and lack of expertise, and suggestions for training to set training requirements for upskilling the industry workforce.

1. Introduction

Buildings are one of the largest users of energy, accounting for 32% of total global final energy use and 19% of total energy-related greenhouse gas (GHG) emissions [1]. The Paris Deal requires Australia to reduce emissions by 26–28% from 2005 levels by 2030 and reach net zero emissions nationally around 2050 [2]. The building sector in Australia accounts for approximately 23% of overall GHG emissions, and modelling results show that if no further action is taken, it could potentially consume almost 50% of Australia's carbon budget by 2050 [3]. Such evidence indicates that reducing the energy consumption of buildings is crucial for attaining the requisite reductions of overall energy use and emissions. However, many buildings designed to be energy efficient have failed to live up to their potential for reduced energy consumption [4]. There often remains a significant difference between the designed performance of a building and how it performs in reality [5]. The predictions made during the design stage are not completely reliable, and actual savings deviate significantly from the expected savings [6]. The PROBE studies (Post-occupancy Review of Buildings and their Engineering) investigated the performance of 23 buildings previously featured as 'exemplar designs' in the Building Services Journal (BSJ) [7]. The research project that ran from 1995 to 2002, uncovered the performance gap, suggesting that actual energy consumption in buildings will usually be twice as much as predicted [8]. Menezes et al. [9] described a number of studies that show that the actual regulated consumption can be five times higher than the predicted.

Building energy performance gap (BEPG) between the predicted and actual consumption has caused a significant problem for building energy supply and demand management [10]. ESCOs (Energy Service Companies) rely on design stage predictions to make critical decisions. They undertake energy performance contracts that typically guarantee savings as part of their service. If those savings are not attained, they have to reimburse the client the shortfall amount [11]. Such contract conditions undoubtedly increase the appeal of energy efficiency among consumers, but they make ESCOs likely to stick to tried-and-tested ECMs (energy conservation

* Corresponding author.
E-mail address: pwzou@swin.edu.au (P.X.W. Zou).

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measures). The energy performance gap makes them reluctant to invest in high-impact, high-risk ECMs [11].

Furthermore, the requirements outlined in the construction codes are not specific enough. Their requirements and the level of detail mandated by the requirements do not go far and detail enough to capture how the building will actually operate. For example, in Australia, new office buildings are required to meet minimum energy efficiency requirements as stated by the Australian National Construction Code (NCC) Section J. Apart from that, there are two other rating systems in Australia: NABERS (National Australian Built Environment Rating System) and Green Star in Australia, which are not mandatory. Under the Australian Commercial Building Disclosure (CBD) Program sellers and lessors of office spaces of 1000 m^2 or more need to have a NABERS rating but no minimum requirements have been specified. Similarly, government office buildings with greater than 2000 m^2 net lettable area should have a mandatory 4.5 star NABERS energy rating. However, the Australian NCC Section J regulation is very relaxed and the buildings designed to meet the minimum compliance under Section J do not pass the current best practice of NABERS 4.5 stars and Green Star 5 star in Australia. Besides, there are no regulations nor requirements specifically related to building simulation software. Any software with the capability to simulate complex building physics and HVAC operation can be used to calculate building energy consumption. Lastly, there is no requirement to check and compare the actual operation and energy consumptions with design results.

Therefore, it is crucial to enhance the reliability of design stage energy consumption estimates and minimize the energy performance gap. Performance gap is caused by various factors that may be related to building design, simulation, construction, material, operation or occupancy. The scope of this study is limited to the strategies that are relevant to designers only. While there are existing studies about the factors of energy performance gap, there is an absence of a comprehensive list of the causing factors and the coping strategies. On the other hand, building energy is a growing industry being fuelled by a rapidly expanding technological development. New factors and challenges constantly emerge within the industry. The aim of this current research is to identify the factors that result in energy performance gap and to find out strategies that can be applied in the design stage in order to minimise the gap. The focus of this research is major office buildings. In order to fulfil the research aim, the following objectives were formulated for this study:

i. To investigate the design-related factors that cause energy performance gap in office buildings.
ii. To gain a comprehensive understanding of the relationships and the causal effects of the factors on the performance gap.
iii. To seek strategies that can be applied in order to minimize the performance gap.

The rest of the paper is structured as follows: Section 2 enlists and describes the factors of energy performance gap gathered from existing literature. Section 3 discusses the research processes followed in this study including sampling, data collection and qualitative data analysis. Section 4 describes outcomes of the qualitative interview that resulted in the identification of three broad categories of factors of energy performance gap as well as strategies that are hoped to help mitigate energy performance gap in future projects. Section 5 presents conclusions.

2. Review of factors of building energy performance gap

From the literature, design stage estimation of savings, simulation, and possible sources of performance gap were reviewed. Studies about the factors causing the gap and the measures of minimizing the gap were reviewed. A preliminary list of factors contributing to energy performance gap was compiled. A list of measures to mitigate the gap was also compiled.

Several factors in the design stage result in unreliable estimates. According to Kampelis et al. [12], the performance gap is often related to the incorrect use of calculation methodologies and tools or input parameters in the design phase. A study found that modelling assumptions made within the design and modelling community were extremely erratic with very little correlation between modellers and highly inaccurate as compared to the results of a validated model [13]. A major source of inaccuracy is the underestimation of operating times. In a study conducted by Masoso and Grobler [14], 19–28% (average 23%) of the buildings' energy went to the unoccupied part of the weekend. This is especially true of buildings that have adopted a security system, which do not allow networked equipment to be switched off. HVAC systems are run outside of working hours as well. Virote and Neves-Silva [15] suggest predicting the utilization patterns of a building using data from buildings with the same activities, in the same geographic area and occupied by people that share the same cultural background. Masoso and Grobler [14] mention the necessity of creating profiles of energy consumption of both the occupied and non-occupied times of buildings in all kinds of climates and incorporating them to develop elaborate input profiles for simulation accuracy.

A tendency to evade accountability is demonstrated in the actions of project participants, who are wary of Post Occupancy Evaluations because they think that the findings – which inevitably bring both good and bad news – may not enhance their reputations [8]. According to expert, designers often shun feedback as they do not want their acceptance of feedback to be construed as an admission of guilt. Masoso and Grobler [14] offer a number of resources that can be put together to develop accountability ranging from incentives to punitive measures.

Poor communication is another factor that plays out in building projects in numerous ways and leads to energy performance gap. For instance, according to Bogers et al. [16], briefings, which are supposed to convey client's expectations and requirements, are not clear, consistent or complete. Problems can occur when the client's aim and purpose behind undertaking the retrofit are not clearly conveyed to the design team and onwards through the following stages [5]. On the other hand, the designer might fail to communicate the level of management, expenditure and vigilance that he expects from the occupant and facilities manager. This might lead to the occupants taking the building for granted or finding the building too demanding and dissatisfactory later down the road [17].

Additionally, the success of building energy-efficiency systems largely depends on uncertain factors including occupancy and weather [18]. Parameters like occupancy and weather with high degrees of uncertainty are said to be stochastic and require stochastic models to account for their dynamic quality. Over the past several decades, fixed profiles have been used in building energy simulation models representing occupants, not giving due regard to the extreme uncertainty related to occupant behaviour [19]. Uncertainties and errors in these stochastic factors get propagated to the predicted energy consumption [20]. While it is highly difficult to measure these inputs with absolute precision, we can apply uncertainty analysis to study the dispersion of the values they assume and the degree of uncertainty this casts upon the output. On the other hand, it is difficult, if not impossible for simulation models to simulate every condition that may affect the performance of buildings with absolute precision. Simulation software tend to over-simplify building and building systems, and are based on assumptions of thermal processes, and algorithmic differences

Table 1
Summary of factors and strategy.

Factors	References	Strategies
Undocumented changes	[25,9,26]	Improved communication; Close feedback loop; Regular meetings.
Miscalculated loads	[14,17,5,15,27]	Thorough measurement of loads; Revise plug loads using sub-metered data; Predict utilization patterns using data from similar buildings; Creating occupied and non-occupied hour profiles of energy consumption in all climates for elaborate input profiles.
Lack of Database	[28,29]	Database development with data on building attributes and occupant behaviours.
Inefficient design/Low buildability/On site modifications	[17,5,30]	Encouraging the use of standard sizes; Follow-up investigation, participation of designers
Lack of designer accountability	[8]	Rewards/penalty to increase accountability.
Lack of user accountability	[31,14,32,33]	Energy awareness campaigns, incentives, punitive measures Monitoring.
Poor designer-client communication	[16,17]	
Design assumptions	[25,5,34]	Use of updated weather files
Uncertainty of simulation inputs, stochastic uncertainties	[11,35,36]	Refining inputs (e.g. updated weather files) to calibrate simulation models Performing uncertainty/sensitivity analysis
Imperfection of simulation models	[21,9,22]	Improve simulation engines; Calibration

Table 2
Profiles of the interviewees.

Respondent	Position	Experience
R1	Client relationship manager	5 years
R2	Electrical Engineer/Energy Manager	11 years
R3	Mechanical engineer/Energy Manager	5 years
R4	Civil engineer/Sustainability and energy expert	15 years
R5	Environmental manager	10 years
R6	Senior Sustainability Engineer	6 years
R7	Energy solutions manager	5 years
R8	ESD Engineer	11 years
R9	Architect/ESD Engineer	15 years
R10	Sustainable Building Advisor	14 years
R11	Mechanical Engineer/Director	20 years
R12	Architect/Sustainability Manager	10 years
R13	Energy Analyst/Client Energy Manager	10 years

[9,21]. Polly et al. [22] discusses a number of software issues that lead to an over or under-prediction of energy use. Each simulation software offers its own set of strengths as well as weaknesses [23,24]. Resolving issues within simulation software requires isolating the issue to a sub-system within the software and revising the solution process until it agrees with a verified numerical solution [22]. However, each versions of the leading building simulation programs are rigorously validated using international standards. For instance, EnergyPlus is validated by BESTest (Building Energy Simulation test) developed by International Energy Agency (IEA). The IES VE is validated by ASHRAE Standard 140. The validation procedure involves the testing of HVAC system, building fabrics and dynamic heat balance. Hence, these software are capable of simulating all fluid flow and heat transfer phenomena in a building with reasonable accuracy. Analysing software issues is outside the scope of a designer's responsibility. However, there are a slew of simulation packages to choose from and designers should make this choice with enough consideration to the nature of the building, project-specific requirements, characteristic strengths and shortcomings of the available choices of simulation software. What is more important is how the components in a simulation engine are used by the designers to develop the simulation model of the desired building and whether the model truly represents the actual building in terms of design parameters and operation.

A summary of factors, their sources and relevant strategies is shown below in Table 1.

3. Qualitative research

As stated in previous section, the aim of this research is to investigate factors causing building energy performance gap and seek strategies for minimising the gap, which indicates the need for qualitative method of data collection and analysis. Interview method is particularly useful for collecting qualitative data and getting the story behind a participant's experiences, as it allows the interviewer to pursue in-depth information around the topic. Therefore, interview is the ideal research method for this research. Data was collected directly from the respondents through a semi-structured interviews. Responsive, flexible and interactive questioning techniques were applied.

3.1. Sampling

In this research, purposive sampling was conducted based on the prospective respondent's potential contribution to the knowledge about the factors impacting building energy performance gap. The gap is caused by factors that stem from various stages including design, construction, commissioning and occupancy. This study was designed to address the design-related factors and to investigate strategies that can be applied in the design stage. Hence, the chosen respondents were working in various positions in the building energy industry relevant to design and delivery, such as architects, civil engineers, mechanical engineers, electrical engineers, ESD engineers, sustainability engineers, energy analysts and so on. They had at least 5 years of experience. Table 2 lists the respondents selected for the interview along with their roles in the industry and the number of years of experience that they possessed. While details are given in later section, data saturation was achieved after the interview with respondent R6.

3.2. Semi-structured interview

The interview questions were designed to find out factors causing energy performance gap and relevant strategies that can be implemented to close the gap. In this study, semi-structured interview process was selected. A set of instructions and a list of key questions was used to ensure a thorough coverage of certain significant queries. However, supplementary questions were added depending on the responses received during the interview, thus

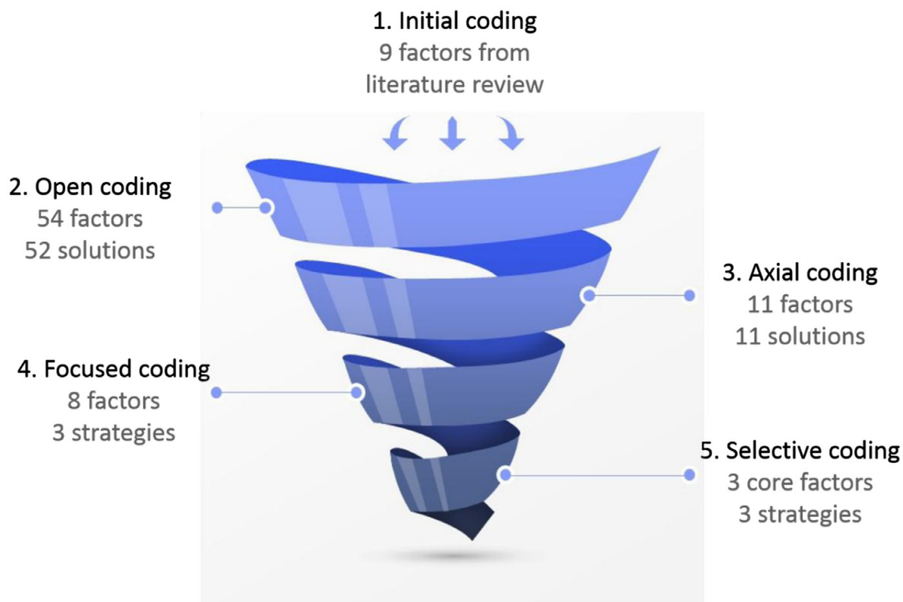

Fig. 1. A funnel diagram illustrating the process of coding and analysing interview data on Nvivo.

remaining receptive to any additional relevant information that the interviewee had to offer. The interview questions have been provided in the Appendix 1. In total, thirteen (13) interviews were conducted altogether, of which 12 were conducted over the phone and one in person. The interviews lasted 25 min on average. They were digitally recorded with the permission of the respondents and transcribed verbatim. Key themes were identified through a thorough qualitative analysis of the interviewee responses using the qualitative analysis software NVivo.

3.3. Qualitative data analysis using NVivo

The interviews were transcribed verbatim and read through line-by-line. This was done with an aim to get a basic understanding of the conversations without searching for any answers in particular, only noting seemingly important concepts. The transcripts were then uploaded into NVivo for coding. As shown in Fig. 1, the coding was carried out in 5 steps, which are described below:

3.3.1. Initial coding and developing themes

The next step was to derive codes which are indexes of key concepts in the transcript. This was done by highlighting the exact words from the text that appeared to capture key thoughts [37], including factors and strategies. Themes are defined as a key category identified by the analyst through their data that relates to the research questions and that is made up of codes identified [38]. Following the directed content analysis method, the findings from the literature, comprising 9 factors, were allowed to form the initial set of nodes. The codes that fell into the predetermined set of nodes were coded into these nodes. In order to identify other key themes within the transcript, word frequencies were run on NVivo to examine words that were the most used by the respondents. Only words containing 5 or more words were included in the query in an attempt to remove unnecessary words. The words representing factors including communication, experience, accountability and infiltration were identified through this query, establishing these factors as key themes and confirming their significance. Then, additional nodes were generated based on these terms.

3.3.2. Open coding

New nodes were created as the transcripts presented new factors and new strategies. This was done keeping an open mind without worrying about the number of codes. First, the interview answers were assembled into individual groups for every respondent, creating one group for each respondent, and then analysed. Then, the responses to each question received from all respondents were put together in one group, creating a single group for each interview question, and the analysis was carried out again. Thus, the entire transcript was analysed twice during which, a total of 106 nodes were identified within the data, among which 54 nodes represented factors and 52 represented strategies (Fig. 2). Nodes are a representation of themes in NVivo. NVivo's help system defines a node as a collection of references about a specific theme, place, person or other area of interest.

3.3.3. Axial coding

This initial open coding was then followed by axial coding. The purpose of axial coding was to bring coherence by reassembling the factors by searching for connections between them in terms of strategies. This was accomplished by first grouping related strategies together to form a single strategy. 37 strategies were identified initially. After grouping similar strategies together, 11 core strategies were formulated. Then, factors corresponding to the strategies were identified. 11 group of factors was created, one for each strategy. Hence, axial coding was used to identify similarities between strategies, to group them together and finally, to pair factors with their corresponding strategies. As a result, 11 strategies and 11 group of factors were identified.

3.3.4. Focused coding

Next, the process of focused coding was applied to narrow down the list of factors and solutions resulting from the axial coding. Every factor grouped together with a common solution in axial coding were checked closely and compared with each other to determine if they were repetitive. When two factors that were too similar to each other were spotted, either they would be combined or one of them would be dropped. 8 factors were identified through the process of focused coding, namely, i. Inaccurate design parameters, ii. Failure to account for uncertainties, iii. Lack of

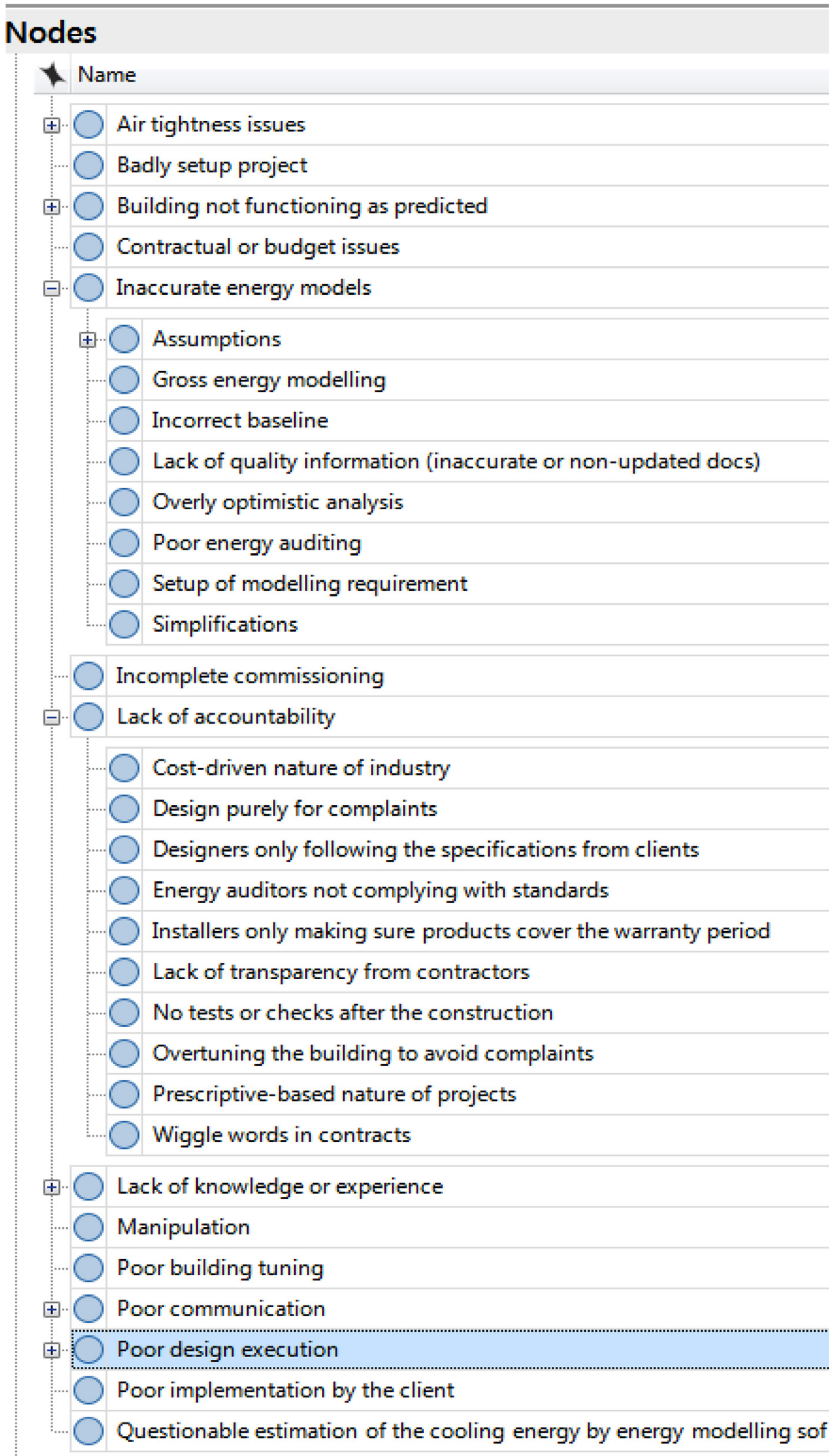

Fig. 2. Codes generated on Nvivo.

accountability, iv. Poor communication, v. Lack of knowledge and experience, vi. Inefficient and over-complicated design, vii. Lack of post-testing, and viii. Lack of feedback. Similarly, the 11 solutions were categorised into 3 categories: strategies for better regulation, strategies for project team, and suggestions for training.

3.3.5. Selective coding

Lastly, three core categories of factors were identified as a result of selective coding. This was accomplished through a close examination of the 8 identified factors, which helped to identify the relationships among them. It led to the theory that energy per-

Table 3
Factors and strategies after qualitative analysis and coding using NVivo.

Factors	Sub-factors	Strategies	Suggestions for implementation of the strategy
Inaccurate energy models (F_A)	Inaccurate design parameters (F_A1)	Better auditing and information collection (S1)	Access to detailed information about building; Better metering, sub-metering and smart-metering; Information based on in-practice testing.
	Failure to account for uncertainties (F_A2)	Accounting for probable/eventual inconsistencies (S2)	Accepting and accounting for risk of failures; Price forecasts; Only specify products from trusted manufacturers-so it is more familiar and has less risk of failure.
Poor norms (F_B)	Poor communication due to lack of guidelines for communication and badly setup project (F_B1)	Carefully planned communication protocol (S3)	Communication with other stakeholders; Engaging with the maintenance teams; Comprehensive design detailing; Having an engaged building manager or facilities manager; Protocols or guidelines for better communication; Providing alerts in reports.
		Implementing effective project management methods (S4)	Better leadership; Building passport system/BIM; Solid clear contracts.
	Lack of accountability/irresponsible short-sighted behaviour (F_B2)	Regimented quality control process for procurement (S5)	Certified auditor accreditation; Developing better evaluation criteria to determine who gets jobs; Well-developed and ongoing relationship with the client.
		Stringent standards of performance for project participants (S6)	Holding contractors accountable to an end outcome; Longer warranty periods; More strict targets in the building code for air tightness.
		Aligning motivations to long term benefits (S7)	Investing in detail energy measurement and verification; Make everyone in the project aware that energy management is a top priority.
Human oversight (F_C)	Inefficient and over-complicated design (F_C1)	Education and training at different levels (S8)	Educating designers in terms of passive design with simpler control systems; Integration of environmental design and sustainability within architectural coursework in universities and as part of professional registration
	Lack of knowledge and experience (F_C2)	Bringing in expertise (S9)	Better training to operation team; Educating procurement managers; Educating the construction industry; Hiring trained professionals; Independent commissioning agents; Having an advisor to guide end users; Automated alarm systems; Automation to mitigate human error; Improved systems (QR codes).
		Implementation of automated and QR code systems (S10)	
	Poor performance due to lack of post-testing (F_C3)	Implementing an effective feedback system for designers based on post-testing (S11)	Post-occupancy testing Monitoring;
	Lack of feedback and experiential learning (F_C4)		Ongoing feedback loop after installation; Database development for future- e.g. measuring air changes per hour and creating database of measured values; Building tuning period; Proper commissioning; Revising commissioning regularly.

formance gap in the design stage is caused due to three major factors: (a) poor computation and estimation of parameters leading to inaccurate energy models; (b) poor industry practices and norms that are incapable of fostering accountability and that hinder communication; and c) lack of knowledge that cause oversights and errors, compounded by lack of feedback for improvement. Thus three broader categories named inaccurate energy models, poor norms and human oversights were developed which are discussed in Section 4.

4. Results of qualitative analysis

4.1. Design-related factors causing building energy performance gap

The three core factors, their sub-factors, their corresponding strategies and suggestions for implementation of the strategies have been presented in Table 3.

4.1.1. Inaccurate energy models

Inaccurate energy models maybe caused when what was assumed during the making of that model does not match up with reality. They are caused by two sub-factors: inaccuracy of design parameters, and failure to account for uncertain parameters. The former can be optimised through observation or direct measurement but uncertain parameters such as weather and occupancy are harder to predict precisely and are called stochastic factors.

Inaccuracy of design parameters: Several respondents substantiated that there is a lack of good auditing and detail data logging which leads to incorrect modelling of facility. One common consensus was not monitoring plugs and circuits sufficiently. Only using gross energy metered data in a building fails to pick up subtle nuances regarding the actual operating pattern of the systems. Similarly, incorrect information may end up being used in models as a result of a lack of updated information. When one party fails to deliver on their responsibility to convey some information to another party, it causes the receiving party to end up with inaccurate or non-updated documents in their hands. Consequently, any decision they make based on that inaccurate document is likely to be wrong, and can possibly lead to inaccuracy.

Failure to account for uncertainties: New complex systems bring unknown complications and higher uncertainty than tried and tested technologies. The problem with complex technologies is that designers are not familiar with complex systems and more likely to make inaccurate assumptions. Therefore in general, new innovations have a greater risk of not performing. This uncertainty is often not considered in the design stage. Similarly, the designed space usage often does not match the way the spaces in the building are used in the post-occupancy stage. Equipment might get added later on by the occupant or the equipment considered in the design stage may be run for longer hours, which can covertly increase the energy demand. When uncertainties related to occupancy do not get enough consideration, it can lead to a massive performance gap. Three respondents highlighted inadequate consideration of air infiltration as a major cause of the gap. While one of them outlined that there are no strict targets in the building code for air tightness, other contended that an underestimated air infiltration and exhaust rate is a consistent design flaw. One of them stressed the importance of measuring air infiltration rates and attesting air changes per hour in buildings.

Strategies: The strategies for coping with inaccurate energy models involve improving auditing and accounting sufficiently for uncertainties. The direct measures that can be taken to implement the coping strategies include 1) obtaining detail information regarding the building such as thermal properties of building envelope materials (from the suppliers), occupancy profile (from the owners or potential tenant), HVAC and lighting systems (from mechanical and electrical sub-contractor), 2) installation of enough metering device to provide feedback to the designer regarding the consumption and operation of the building so that the knowledge can be utilised to improve future energy modelling, 3) Modelling potential problems, 4) Accepting and accounting for risk of failures, 4) conducting comprehensive price forecasts and 5) Using products from trusted manufacturers who could provide sufficient and accurate technical details and specifications of their products or equipment.

4.1.2. Poor norm

Poor industry practices give way to a number of problems such as lack of accountability and poor communication. They have numerous common sub-factors and coping strategies. All of these strategies revolve around changing the way things are done in the industry and putting in place better industry practices.

Lack of accountability: Respondents highlighted the need to make contractors accountable to the outcomes as they might covertly try to escape being held responsible. They also pointed out that building facility managers often do the bare minimum by operating the building only bearing in mind occupant comfort, with little or no consideration to efficiency and savings. Another instance where a lack of accountability is often witnessed is among end users, especially in instances like offices where users do not care about where their energy is coming from and are not held accountable for their energy behaviour. A lack of clearly documented contracts aid people to act in such irresponsible ways. Another underlying cause of the accountability problem is the cost-driven nature of the industry. Regardless of how a designer or a contractor performed in their past project, they will still get another job as long as their cost is accurate and they have a good price on the table.

Poor communication: Respondents agreed that the detachment, often seen of the construction phase of a project from the facilities team that are going to maintain the building, is a major cause of performance gap. Another factor that inhibits people from communicating openly in building energy efficiency projects is the risk averse nature of the industry, where people would much rather advise a safer option instead of risky high-end options.

Strategies: One respondent stated that in cases where the builder has an ongoing relationship with the client, the past job is very important to the next job. While they have to be competitive about the quotations, their performance on the previous job is also taken into account to decide whether they are appropriate for the next one. Thus, developing better evaluation criteria, other than cost, in determining who gets the job is paramount to cultivating more accountability in the industry. Respondents also agreed on the view that the prescriptive nature of projects in the current industry is ineffective and breeds unaccountability. On the other hand, under a performance based contract, a fair bit of capital investment is put in, the project management is more rigorous, and savings are guaranteed, which results in better accountability as well as better communication and better outcomes in general. Thus, the strategies for improved accountability include (1) Setting up a regimented quality control process for procurement by setting up better evaluation criteria other than price quotes, certified accreditation, (2) Setting stringent standards of performance through penalty, rewards, longer warranty periods, stricter targets in the building code, transitioning to performance based contracting, and ensuring regular revision of commissioning, (3) Aligning motivations of project participants to long term benefits by appealing to their core motivators, for instance financial benefit may be more important than environmental benefits to certain owners or vice versa. Building passport system was suggested by an interviewee that refers to keeping an electronic record for all buildings. It starts with storing the plans to a digital file created for the building, continues with photographing the construction process as it is taking place and adding the date stamped photographs to the file, through to capturing and logging the installation of insulation, setup of equipment and so on. It streamlines the inspection process by making it an inherent part of the project. Switching to an effective project management such as BIM or building passport system has the potential both to foster higher accountability by streamlining the process of inspection and to ensure better communication among project participants through sharing of information into a mutually accessible electronic record. Strategies identified from the study for improving communication include 1) setting up effective project management methods and 2) updating the communication protocol.

4.1.3. Human oversight

Human oversights is a broad factor that has been subcategorised into four sub-factors: lack of knowledge and experience, which refers to issues that can be solved through upskilling or use of expertise; inefficient and overcomplicated design which can be resolved through the implementation of passive design, lack of post-testing which needs to be addressed through provision of attesting and quality control of the completed work; and lack of feedback, which leads to stagnation in performance and can be resolved by ensuring that project teams receive constructive feedback after every job that guides them to improve their performance in the next job.

Lack of knowledge and experience: Respondents contended that despite the availability of environmental analysis tools within most BIM packages, most architectural practices see BIM merely as a tool for documentation and creating 3D forms. Skill gaps were identified in other areas too. The adequacy of the quality of training provided to facilities staff compared to the role they're expected to carry out was questioned. The underlying cause of this seems to be a lack of incentive for people with degree-qualification or years of experience to go into facilities over consulting, as facility staff members are purportedly not paid very well. This problem comes more into focus in large projects with complex controls. Sustainable innovation is burgeoning rapidly, ushering in a flux of new technologies. There is an ever increasing uptake of advanced technologies being incorporated into building systems. Designers and facilities staff are more likely to be unfamiliar with the inner workings of such unconventional systems, which increases the chances of designers making wrong assumptions about their operation and makes facilities staff more prone to making blunders in the operation, control or maintenance of these systems, exacerbating the probability of discrepancy between predicted and actual savings.

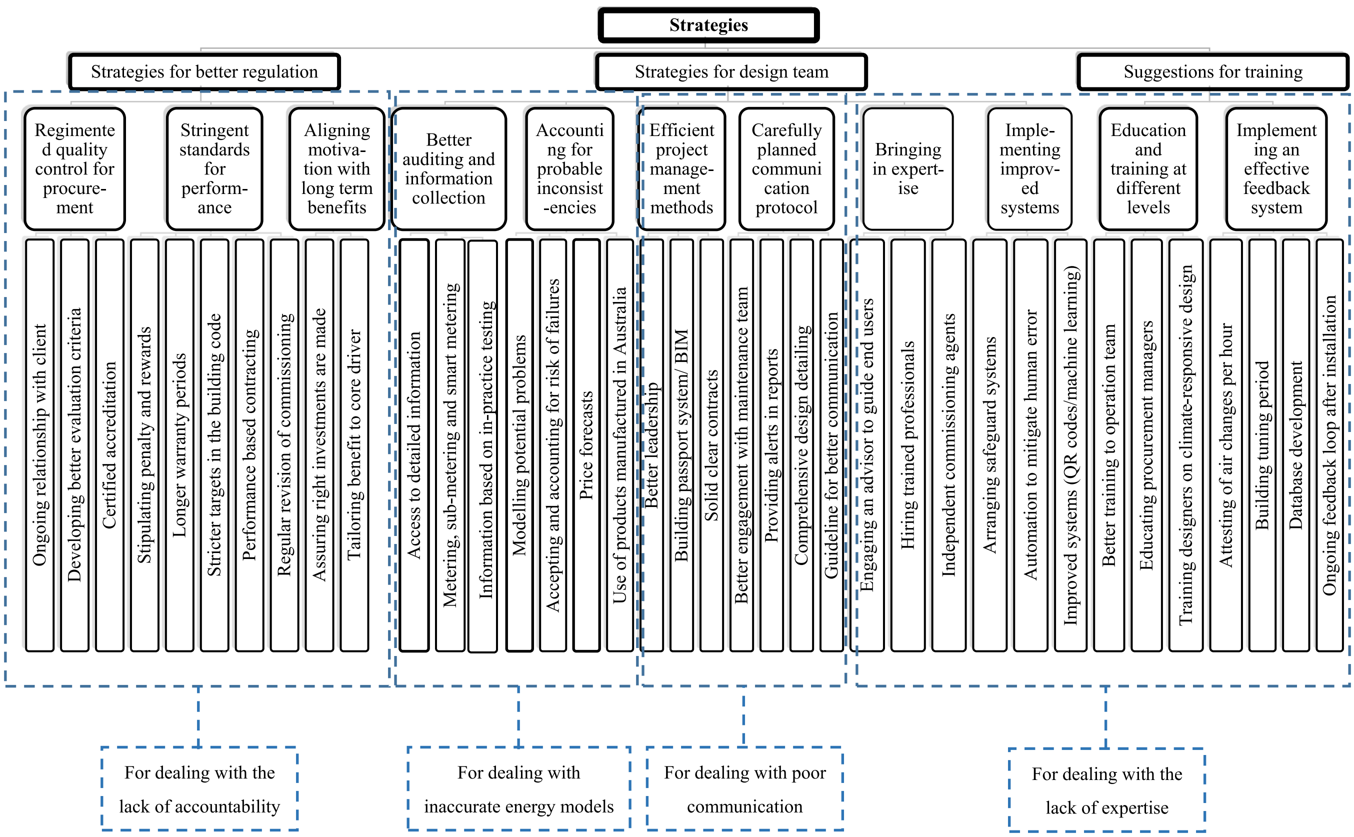

Fig. 3. Framework of strategies.

Table 4
Matrix coding query.

Respondent	No. of codes (Number of times respondent mentioned factor/strategy)																		
	Factors								Strategies										
	F_A1	F_A2	F_B1	F_B2	F_C1	F_C2	F_C3	F_C4	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
R1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
R2	0	0	0	2	0	0	1	0	0	1	1	2	0	0	0	0	0	0	0
R3	4	0	0	0	0	0	0	0	1	0	1	0	0	1	0	1	1	0	0
R4	11	3	3	7	0	0	2	0	2	0	0	2	0	1	1	0	3	1	1
R5	4	3	2	1	0	1	1	1	1	1	3	1	1	0	0	0	0	0	0
R6	7	0	1	4	4	0	6	0	1	0	0	0	0	0	0	0	5	0	0
R7	0	3	5	0	1	0	0	1	0	0	0	0	0	6	0	0	0	1	0
R8	9	1	2	3	0	2	0	1	1	1	0	2	0	1	0	0	1	8	1
R9	2	4	0	3	0	0	0	0	0	2	0	1	0	0	0	0	0	3	0
R10	1	0	1	1	0	2	2	2	0	0	2	0	0	0	0	1	0	4	0
R11	1	0	4	0	0	2	0	1	0	0	0	2	3	0	0	0	0	0	1
R12	0	0	1	2	4	1	2	1	0	0	0	0	0	0	2	1	10	0	0
R13	2	1	1	1	1	1	0	0	0	2	0	0	0	0	2	0	0	0	0
Total	41	15	20	24	10	9	14	7	6	7	8	10	4	10	5	3	20	17	3

Inefficient and overcomplicated design: The major mistake that designers purportedly make is not taking climate responsiveness into account sufficiently. A theme of inefficiency in design was identified from respondents. One respondent described architects and designers practicing in Australia as lacking technical understanding of detailing in terms of design response to climate, as compared to ones practicing in Europe; indicating a need for more accountability on the designer or architect's part for incorporating environmental sustainability principles into their designs. Another respondent maintained that there is a tendency to pile layer upon layer of additional control and functionality, overcomplicating the design instead of passively designing the building and using simpler control systems. It was suggested that Passivhaus design principles should be made a primary architectural skillset.

Lack of post-construction testing: Different kinds of errors can occur during construction and installation phase. The designer cannot predict and account for all of these errors. Hence, all construction should entail a comprehensive post testing procedure. The inspections that do get conducted are reportedly not thorough enough.

Lack of feedback: As identified from literature, a lack of feedback prevents designers from identifying the mistakes they made in the projects they completed. This hinders improvement in the quality of service that design and construction firms provide. One of the respondents used the term "dumb industry" to describe such stagnation that results in uninformed and out-of-touch decisions.

Strategies: Making buildings more resilient and decreasing their overdependence on non-natural systems was suggested by the respondents. Passive techniques including the use of low emittance high-performing glazing with adequate shading and an easily maintainable control system were recommended. Respondents also recommended several ways to compensate for a lack of expertise and offered preventative solutions for human error such as automated systems, machine learning, etc.

Respondents described the application of machine learning in forecasting what the energy consumption should be given a range of variables like occupancy, in using the predicted consumption as a benchmark to determine the efficiency of the actual operation and to locate areas of inefficiency, and to automatically tune the BMS. It would also be useful in understanding how people use buildings in the event of a heatwave in order to improve future design. It would also help make better decisions during the initial stages of building massing, HVAC sizing and HVAC layouts. They also mentioned an adaptive PI control where the system self-tunes and learns for itself as time goes. They shared that it is becoming cleverer and more efficient in understanding the environment by taking real time measurement of other core predictors such as humidity and occupant number. They referred to similar smart systems called optimizer routines that interpret from weather forecast and optimize building energy use in terms of controlling the start time of the building in the morning so that the building reaches a comfortable temperature by the beginning of occupancy hours. Other respondent referred to this process as “predictive optimization” and predicted for it to become standard in the marketplace in 3 to 5 years, depending upon its cost-effectiveness.

The strategies identified involve (1) integration of environmental design and sustainability by universities in their architectural coursework, by the architectural registration board as part of professional registration and by architectural institutes as part of continued professional development, (2) bringing in ICAs (Independent Commissioning Agents) to compensate for a lack of expertise, (3) using improved systems such as automated systems, QR code systems and machine learning to eliminate human error, (4) monitoring and post testing of buildings to attest that the building was built as specified for the energy rating it achieved, (5) structuring contracts in such a way that owners are required to provide information about the building so that designers get feedback about their designed building after it goes into operation, (6) development of a public database based on the comprehensive monitoring that all designers can access and use to make necessary assumptions in the design stage.

4.2. Theoretical saturation

After the analysis, theoretical saturation was confirmed using Matrix Coding Query on Nvivo. The purpose of this query is to display the number of times a sentence or a group of sentences about a given topic was recorded in a document, such as a transcript. A topic of interest is called a node in Nvivo and the act of recording sentences into the node is called coding. This query then retrieves a table displaying the number of times each node was coded within every transcript. Thus, using this query, Table 4 was generated displaying the number of times each factor and strategy was mentioned by each respondent. This table was then used to identify the interview where a given factor or strategy was first mentioned and coded. R1-R13 represents identifiers assigned to the respondents in a chronological order of the interview. FA, FB, FC are the three main factors that were identified from the study. They were categorised into two, two and three sub-factors respectively which are denoted by FA1, FA2, FB1, FB2, FC1, FC2, and FC3. Similarly, 11 strategies were identified from the interview method which are indicated by S1-S11. For instance, the first factor (FA1) was coded 41 times altogether throughout the interview process-4 times by the respondent R3, 11 times by R4 and so on. This analysis showed that all the factors and strategies were identified by the 6th interview, thereby identifying it as the point of theoretical saturation. In other words, the respondents after this point covered the codes already generated from the earlier interviews and failed to generate any unique code. This suggests that the point of theoretical saturation and data satisfaction was successfully reached.

4.3. Framework of strategies

A framework of strategies has been recommended on how to strategically address the energy performance gap in the design process as shown in Fig. 3. The framework has three categories-strategies for better regulation (for better accountability), strategies for project team (for accurate energy models, better communication and lack of expertise), and suggestions for training (for lack of expertise). Each strategy aids to cope with different factors of energy performance gap described in the previous section. Strategies for better regulation is focused on fostering more accountability in the industry. Strategies for project team are directed towards enhancing the industry practices so as to ensure effective communication among various stakeholders, as well as towards minimising the inaccuracy of energy models. Suggestions for training aiming at educating the industry and upskilling of designers and other members in the industry that they rely on in building projects. Although the study was carried out in Australia, these strategies are not region-specific. They would be relevant and applicable to other regions as well, with some modifications if needed.

5. Conclusion

The research was aimed at identifying the factors that result in energy performance gap and finding out strategies that can be applied in the design stage in order to minimise the gap. Interviews with key actors in the building energy sector were carried out till the point of theoretical saturation. This research contributes to the knowledge base by identifying 8 critical factors that cause energy performance gap namely, i. Inaccurate design parameters, ii. Failure to account for uncertainties, iii. Lack of accountability, iv. Poor communication, v. Lack of knowledge and experience, vi. Inefficient and over-complicated design, vii. Lack of post-testing, and viii. Lack of feedback. Through an in-depth analysis of the 8 identified factors, a theoretical framework was proposed that groups them into three broader categories named inaccurate energy models, poor norms and human oversights. The framework explains the relationship among the factors and categorises them in terms of the strategies needed to be applied in order to address these factors.

Several sub-factors have also been identified based on the experiences shared by the interview respondents. As the sample consisted of experienced building energy professionals currently engaged in the industry, it is hoped that the factors that they identified will provide designers and project participants with a practical understanding of how they manifest in projects helping them to recognise and deal with the factors early on in future projects. The study also contributed practical strategies broadly categorised into 3 groups: strategies for better regulation, strategies for project team, and suggestions for training. Each strategy is reinforced by implementation suggestions that are hoped to practically guide project teams in taking necessary steps to address the energy performance gap in the design stage. In the future follow-up research, a PESTEL analysis could be applied to assess the frameworks proposed in this paper, to evaluate their feasibility and suitability in terms of political, economic, social, technological, environmental and legal (PESTEL) aspects.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.03.013.

Appendix 1. Interview Guide: Instructions and Prompt Questions

1. How much of a role do you think does the design stage play in energy performance gap? How responsive do you think is the current building energy efficiency industry to energy performance gap? Have you seen any poor decision or any common industry practice that commonly results in energy performance gap and that should be reformed?

2. I would now like to introduce the sources of data used during the design phase (and this might include audit reports, briefings from the client, design guidelines, weather files, etc.). I'm naming the sources of data based upon which savings estimation is calculated. I'd like to know your opinion on the accuracy of these data sources. E.g., literature says that assuming values from guidelines and different thumb-rules often leads to errors. Some papers say that unclear and incomplete briefings also lead to too many changes and inconsistencies to the design. How do you think can the accuracy of design inputs be improved?

3. Now I'd like to talk about communication. I read that poor communication often leads to poor results in energy efficiency projects. An example I read about was between architects and mechanical engineers. The complaint was that sometimes architects will decide the wall thickness independently and then the mechanical engineer will look at it later on and then decide the HVAC size accordingly. The complaint was that maybe they could have worked together and arrived at a more economical alternative by maybe increasing the insulation by a couple millimeters or something. Another common complaint is that after the estimation of savings occurs, design modifications and cost cutting changes will be made and the energy modeler doesn't get informed of these changes. How do you think should such problems be addressed, problems that are created by a lack of communication among different teams in the same project?

4. I'd like to discuss a very closely related topic. An industry person said that designers often shun post occupancy feedbacks because they don't want their acknowledgment of the feedback as an admission of guilt. He said that the reason why we have poor communication, open feedback loops, poor quality of predictions could all be traced back to a lack of accountability. How can we foster more accountability among different stakeholders including design team, construction team and clients?

5. I once read an audit report of a building and the problem mentioned was that the building had so many advanced complicated features that the designers were not completely familiar with those technologies and their control systems. So, their wrong assumptions about the control system led to a huge discrepancy between the predicted and actual consumption. How can we address this problem arising from the rapidly advancing technologies and lack of enough expertise of them?

6. I'd like to discuss another finding from a real building. It was a retrofitted office building which heavily relied on giving up comfort for the sake of energy savings. The office building shut off its hot water connection, reduced the HVAC size to half. Of course savings were achieved but the office users probably had to give up a lot of their comfort to achieve that saving and maybe they weren't all happy. So what do you think about this practice? Is it a good way to save energy?

6. Now let's talk about building automation. In an attempt to make buildings more controllable and predictable, fixed systems such as fixed windows instead of operable ones are being used. How much of a problem do you think can unexpected problems have on the functioning of such automated buildings? What if issues like manual overriding, or sensors failing, or calibration issues make the air-conditioning to stop running in summer. What do you think about the increasing trend of building automation?

8. How is machine learning being applied in the current industry? What do you think about the role of machine learning in building energy modeling?

9. Do you think current level of government efforts in the direction of building energy efficiency is adequate?

10. What does the current status of Passivhaus look like and what are the major barriers of its implementation in the current industry?

11. What are the barriers to the implementation of BIM in the current industry?

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