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Heiselberg, Per Kvols

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ARE BUILDING MODELLERS LITERATE? - STUDYING THE RELATION BETWEEN MODELLING LITERACY AND THE PERFORMANCE GAP

Salah Imam[1], David A. Coley[1] and Ian Walker[2]
1. Department of Architecture and Civil Engineering, University of Bath, Bath, UK
2. Department of Psychology, University of Bath, Bath, UK
Imam.salah@bath.edu, d.a.coley@bath.ac.uk, i.walker@bath.ac.uk

ABSTRACT

One of the most discussed issues in the building design community is the performance gap. In this research, we investigate whether part of the gap might be caused by the modelling literacy of design teams. 108 building modellers were asked to comment on the importance of obtaining and using accurate values for 21 common modelling input variables, when estimating annual energy demand by dynamic simulation. The questioning was based on a real domestic dwelling for which high resolution energy data had been recorded. A sensitivity analysis was then conducted using a model of the building by alternating one parameter in each simulation. The effect of each alteration on the annual energy consumption was found and a ranked list generated. The order of this list was then compared to that given by the modellers for the same changes in the parameters. A spearman-ranking value of 0.43 was found and an R^2 value of 0.28, which indicates little correlation between which variables were thought to be important and which proved to be. In addition, there was no correlation between modellers, with many ranking some parameters as important that other thought irrelevant. Using a three-part definition of literacy it is concluded that this sample of modellers, and by implication the population of building modellers, cannot be considered literate. This suggests an opportunity and need for both industry and universities to increase their efforts with respect to building physics education, and if this is done, a part of the performance gap could be closed.

Keywords - literacy; building modellers; simulation; performance gap; input-variables.

1. INTRODUCTION

Many policies and actions are being implemented by governments with the aim of reducing greenhouse gas emissions. In developed countries, buildings commonly account for up to 40% of such emissions [1], making them a clear focus. Unfortunately, there is a proven gap between the energy use generated by models of buildings used to aid their design and ensure compliance with national building codes, and monitored energy consumption of the buildings once built. Many researchers claim that the measured energy consumption is frequently twice or more than that of the design stage prediction [2, 3, 4], and although many studies have explored the performance gap from various perspectives, such as the role of poor workmanship or occupants' behaviour, the literacy of building energy modellers is rarely questioned. In addition, the literature indicates that in general professionals (architects, engineers, sustainability experts, etc.) do not tend to criticize themselves and thus a culturally embedded lack of reflection might contribute to the performance gap [2, 3, 4, 5].

Modelling professionals are limited in the time they can apportion to any project and hence need accurate inbuilt knowledge of the impact of modelling any element of the building in less than ideal detail might have. For example the impact of missing out a thermal bridge. The basis for these judgment calls might be in part based on experience, but it is likely to also be embedded within an organisation or just commonly accepted within the modelling community [6, 7]. Professionals in general are known to be open to change if evidence is presented [8], and this paper attempts to provide this evidence in a robust way, by asking the question, how accurate in general are such professionals' judgments?

2. BACKGROUND

2.1 Literacy

The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines literacy as the "ability to identify, understand, interpret, create, communicate and compute, using printed and written materials associated with varying contexts. Literacy involves a continuum of learning in enabling individuals to achieve their goals, to develop their knowledge and potential" [9]. Some have argued that this definition of literacy should be expanded to include the capability to use computerized tools efficiently and correctly [10].

There is no single method to monitor and measure literacy levels, but there are various methodologies that can be followed depending on the aim of the study. According to UNESCO, "typically countries measure literacy levels by undertaking self-assessment questionnaires and/or by means of a proxy variable utilizing the number of years of primary schooling (i.e., 6 or 8 years of primary schooling equals a literate person), typically literacy rates are assigned so that people over 15 years of age are designated as literate" [11]. Unfortunately, this does not give a robust method for measuring literacy levels in other settings. An alternative is to use tailored questioning to assess literacy.

There are many ways one might define literacy with respect to building physics and thermal modelling, and we are after a measure which is more independent and about modelling in general, not about a certain simulation package or method. The assessment method also needs to provide a numeric result or a ranking in order that a quantitative assessment of literacy can be made.

Here we suggest a suitable requirement for literacy within a population to have been demonstrated is that we might expect that when given a real project the population of modellers should: **1.** approximately agree on the important parameters that need to be included in the model; **2.** approximately agree on the rank order of the importance of a list of possible input parameters; **3.** that their rank ordering of the impact of given changes (perturbations) to the values of these parameters should approximately agree with that given by a sensitivity analysis of the parameters within a thermal model.

2.2 Building Energy Modelling

Researchers have noted the influence that the building design industry has had on building performance simulation (BPS) tools and vice versa. This development has meant more complexity without evidence that the complexity is manageable by all professionals [12]. For example, architects are regularly using BPS tools, despite them being described as generalists [13, 14, 15, 16, 17, 18].

Many studies highlighted that most tools available are inadequate to deal with early design stages. Furthermore, they are not user friendly [19, 20, 21, 22]. The building simulation industry became aware of this and tried to tackle it by producing more friendly interfaces. However, many barriers still exist in using these tools [12].

It has been argued that the most important capabilities of these tools are *usability*, *computing ability*, *data-exchange* and *database support* [23]. Researchers have also stated the importance of what they called "functional criteria" of BPS tools, which again addresses the question of usability [16]. Despite researchers' concerns about usability, tools over the years have became more and more complex.

Attia et al. (2012) performed a survey with approximately 150 architects, with the aim of ranking the selection criteria of BPS tools according to their importance from the user point of view. Results showed that model intelligence had the highest priority (Figure 1). (The study defined model intelligence "as the ability to advise the user with design optimisation options based on a range of early stage input.") Accuracy was considered the least important [12].

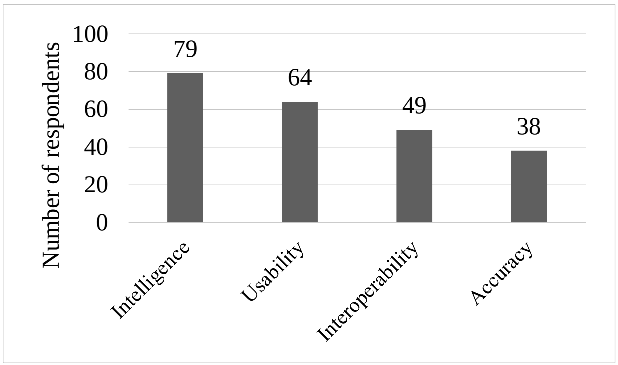


Figure 1: Architects' ranking to the importance of simulation tool features (data from Attiaa et al., 2012).

2.3 The Performance Gap

The literature indicates that a disconnect between modelled and actual performance can occur in each of the three broad stages of: design, construction and operation [2, 24].

- **The design gap**

Many studies have concluded that the design phase is a frequent cause of the gap [24, 4]. Reasons include misunderstanding of the design performance targets between design team and client, or even between the design team members [25]. In addition, De Wilde (2014) pointed out that even if the design itself is properly outlined, underperformance can still occur if the design team did not take into consideration buildability, simplicity or the construction sequence. Other papers have focused on the specification of advanced systems and technologies due to the level of complexity of the system and its controls [4].

The 2014 Zero Carbon Hub report "Closing the Gap" observed that professionals have a limited understanding of the impact of their design decisions on the actual energy performance [5]. For example, how much might improving the U-value by 10% reduce heating energy consumption in a particular climate. But this observation was not based on a quantitative assessment, and is hence questionable.

Knowledge of the impact of uncertainties in the design stage is another level of literacy that is understudied, and it is unknown if practitioners gain the required knowledge to address this after many years of experience or not, but given that few buildings are monitored after construction by their designers, this seems unlikely.

It is known that incorrect use of simulation tools will result in unreliable predictions at the design stage, which will lead to the gap later on, therefore, the user has to have a minimum level of knowledge and skills to be able to use these tools properly [26]. De Wilde (2014) pointed out that the required knowledge includes the ability to define correct input data within the model [4]. Nevertheless, even with an experienced user, many predictions will still be inconsistent and lacking in certain areas, mainly arising from issues of uncertainties such as occupancy behaviour and weather data [3].

- **The construction gap**

Another issue that can cause a performance gap is the construction process. Many studies, including industry reports and papers analysing various scales and types of case studies, have pointed out that the onsite construction quality often does not agree with design specifications. More particularly, there is a lack of attention to aspects related to insulation and airtightness [3, 28, 4]. In many cases, both builders and engineers are responsible for the resultant discrepancy in buildings performance, but studies are not able to identify nor quantify the exact source of the gap.

- **The operational gap**

A building's operational stage is repeatedly cited to be a major reason for the discrepancy with the design stage predictions. More particularly, studies often put the blame on occupants' behaviour [29, 3, 30, 4]. Menezes et. al. (2012) suggested that by using proper post occupancy evaluation data, more knowledgeable design stage assumptions might be possible in future and hence reduce this contribution to the gap [3]. However, such data is rarely collected.

3. BUILDING SIMULATION MODELLING

3.1 Case study building

The particular building chosen in this study was a typical UK semi-detached house, which was recently renovated to meet the L1B requirements (essentially an upgrade to the relevant building codes). The building was modelled in detail using IES and the model validated using hourly measured gas, electricity, occupancy and indoor temperatures.

3.2 Modelling approach and limitations

Weather input data: Observed weather was recorded for the project from a weather station approximately 3 miles from the house. This gave, dry bulb temperature, wet bulb temperature, atmospheric station weather, relative humidity, wind direction and wind speed. Radiation data were taken from the World Meteorological Organization's website for Camborne (the closest available location) with similar climate characteristics and hourly measured weather data (2004-2014). Other data were from the EPW for London.

Heating use: System use was determined based on observations of measured energy consumption, and indoor temperature variations for each space. The heating set-point (21ºC) was based on the measured indoor temperature.

Building geometry: Internal and external dimensions and openings of the case study building were modelled carefully using to-scale drawings.

Surroundings: The surrounding environment of neighbouring buildings were modelled in detail as they provide extensive shading. The case study building has no external self-shading except for 200 mm extrusions above doors, a 100 mm extended roof perimeter and a 100 mm recession around windows and doors.

Glazing ratio: The plans gave a glazing ratio of 25% overall with 21.8% on south and north facades respectively. The east façade contains only one window, representing 2.3% of the area. Doors area was 1.6 m^2 (solid doors with no glazing).

Natural ventilation and Occupancy: Modelling natural ventilation depends on assumptions, for example, it is highly unlikely a modeller can accurately determine when and which windows will be opened, and for what length of time. Therefore, modellers usually use assumptions that are under-descriptive of the actual behaviour of occupants which is considered "uncertainties". For the purposes of this research, and starting from reasonable assumptions, the ventilation and occupancy were adjusted to give a high correlation between measured and simulated heating energy demand and temperature (measured on an hourly basis).

Building's envelope: The air permeability of the building envelope was not measured but set as 10 $m^3/h/m^2$ at 50 Pa in order to comply with the standard set by the building code (Part L). U-values were as detailed in (Table 1).

Table 1. U-values of case study building

Element	Modelled U-values (W/m^2K)
External walls	0.35
Pitched Roof	0.26
Floors	0.25
Windows	1.6
Doors	1.8
Internal walls	1.8
Internal floor/ceiling	1.0

Internal heat gains: The sensible gains for people were set to 75 W/person in accordance with the ASHRAE handbook (2013). A maximum of four people were assumed to be in the house, with occupancy linked to the measured occupancy profiles of each space. Gains from lighting were controlled based on the illuminance level required for each space and occupancy period. Finally, internal gains from equipment and cooking were assumed as an average based on the ASHRAE handbook (2013). The appliances were linked to occupancy profiles of each space in order to provide an average value of consumption. This action was performed with an understanding that not all appliances are linked to occupancy profiles, for example fridges.

3.3 Model validation: Building simulation modelling vs measured data

In order to validate the model, one year of detailed gas consumption and indoor temperature monitoring was obtained and correlated with the simulated case study results. The data was compared on hourly intervals across the entire year. The correlation between measured monthly gas consumption and the simulated model gives an R^2 of 0.93 (Figure 2). While (Figure 3 and 4) indicates a strong correlation remains on hourly basis. As illustrated in (Figures 5 and 6) a good correlation is found between both peak and average indoor temperatures in all spaces. The model can thus be considered as validated.

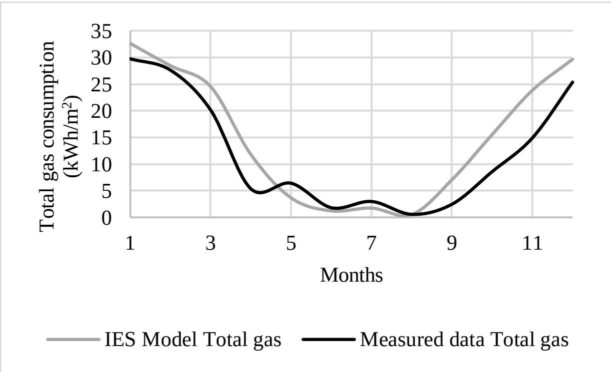


Figure 2: Monthly correlation between measured and simulated gas consumption for the case study building, which indicates a close relation (R^2 value of 0.93).

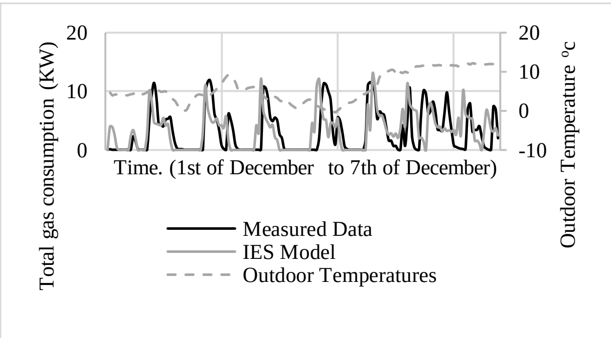


Figure 3: Simulated and measured hourly gas consumption for a week in December, in relation to measured outdoor temperatures (R^2=0.73).

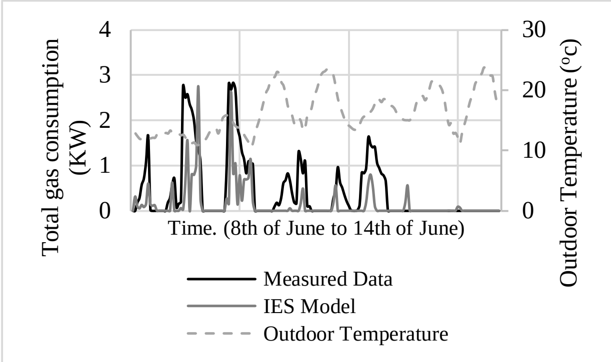


Figure 4: Simulated and measured hourly gas consumption for a week in June, which indicates a relatively close correlation (R^2 = 0.59)

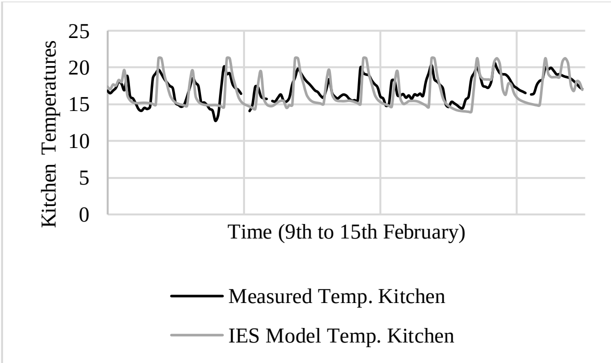


Figure 5: Plot of both simulated and measured indoor temperatures for the kitchen space for a week in February (R^2 = 0.61).

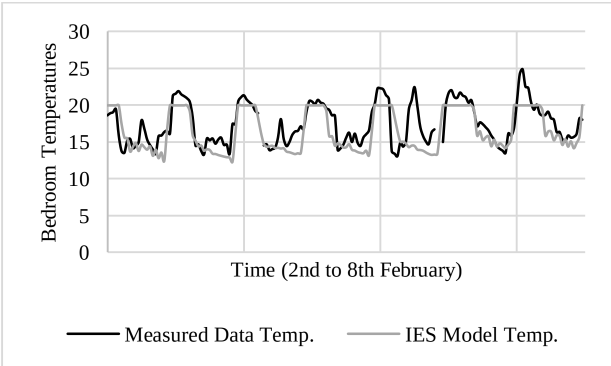


Figure 6: Plot of simulated and measured indoor temperatures for the bedroom space for a week in February (R^2= 0.63).

Table 2. Perturbations performed on each input parameter

Input parameter	Base value	Altered value	Scale of Alteration
Glazing ratio	17.3 %	19 %	10 % greater than actual and modelled ratio
Installed window U-value	1.6 W/m^{2}K	1.92 W/m^{2}K	20 % greater than installed and modelled value
Walls U-value	0.35 W/m^{2}K	0.42 W/m^{2}K	20 % greater than installed and modelled value
Occupancy period	13 hr/day	16.25 hr/day	25% greater than the average measured and modelled period per day
Airtightness	0.25 ach	0.3 ach	20 % greater than the assumed and modelled value
Roof U-value	0.26 W/m^{2}K	0.31 W/m^{2}K	20 % greater than installed and modelled value
Thermal bridging	10% increase in each element U-value	Thermal bridges ignored	Ignoring thermal bridging

Winter indoor temperature set-point	21 ºC	19 ºC	The modelled value being 2 ºC lower than reality
Natural ventilation	MacroFlo profiles	Constant airflow at 1 ach	Assuming the air flow is constant at 1 ach when occupied, against the base case of assuming windows are open during occupied period, if (T_{in} > 25°C, RH > 65% or CO_2 concentration > 1000 ppm)
Ground floor U-value	0.25 W/m^{2}K	0.3 W/m^{2}K	20 % greater than installed and modelled value
Building geometry	39.5 m^2	32 m^2	Using internal dimensions for the building rather than external
Ventilation rate	1 ach	1.1 ach	10% increase
Shading from surroundings	Modelled surroundings	Ignore their effect	Ignoring shading from the surrounding homes etc.
Windows recession	100 mm	200 mm	Assuming windows recessed 100 mm further into the building
The position of windows in walls	Base model position	0.5 m downwards	Assuming a 0.5 m vertical shift down from the actual position on each facade
Density of block used as inner leaf of wall	1.40 Tonne/m^3	1.54 Tonne/m^3	20 % greater than installed and modelled value
Internal gains from appliances and lighting	52.8 W/m^2	58.0 W/m^2	10 % greater than installed and modelled value
External doors opening	10 openings/day	Continuously closed	Ignoring the fact that the external doors might be opened 10 times a day, each time for 30 seconds
Internal gains from cooking	12 W/m^2	0 W/m^2	Ignoring heat gains from cooking
Thermostat location	Thermostat only in the living room	Thermostat in each space	Assuming thermostats in each room rather than just in one room (modellers often assume the former)
The use of curtains	Used at night	Ignore their effect	Ignoring the use of curtains at night
Note: In order to provide reasonable alterations, a simple "test model" was performed to understand where the most critical changes are (thermal envelope and occupancy patterns). While other parameters such as window recession and building geometry are based on reasonable assumptions and of similar studies.			

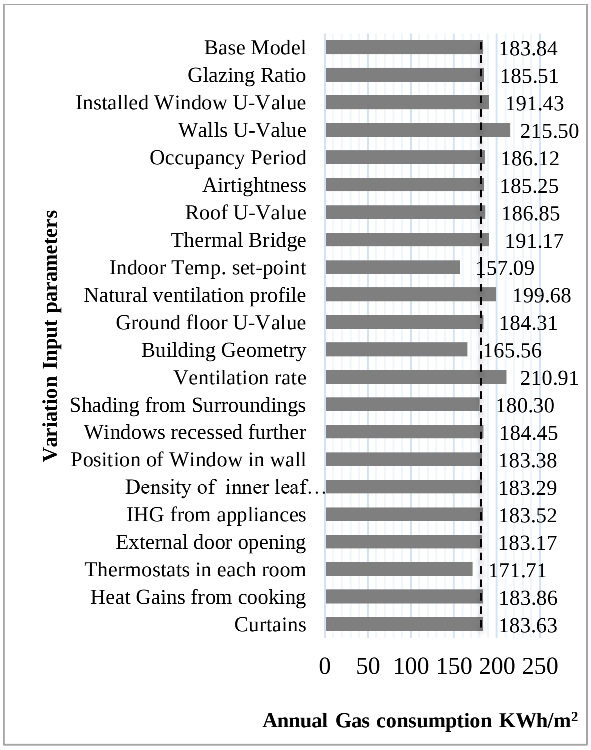


Figure 7: The impact of each perturbation on the annual gas consumption compared with the base model consumption

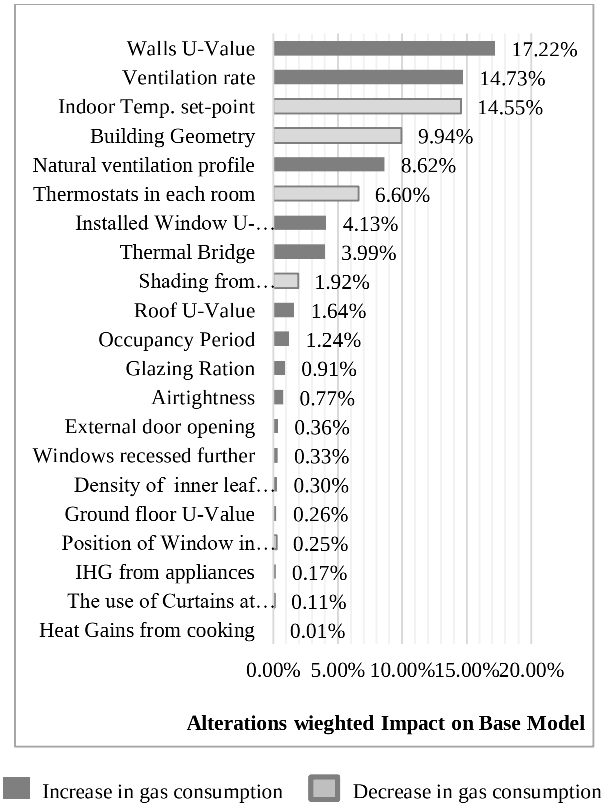


Figure 8: Weighted impact of each perturbations on the annual gas consumption

4. SURVEY

4.1 Method

- **Survey design**

From a psychological perspective, "A person's perception of how a system operates is often referred to as a mental model. This might come from educated understandings via literature and mentorships or simply from practical experimentation with the controls – and in both cases their mental model might or might not be accurate" [31]. Within this context, the survey conducted in this research aims to reveal the energy modelling "mental models" of professionals in the construction industry. This was done by asking questions using two standard social science approaches: *the free form method* and *the given list method* [31], see (Table 3). A detailed description of the building and the surroundings (including photographs) was given to the participants.

Table 3. Survey questions and their purposes in respect to the research hypothesis

<table>
<tr><th colspan="3">Free form method</th></tr>
<tr><th></th><th>Survey question(s)</th><th>Purposes / Aims</th></tr>
<tr><td>Question 1</td><td>List the 3 most important parameters that if not included or included less accurately in a thermal model of the case study building, might affect the annual heating demand significantly.</td><td>To discuss any common input-parameters that participants might consider have a significant impact on the annual heating demand.</td></tr>
<tr><td>Question 2</td><td>List 3 parameters that you might not normally include, as they do not have a great impact on the annual heating demand.</td><td>To encourage participants to include input-parameters that they might not normally consider. Hence, parameters not included in their answers, will more likely not used by participants in actual projects.</td></tr>
<tr><td>Question 3</td><td>List any other parameters that you might include in a thermal model of the case study building and might have a moderate effect on the annual heating demand.</td><td>To give participants the chance to add any other input parameters that they might sometimes include in a thermal model of the case study building.</td></tr>
<tr><td>Structure concept</td><td colspan="2">Not providing users with a list of parameters - at this stage - was intentional, to not attract them to certain input-parameters that need to be included in the model.
Clarify what participants can take or not take into consideration in a thermal model of the case study building and to identify their natural thoughts regarding the modelling stage assumptions.
Dividing this section into 3 questions was to limit the answers to 3-5 options, making it easier for participants to understand [32].</td></tr>
<tr><th colspan="3">Given list of input-parameters method</th></tr>
<tr><th></th><th>Survey question(s)</th><th>Purposes / Aims</th></tr>
<tr><td>Question 1</td><td>Rate the list of parameters provided in the survey (1 to 5 scale.1=small impact and 5=significant impact) based on your judgement of impact on annual heating demand due to variations applied to each parameter (Table 2).</td><td>Identify the perception of the design team of potential errors due to some parameters and their effect on the annual heating energy demand.
The answers were obtained in a form of a "ranking list" and compared with the "accurate ranking" obtained from the validated simulation model.
This comparison set forms the base for evaluating their modelling literacy.</td></tr>
<tr><td>Notes</td><td colspan="2">Details of the case study building was clearly illustrated to participants in the survey.
Once participants proceeded from the "free form" question to the "given list" question, they were not able to return back and edit their responses. Hence, the case study description was repeated to be accessible while answering both questions.
The "error factors" applied to each input-parameter were assumed to be due to lack of knowledge in the design stage or poor workmanship on-site.</td></tr>
</table>

- **Sampling method**

The target respondents were chosen from professionals in the construction industry: architects, engineers and energy analysts. All of whom made regular use of dynamic thermal models. Random sampling [33, 32] was used to generate the population sample.

- **Participants**

Participating employees were from engineering and architectural firms involved in the design process of a range of national and international projects, and included some of the world's largest engineering and architecture practises. Emails were sent to directors to ask whether it was possible to visit their firm to ask employees to complete the survey. Many replies welcomed the idea, resulting in 31 respondents. The online questionnaire was also sent directly to professionals drawn from LinkedIn and respondents were also garnered by posting on online building energy modelling groups, resulting in an additional 77 respondents.

The whole process resulted in 108 participants who completed the survey; a further 12 participants failed to fully complete it. Questionnaire results were anonymous. The names of the firms participating in the survey cannot be reported due to confidentiality. (Figure 8) shows the nature of participants, in terms of years of experience in the construction industry. The highest academic degree achieved related to this field was reported as: bachelors (34 participants), masters (66), PhD (8). 81% of respondents selected IES VE as the simulation software they use for energy analysis.

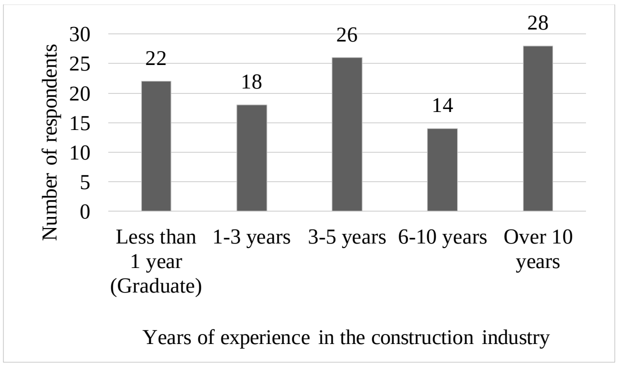


Figure 9. Participants' years of experience in the construction industry

4.2 Results

- **Free form method**

In this form of the survey participants were not given a list of parameters to choose from, but asked to separately list parameters they considered highly important, moderately important, or unlikely to be important. Parameters listed by participants for this form are shown in (Figures 10, 11 and 12).

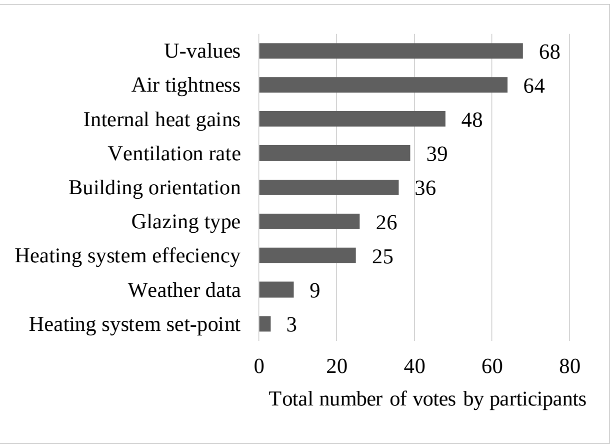


Figure 10. Question 1: Input-parameters assumed by participants to have a significant impact on the annual heating demand.

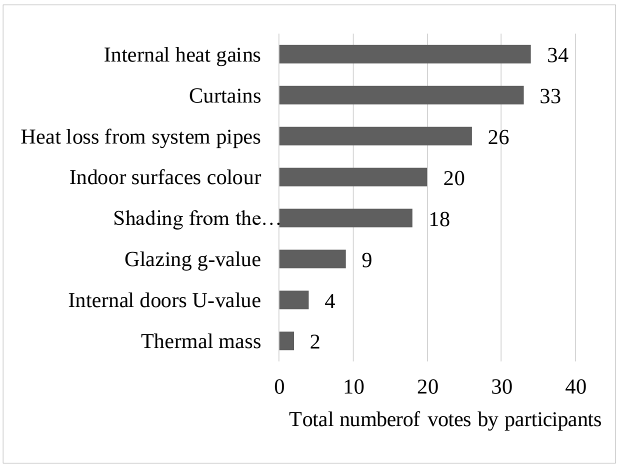


Figure 11. Question 2: Input-parameters that participants might not normally include in a thermal model of the case study building.

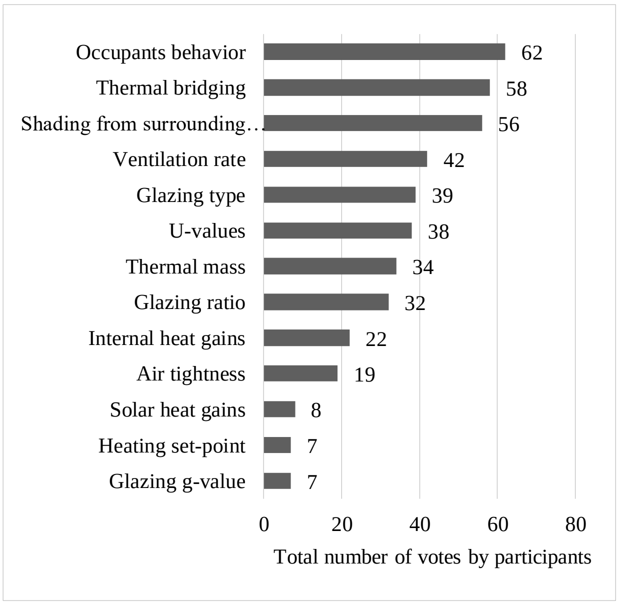


Figure 12. Question 3: Input-parameters assumed by participants to have a moderate impact on the annual heating demand.

- **Given list method**

For this part of the survey, participants were given a list of 21 input parameters and the perturbations used in the sensitivity analysis (see Table 2 and 3). Participants were asked to indicate the relative size of impact for each parameter variation on the annual heating demand by scaling them from 1 to 5. The ranking given by the participants is shown in (Figure 13). The weighted average for any parameter was calculated as:

$$\frac{x_1\, w_1 + x_2\, w_2 + x_3\, w_3 \ldots x_5\, w_5}{Total\ number\ of\ respondents}, \qquad (1)$$

where *x* is the response (1-5) and *w* is the response count.

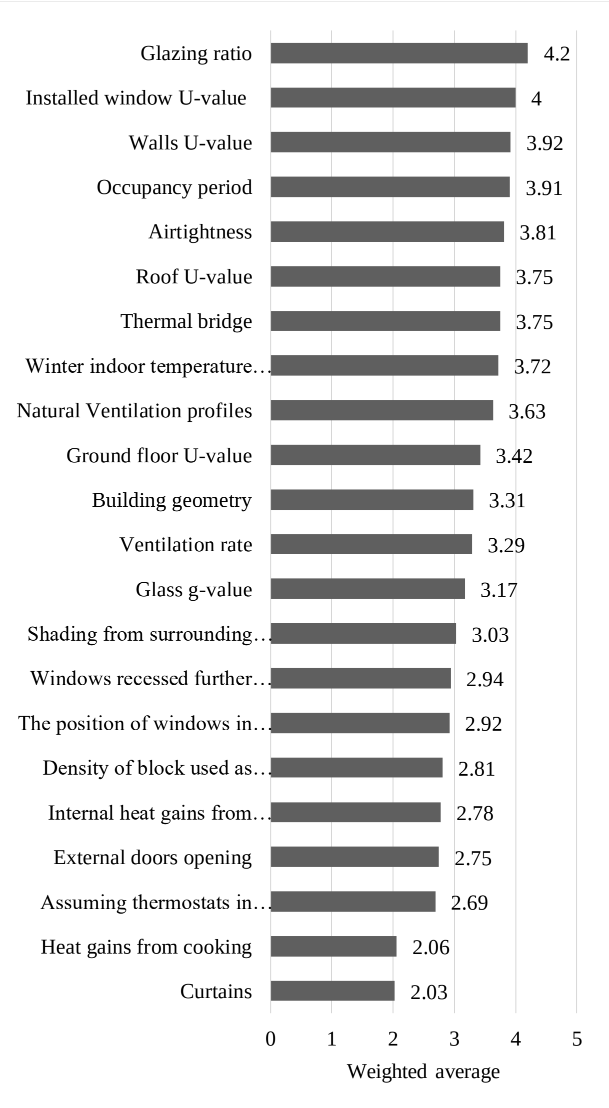


Figure 13. Ranking of the given parameters based on a total of 108 participants (Equation 1) when asked to indicate on a scale of 1-5 the relative size of impact for each parameter on the annual heating demand (Based on the alterations stated in Table 2).

4.3 Results and discussion

- **Un-mentioned parameters**

Re-plotting the freeform results so as to concentrate on parameters not mentioned by one or more individuals provides some surprising results (Figure 14). All parameters were subject to being overlooked except U-values. For example, although "internal heat gains" was mentioned 104 times out of 108 responses, 34 participants considered it to be the type of parameter that they would not normally include in such a dynamic model. Similarly, 18 participants considered the inclusion of shading from the surrounding environment to not be worth including, whereas 56 respondents highlighted this parameter to be considerably important. This is still surprisingly low given that participants were provided with a photo of the surrounding area that shows the building is surrounded by buildings of a similar height.

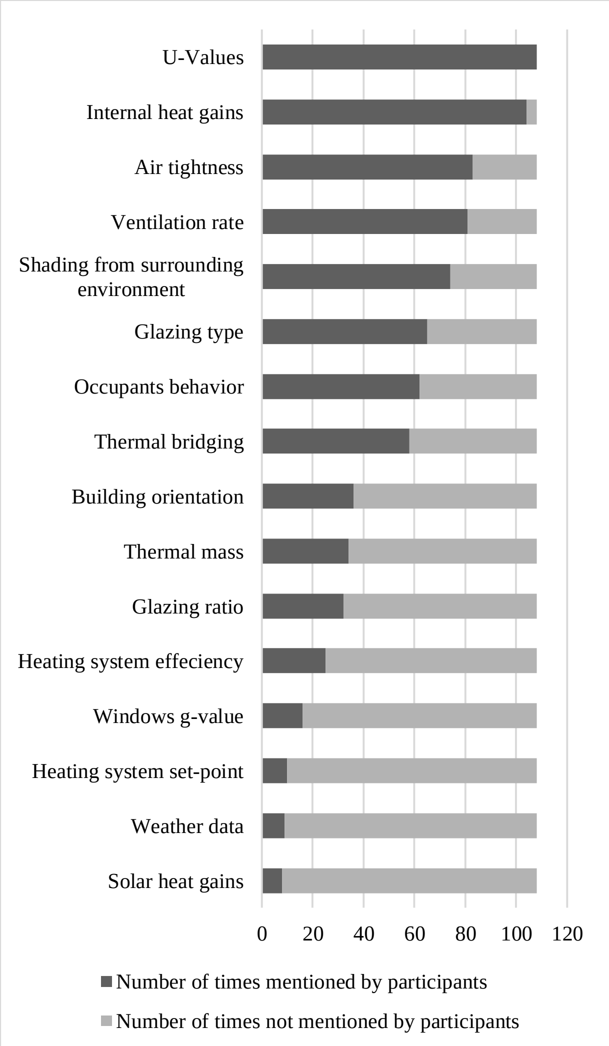


Figure 14. The most impactful input-parameters mentioned by participants in the freeform question highlighting the number of times each parameter was not mentioned.

- **Comparing and contrasting the results from both survey methods**

Comparing the results obtained from both methods highlights that a parameter's ranking can differ significantly. For example, in the freeform question, 70% of participants did not mention *glazing ratio*, while 42% and 23% did not include *occupancy period* and *airtightness* respectively. Whereas, the top 5 ranked parameters in the given list question included all 3 parameters as shown in (Table 4).

Table 4. Comparison between the Top 5 ranked input-parameters in the "given list" question and the number of times participants did not mention these parameters in the "free form" question.

Top 5 ranked input parameters	
Given list method	Number of participants who did not mention this parameter (Total of 108 participants)
Glazing ratio	76
Installed window U-value	0
Walls U-value	0
Occupancy period	46
Airtightness	25

One of the clearest differences between the participants and the ground truth provided by the model is in the impact of changing the glazing ratio (a 10% increase in glazing ratio was presented to the participants and modelled). Although assumed by the participants to be the parameter with the greatest impact, the modelling showed it to only be the 12th and giving an increase of only 0.91% in heating energy use (183.84 to 185.51 kWh/m^2/year). Similarly, installed window U-Value was given by the participants as the second most important, whereas, it was the 7th in the simulation model.

For a few cases the participants and the model are in better agreement. For example, the impact of changing the wall U-value was voted by the survey as 3rd, which is relatively close to the finding of the simulation study, which placed it 1st, with an increase of 17.22% in heating energy use. This outcome is probably logical, because of the large surface area of this element and the relatively large perturbation assumed (20%). Ignoring the use of curtains at night, ignoring the internal heat gains due to cooking and a 10% increase in heat gains due to appliances also showed agreement between the participants and the model. All are viewed by the participants and validated by simulation as being of little impact, securing the last 5 slots in the ranking of both the survey and the simulation model. However, in the case of indoor temperature set-point being reduced by 2^{o}C, the survey gave a rank of 8th, yet the simulation model shows it to be the 3rd; with gas consumption decreasing from the base case by 14.55%.

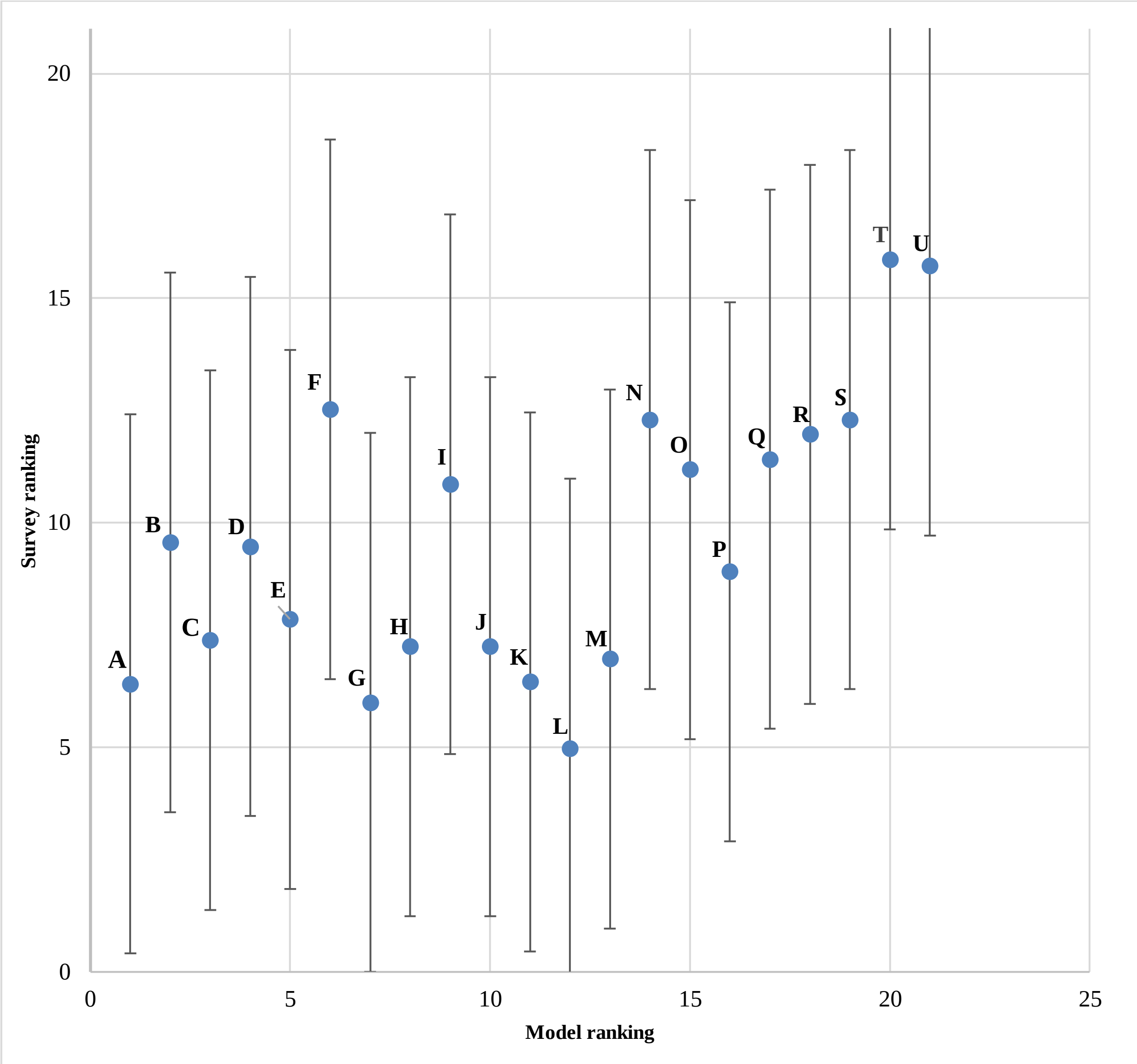
As discussed earlier, the sorted list of parameters given by the survey participants was in the form of a 1 – 5 scale. However, the ranking produced by the simulation model is listed from 1 – 21 based on the recorded impact on the annual gas consumption. In an effort to analyse the findings taking in consideration all individual responses, all parameters were organised according to the punctuation given by the survey and the 1 – 5 scale given by each individual was sorted to be in accordance with the 1 – 21 model ranking list. Additionally, the mean and standard deviation were calculated to each parameter. This action was performed with the understanding that a part of the precision was lost in this conversion, as some parameters will need to have the same score.

Nevertheless, It is clear that there is a large variability in the survey responses and in all cases, the means are far from being accurate with a Spearman ranking of 0.43 and an R^2 value of 0.28 (Figure 15). This suggests no correlation between the thoughts of designers and the modelled results and indicates that, when measured in this way, modelling or building physics literacy may not be high in the participants.

(Table 5) presents the Spearman ranking correlation and the R^2 value for each group depending on years of experience and the highest level of academic degree. It cannot be argued that for example: participants with less than one year of experience are proven to be more literate, as the number of participants in each category varied, yet, it is an indication that there is an urgent need for further investigations to understand the basis in which modellers' literacy can be improved.

Table 5. $R^2$and spearman correlation values for each group depending on both years of experience and highest academic level

Group	**R^2 value**	**Spearman correlation value**
Years of experience		
< 1 year	0.36	0.59
1-3 years	0.33	0.56
3-5 years	0.24	0.47
6-10 years	0.37	0.59
> 10 years	0.20	0.42
Academic level		
Bachelors	0.35	0.58
Masters	0.33	0.56
PhD	0.20	0.42



A	Walls U-value (20% increase)	**L**	Glazing ratio (10% increase)
B	Ventilation rate (1.1 ach instead of 1 ach)	**M**	Airtightness (10% increase)
C	Inter indoor temperature set-point (2°C lower)	**N**	External doors opening (Ignore)
D	Building geometry (Using internal dimensions)	**O**	Windows recessed (100 mm further)
E	Natural ventilation (change to constant ach)	**P**	Ground floor U-value (20% increase)
F	Heating set-point (thermostats in each room)	**Q**	Position of windows in walls (0.5 m down)
G	Installed window U-value (20% increase)	**R**	Density of inner leaf wall block (10% increase)
H	Thermal bridging (Ignore)	**S**	Internal heat gains from appliances (10%increase)
I	Shading from surroundings (Ignore)	**T**	The use of curtains at night (Ignore)
J	Roof U-value (20% increase)	**U**	Heat gains from cooking (Ignore)
K	Occupancy period (25% increase)		

Figure 15. Scatter plot comparing survey results (mean and standard deviation) and simulation model ranking

5. SUMMARY AND CONCLUSION

The performance gap is considered a problem that might affect all new buildings or the refurbishment of older ones. This creates a gap between reality and the policies implemented by governments to reduce energy use and greenhouse gas emissions. Previous studies tried to tackle this problem from various perspectives such as highlighting issues concerned with the role of poor workmanship or occupants' behaviour. The research reported here tackled this problem from the earlier stage of energy modelling, or, more precisely, the building physics literacy of building energy modellers. The literature indicates that this is an understudied area and is highly important as architects, engineers and modellers do not tend to consider themselves as a contributing factor to the performance gap, but rather consider construction quality and occupants to be the problem.

From the results reported here it is clear that all three tests of literacy suggested in section 2.1 have been failed by the sample of participants. Participants do not: **1.** approximately agree on the important parameters that need to be included in the model; or **2.** approximately agree on the rank order of the importance of a list of possible input parameters; or **3.** cannot rank order the impact of given changes to the values of 21 common parameters such that they approximately agree with that given by a sensitivity analysis of the parameters within an industry standard and validated thermal model.

Being that the sample size was reasonably large (108), this conclusion is likely to be valid on average also for the whole population of thermal modellers. Further research is needed to identify the current state of modelling literacy using a larger population sample and various building types as case studies. Furthermore, future research should identify new ways to teach building physics in both academic and industrial domains, as this clearly emphasises a potential gap that can be bridged.

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