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THE GAP BETWEEN SIMULATED AND MEASURED ENERGY PERFORMANCE: A CASE STUDY ACROSS SIX IDENTICAL NEW-BUILD FLATS IN THE UK

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ABSTRACT

Monitoring of completed buildings often identifies significant gaps between the predicted and actual energy use of buildings. This is referred to as the ‘energy performance gap’. To date, most research on the energy performance gap has focussed on non-domestic buildings; this paper presents a case study from the UK domestic sector. Monitoring equipment was installed in six identical flats located in a new-build apartment building. The actual energy used during the first year of occupation is compared with the design stage normative Standard Assessment Procedure calculations as well as seven transient DesignBuilder models produced by a cohort of seven MSc Architecture students. As six identical flats were investigated, the paper provides a unique opportunity to develop an energy use distribution on the monitoring side of the energy performance gap. The work demonstrates that the energy performance gap is evident in the domestic sector.

INTRODUCTION

With energy efficiency targets becoming stricter and energy prices increasing, there is a growing interest in the discrepancy between the predicted and measured energy use of buildings. This difference between predicted and measured energy performance is commonly referred to as the 'energy performance gap' (de Wilde, 2014; de Wilde & Jones, 2014; Menezes et al., 2012; ZCH, 2010; Turner & Frankel, 2008).

The energy performance gap has been shown to be quite significant, with buildings commonly using 1.5 to 2 times more energy than was expected (CarbonBuzz, 2013; Turner & Frankel, 2008). This issue however is not only of interest to building science researchers, but also constitutes a serious problem for the building and construction industry. The energy performance gap defines a clear problem with the products of the industry (i.e. buildings) not meeting their quantified ambitions and as a result undermines the credibility of the building design and engineering disciplines.

Moreover, if a performance gap already exists for buildings that are designed to function within today's occupancy schedules and climate conditions, the building industry is even less well-placed to develop buildings that are resilient and robust for future changes in occupation and climate.

Without bridging the performance gap the industry cannot expect to move towards new business models such as performance contracting, where a client pays for a specified indoor climate rather than for hardware (building and subsystems) with unspecified operation conditions.

In recent years, much effort has been placed on closing the energy performance gap, with attempts to address the broad range of causes of the energy performance gap, from improving the predictions of energy use at the design stage provided by simulation tools (Jankovic, 2013; Lee et al. 2013; Sun et al., 2011), to addressing the defects and quality issues that arise during the construction stage of buildings (Bell et al., 2010) as well as gaining a better understanding of the role of occupants’ behaviour during the operational phase (Wei et al., 2014; CarbonBuzz, 2013; Dasgupta et al. 2012).

This paper investigates the energy performance gap for the domestic part of the building sector. To date, most of the energy performance gap research has focussed on non-domestic buildings (de Wilde et al, 2013; Menezes et al., 2012); dwellings have almost entirely been overlooked in the discussion. This is because domestic buildings are less likely to be subject to transient building simulation and building performance evaluation monitoring; however, it risks missing out on a key sector of buildings.

CAUSES OF THE ENERGY PERFORMANCE GAP

The literature indicates that a range of factors throughout the building lifecycle, from planning and design to operation, contribute to the energy performance gap. For a detailed review of the root causes of the energy performance gap, see de Wilde (2014). It should be noted, that the issues contributing to the energy performance gap will vary between buildings and there are likely to be a number of different contributing factors within any single building.

Planning and design stages

During the planning and design stages, poor communication between different parties (design team, clients, contractors, etc.) about the expected performance of the building has been suggested as a key initial problem later leading to the performance gap (Newsham et al., 2009).

Furthermore, the building design itself may also have an impact, for example, due to wrong or missing construction details, lack of simplicity or buildability in the design, poor sequencing of the construction process and the incorporation of inefficient or oversized systems.

The integration of energy saving technologies in buildings, in particular novel and advanced technologies have also been noted to contribute to the performance gap. In many cases technologies underperform compared with the manufacturers' expectations and their performance degrade over time (Williamson, 2010).

The second key cause of the performance gap within the design stage relates to the modelling and simulation. The predictions of the expected energy use of the building once operational are often affected by the sheer lack of information available to the modeller at the design stage regarding the future occupancy and operation of the building and its services (Menezes et al., 2012), as well as actual weather conditions (Turner & Frankel, 2008) In addition, the competences of the modellers making the energy predictions at the design stage are also a root problem (Dwyer, 2013). Any use of incorrect methods, tools or component models will result in unreliable predictions and a gap later down the line.

Construction stage

Another range of causes of the energy performance gap arises during the construction and handover stages (Bell et al., 2010). Achieving the desired insulation and airtightness levels are sometimes difficult; errors and defects might be hidden from view as constructions are typically layered.

There are also direct impacts of change orders and value engineering. Whilst change orders might appear to substitute equivalent products, these might not be from a detailed thermal point of view. Value engineering might actually remove elements of the thermal system that are seen to be overly expensive but which were critical in achieving the desired performance. Building commissioning and hand-over are also difficult processes that typically do not allow for full performance testing due to budget and time constraints (Bunn & Way, 2010).

Operation stage

Once a building is in use, the building operation also contributes to the performance gap. The behaviour of the occupants is often different to those assumed during the modelling at the design stage (control settings, the opening and closing of windows and doors, plug loads, etc.). This factor is the most commonly stated cause of the performance gap (Jones et al. 2015; Wei et al., 2014; CarbonBuzz, 2013; Dasgupta et al. 2012). The actual weather conditions also rarely match those used in the predictions of energy use.

Furthermore, building performance evaluation monitoring of buildings, also has its own issues and uncertainties (NMN, 2012); this is especially true when it comes to capturing contextual factors such as weather data and occupant behaviour. Measurement can often have issues with accuracy, missing or incomplete data, as well as implausible values, which lead to a 'level' of error in the results collected from metering. Post-processing and cleaning of metering data is therefore essential, but can introduce further threats to the validity of the results.

METHODOLOGY

This paper investigates two types of energy performance gap: a Type 1 gap between 'first principle' energy models (transient DesignBuilder simulations) and measurements undertaken on actual buildings as suggested by de Wilde (2014), and a new Type 4 gap between normative methods used for compliance testing (SAP calculations) and measurements undertaken on actual buildings. The latter is an addition to the already existing Performance gap typology developed by de Wilde (2014).

Case study

This paper takes a case study approach and presents an investigation of the energy performance gap for six purpose built flats located on a new-build housing estate in Torquay, a town in the South West of the UK. The six flats were located in an apartment building (Figure 1) constructed to Code for Sustainable Homes (CfSH) Level 4, a voluntary national standard for the sustainable design and construction of new homes (DCLG, 2010). On paper, the flats investigated exceed regulatory compliance and could be described as 'low energy' or 'high performance' homes.

Figure 1 Case study apartment building constructed to Code for Sustainable Homes Level 4

The choice to construct the homes to a higher construction standard than is currently mandated by the building regulations was taken in the context that all new homes in England must be 'zero carbon' from 2016 (DCLG, 2011; ZCH, 2011) and the project would offer a learning opportunity before this change came into force.

Two thirds of the housing estate consists of affordable homes (general need, shared ownership and sub-market rent) that will ultimately be operated by a housing association and therefore a philanthropic desire to construct homes that provided the future occupants the greatest comfort at the lowest cost was important.

The six purpose built flats are identical in layout (80.5m^2) (Figure 2), construction standard (CfSH Level 4) (Table 1), orientation (South East) and building services installed (Combination boiler for space and hot water heating). The stated orientation relates to the direction of the façade containing the living room and bedroom windows.

As the project monitored identical dwellings, this offered a unique opportunity to develop an energy use distribution that reflected the impact of design independent factors to the performance gap, such as occupant behaviour, variation in plug in equipment, and others.

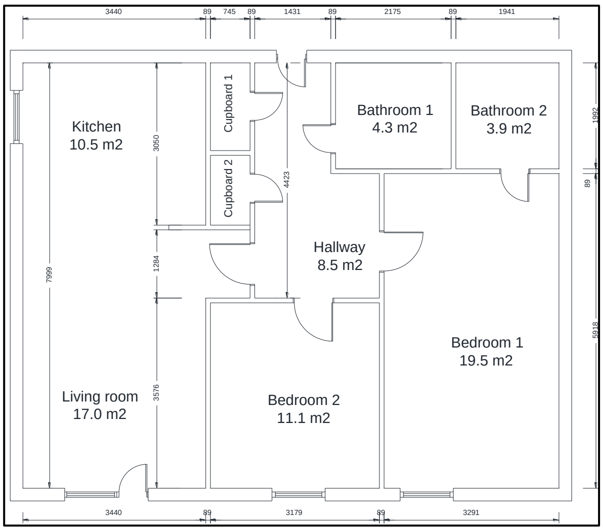

Figure 2 Floor plan of the purpose built flats (Not to scale – dimensions in mm)

Data generation and collection

To investigate the energy performance gap, the following types of data were collected for the six flats located in the case study building:

1. Simulated energy use data:

a. Design stage normative Standard Assessment Procedure (SAP) calculations

b. Transient DesignBuilder simulations

2. Measured energy use data.

Normative SAP calculations

Design stage normative SAP calculations were obtained from the original architectural design team.

Table 1
Specification for CfSH Level 4 flats

ELEMENT	EXPECTED PERFORMANCE
External walls	0.1 W/m^{2}K
Floors	0.13 W/m^{2}K
Windows	1.2 W/m^{2}K (g-value 0.56)
External doors	0.55 W/m^{2}K
Roof	0.10 W/m^{2}K
Main heating	Combination boiler 91% efficiency and gas saver
Heating control	Time and temperature zone control
Ventilation	Mechanical Ventilation with Heat Recovery (MVHR)
Generation	0.55kWp PV
Airtightness	2 m^3/hr.m^2

The SAP methodology is based on the BRE Domestic Energy Model (BREDEM), which provides a framework for calculating the energy consumption of dwellings. The SAP methodology is used for compliance testing of energy performance against Part L of the Building Regulations for England and Wales, as well as for domestic energy rating systems, such as, the Energy Performance Certificates and Code for Sustainable Homes.

The SAP works by assessing how much energy a dwelling will consume, when delivering a defined level of comfort and service provision. The assessment is based on a monthly calculation method, assuming standardised occupancy and behaviour and estimates the annual energy consumption for the provision of space heating, domestic hot water, lighting and ventilation. The method does not calculate energy use related to 'unregulated loads' (i.e. not controlled by Building Regulations), such as electricity consuming equipment (e.g. electric showers, secondary electric heating), appliances and cooking.

The SAP calculations were undertaken by the architectural design team using the software, JPA Designer SAP 2012, Version 9.81. The design stage SAP calculations were obtained for each of the six flats being investigated. As the flats were identical, the predictions of energy consumption were also identical; therefore only one annual gas and electricity use consumption are presented for the normative SAP results.

Transient DesignBuilder simulations

Seven transient DesignBuilder models of the case study building were produced by seven MSc Architecture students (see example in Figure 3). The students were enrolled on a 12-week optional module about Building Performance Simulation led by the first author of this paper. The course provided week-by-week tuition from basic geometric operations through to detailed HVAC. None of the students had previously used DesignBuilder software, but all had experience with 3D modelling software (Revit, SketchUP, ArchiCAD, etc.) and some with IES-VE.

To construct the simulation models, the students were all given exactly the same information about the case study building (i.e. drawings and construction specifications). The students were also shown how to use the standardised DesignBuilder activity templates for defining the model data for each room type (e.g. occupancy density and schedules, heating Setpoint Temperatures, Domestic Hot Water consumption rate, etc.) as well as how to create their own activity templates. The students were instructed that the activity templates should reflect the lifestyle of a young working couple living in the flat.

Because the research sought to quantify the contribution of the individual modeller to the performance gap, the students' modelling inputs for the construction specifications and occupancy behaviour were not controlled.

The transient models were all produced in DesignBuilder, Version 4.2. Annual estimates of gas and electricity consumption were obtained for the six flats within each of the seven student models. As some variations in the predictions of energy consumption were evident between the six flats within each of the models, for this paper, the annual gas and electricity consumptions are mean values for the six flats in each model.

Figure 3 Example transient DesignBuilder model of the case study building

Measured energy use data

To collect the actual gas and electricity consumptions of the six flats, an automated monitoring system was installed in each of the flats. The data were collected as part of a larger Post-Occupancy Evaluation (POE) to assess the actual operational performance of the case study building. This paper reports the energy consumption of the six flats during their first year of occupation from November 2013 to October 2014.

The electricity and gas consumption of the dwellings are collected using pulse output sensors (Figure 4), which are connected to the dwellings' mains gas and electricity meters. The pulse output sensor counts the number of pulses from the meter, which relate to a certain amount of energy passing through the meter. For domestic meters each pulse corresponds to 1Wh (1000 pulses per kWh).

The energy consumption data is transmitted by radio frequency (RF) to a data hub every 5 minutes, which is located in the loft space of the apartment building. The data hub exports the data to a remote server every hour using General Packet Radio Service (GPRS). The data can then be accessed by the researchers via any Internet enabled device.

Figure 4 Pulse output sensors connected to the electricity meter (left) and gas meter (right)

RESULTS AND DISSCUSION

The predictions of annual gas and electricity consumption from the design stage normative SAP calculations and transient DesignBuilder simulations, as well as, the measured annual gas and electricity consumptions are shown in Figures 5 and 6.

Annual gas consumption

In relation to the predictions and measurements of annual gas consumption (Figure 5), it is evident that both a Type 1 performance gap, between 'first principle' energy models and measurements, and a Type 4 performance gap, between normative methods used for compliance testing and measurements exist.

Both the normative SAP calculation and the mean of the seven transient DesignBuilder simulations over predicted the measured mean annual gas consumption. This of course is a favourable performance gap, where less gas was consumed than predicted by the simulation tools. This is to the authors' knowledge, the first such domestic performance gap reported in the literature.

This finding may indicate that performance simulation tools have particular difficultly predicting the actual energy consumptions of 'low energy' or 'high performance' dwellings and may perhaps tend to overestimate rather than underestimate their actual annual energy consumptions. Further performance gap research on these types of dwellings is required to develop knowledge in this area further.

The gas consumption prediction provided by the normative SAP calculation was 1.7 times greater than the measured mean annual gas consumption. The extent of the performance gap varied from 1.1 to 2.3 times greater, when compared with the range of annual gas consumptions measured in the six identical flats.

In relation to the energy performance predictions obtained from the transient DesignBuilder models, the mean of the seven transient models over predicted the measured mean annual gas consumption by 1.5 times.

The large range of predictions of annual gas consumption obtained from the seven transient DesignBuilder models demonstrates the strong impact that the individual modeller also has on the results achieved and thus the extent of the performance gap observed. Despite the seven modellers being given exactly the same information to construct the simulation models, the predictions of annual gas use ranged from 2,654 to 4,292 kWh, 1.6 times higher. Therefore compared to the measured mean gas consumption, the magnitude of the performance gap ranged from 0.9 to 2.0 times greater than the actual annual demand.

A large range (1,640 to 3,302 kWh) of actual measured gas consumptions were also obtained from the six identical monitored flats. All six flats were identical in terms of construction standard (CfSH Level 4), floor area (80.5m^2), orientation (South East) and building services installed (Combination boiler for space and hot water heating).

This finding demonstrates that the extent of the performance gap observed is also the result of other factors, which do vary between the flats, such as the occupied period, number of occupants, occupant behaviour (e.g. thermostat settings, heating duration, proportion of the dwelling heated, hot water use, window and external door opening, etc.) and possible building defects introduced during the construction stage, in some but not all of the flats (e.g. thermal bridges, missing or reduction insulation, reduced air tightness, etc.).

As a result of temporal variations in these other contributing factors, particularly the occupant related variables, the magnitude of the performance gap is also likely to vary from month-to-month and year-to-year, Therefore, it could be expected that exactly the same flat with different occupants residing in it (for example due to a house sale), may well result in a greater or smaller energy performance gap. In the current study, only annual predictions and measurements of gas consumption are analysed but further future research will move to a higher monthly temporal resolution for analysis, which will allow more detailed investigation of the variations in magnitude of the performance gap throughout the year.

Annual electricity consumption

Regarding the predictions and measurements of annual electricity use (Figure 6), again, both Type 1 and Type 4 performance gaps were evident.

Contrary to the predictions of annual gas consumption, the normative SAP calculation and mean of the seven transient DesignBuilder models under predicted the measured mean annual electricity consumption. This is the typical energy performance gap identified in previous research, where the more energy was used than predicted.

The electricity consumption provided by the normative SAP calculation was 0.5 times lower than the measured mean annual electricity consumption and the mean of the seven transient DesignBuilder models were 0.8 times lower.

Overall, the transient DesignBuilder simulations provided a more accurate prediction of the actual electricity demand than the normative SAP calculation. This result can be explained by the fact that the latter prediction method does not include 'unregulated loads' (i.e. not controlled by Building Regulations), such as electricity consuming equipment (e.g. electric showers, secondary electric heating), appliances and cooking, whereas the DesignBuilder simulations can include these additional electrical loads.

In spite of being able to include these unregulated loads in the DesignBuilder simulations, the under predictions of actual electricity consumption identified in the results of this study, suggest that the actual electrical loads related to equipment, appliances and cooking are often higher than assumed by the modellers. This is understandable as information related to the actual ownership and operation of these electrical end-uses is not available to the modeller during the design stage. In fact, the large range (1,243 to 3,582 kWh) of actual measured electricity consumptions obtained from the six identical flats shows the significant effect that variations in the ownership and use of electrical end-uses can have on the annual electricity use.

As previously discussed for the gas consumption, because occupant use of these electrical end-uses is likely to vary temporally, it is also probable that the magnitude of the performance gap for electricity use will vary throughout and between different years.

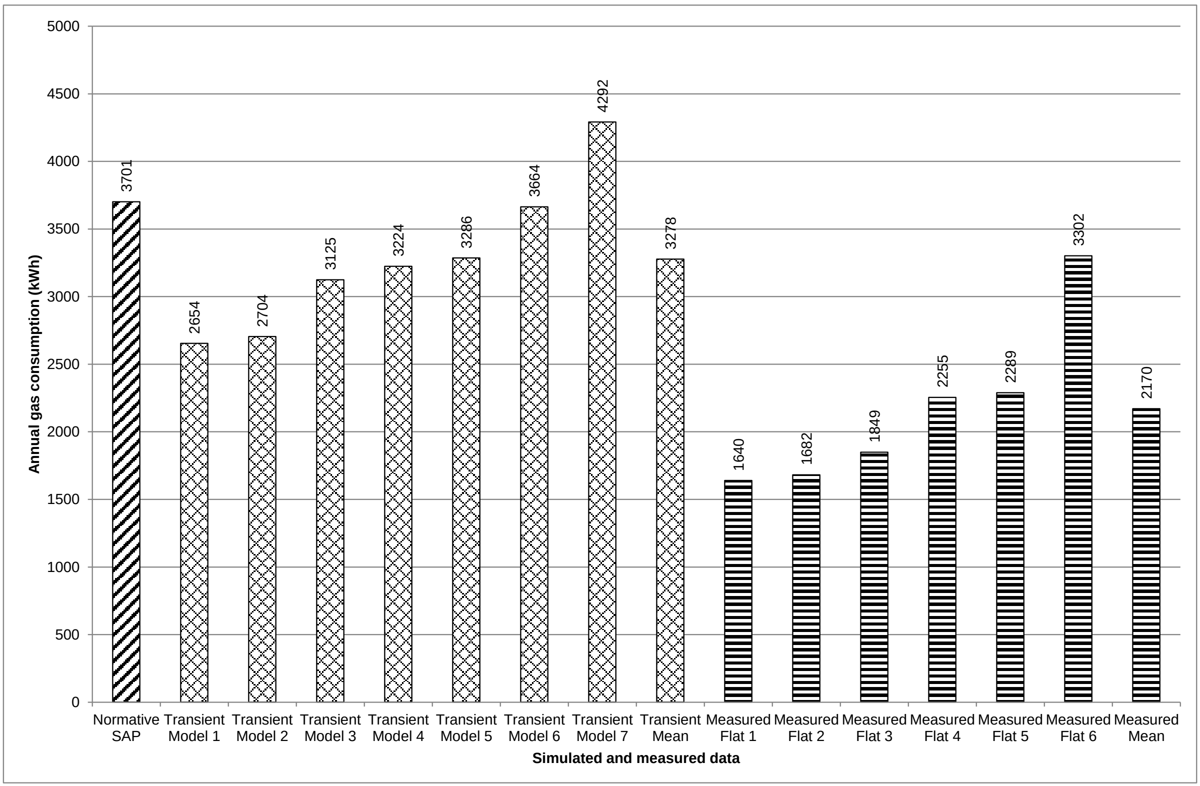

Figure 5 Comparison of simulated and measured annual gas consumption data

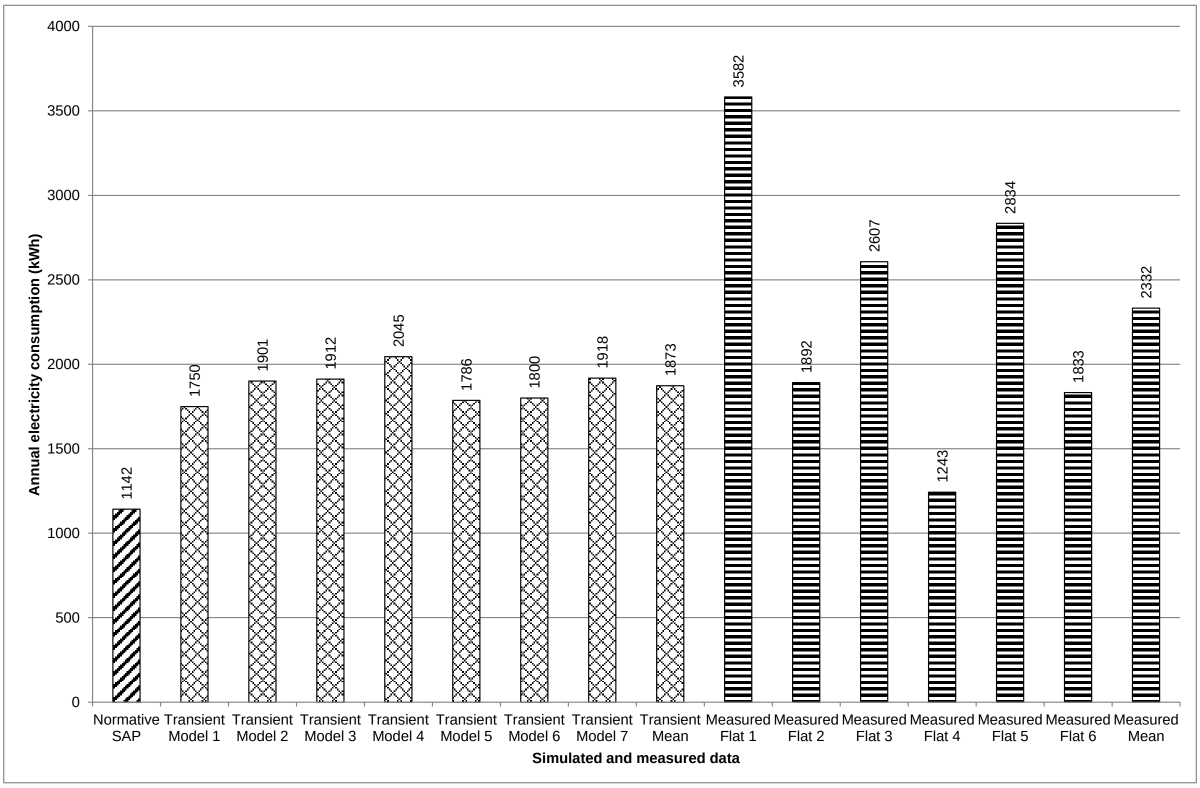

Figure 6 Comparison of simulated and measured annual electricity consumption data

CONCLUSIONS

This paper has reported on a study of the energy performance gap in the UK domestic sector. The key conclusions are:

- A performance gap between simulated (normative SAP calculations and transient DesignBuilder simulations) and measured gas and electricity use was evident.
- The predictions of gas consumption from the SAP calculations and transient DesignBuilder simulations were 1.7 and 1.5 times higher than the actual measured usage, indicating a favourable performance gap, where less gas was consumed than predicted. This is to the authors' knowledge, the first such domestic performance gap reported in the literature.
- The predictions of electricity consumption from the SAP calculations and transient DesignBuilder simulations were 0.5 and 0.8 times lower than the actual measured usage.
- The variations in predictions of gas and electricity consumption from the seven transient DesignBuilder models produced by the MSc students demonstrates the strong impact that the competence of the modellers themselves have on the magnitude of the performance gap identified.
- The range of actual gas and electricity consumptions identified between identical flats shows the impact of design independent factors on the extent of the performance gap, such as occupant behaviour, variation in plug in equipment, etc.

FUTURE WORK

This paper reports on the initial stages of an ongoing programme of research on the case study building which includes:

- Examining the changes in magnitude of the energy performance gap temporally, both month-to-month and year-to-year (the second year of energy monitoring finishes in October 2015).
- Investigating the impact of the individual modeller on the performance gap. What range of different data inputs were used in the transient DesignBuilder models by the seven MSc students when they were provided exactly the same information about the case study building (i.e. drawings and construction specifications) and were told that the flats were occupied by young working couples (occupancy behaviour).
- Producing a calibrated simulation model using a range of additional monitoring data collected in the case study building, including internal and external temperatures, occupancy measurements and window and door opening.

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