Paper No 595: The Sigma Home: towards an authentic evaluation of a prototype building

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Abstract

Offsite construction of housing has generally been developed and tested in terms of physical performance requirements. This paper introduces a combinatory strategy which provides a more complete understanding of the performance of a housing prototype to inform further modification prior to mass production. The paper examines the rationale behind the combinatory strategy and discusses this in relation to the evaluation of a single prototype house built as a demonstration and test site with periodic inhabitation. Each of the contributing evaluation methods is discussed in terms of its effectiveness and issues arising with the experimental process in order to highlight lessons for the development of a more inclusive evaluation of prototype housing in the future.

Overall energy use, associated carbon dioxide emissions, thermal comfort, and air quality within the home are evaluated. The post-occupancy evaluation also includes an assessment of the induction process for living in the prototype home as well as video-analysis of the functionality of the prototype under authentic living conditions. Initial findings indicate that the home provides very satisfactory living conditions with good thermal comfort and air quality. Energy use is higher than expected due to a number of factors, including residents' lack of familiarity with the heating and ventilation systems and lack of airtightness.

Keywords: housing, pre-fabrication, building performance, post-occupancy evaluation

1. Introduction

The work presented in this paper contributes to a developing discussion on how best to evaluate new build housing in terms of its overall performance in order to improve future design. The debate has been brought into sharp focus in the UK through three recent legislative initiatives designed to reduce energy use and associated carbon dioxide emissions. The first of these, the Energy Performance of Buildings Directive (EPBD), requires all housing to provide an Energy Performance Certificate (EPC) when sold. The second is the requirement for all new build publicly funded housing to comply with the Code for Sustainable Homes (CSH). The third is the announcement by the UK government that all new build housing must be "zero carbon" by 2016. At the moment all three initiatives depend on estimated building performance.

Developers have quickly realised, however, that it is also essential to evaluate *actual* performance, given customers' newly informed expectations and the number of buildings that fail to meet building regulation standards when tested [1]. At least one UK association now requires its members to monitor their new developments for two years [2]. The objectives of the research discussed here is the development of a combinatory evaluation process and utilisation of findings to improve a prototype offsite constructed timber frame house before it is rolled out as part of a major sustainable house building programme for a housing developer in the UK.

2. Methodology

Fig 1. Sigma Home viewed from the front

The Sigma Home prototype, developed by the Stewart Milne Group and built in eight weeks as part of the Building Research Establishment "Offsite" exhibition of Modern Methods of

Construction in the summer of 2007, is situated in Watford near London [Fig 1]. The four storey building consists of two semi-detached houses, one of which is being monitored for a year and inhabited for four fortnightly periods (one for each season) by a family of two adults and two children [Fig.2]. It has been designed to CSH level 5 (meaning “zero carbon” emissions for heating and lighting by supplying

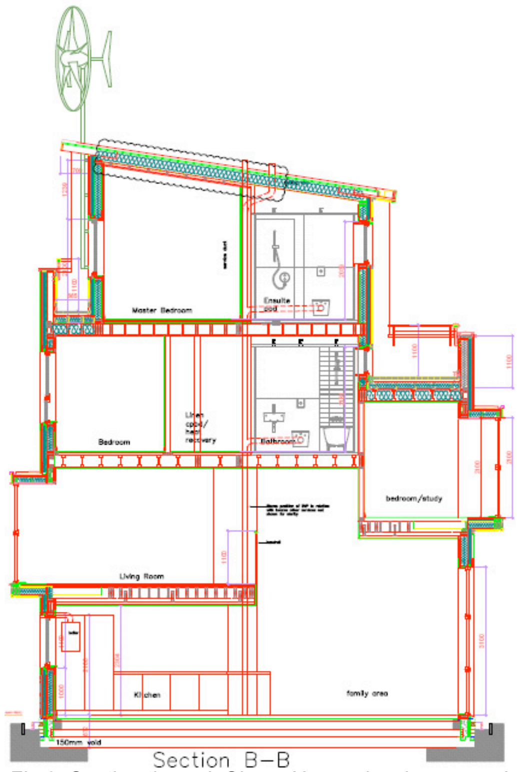

Fig 2. Section through Sigma Home showing open plan

its own renewable energy on site, as well as other sustainability criteria). The home has a designed heat loss parameter of 0.97 W/m^{2}K and includes triple glazed windows, phase-change materials in the internal partitions to add thermal mass to the lightweight structure as well as photovoltaic and solar thermal panels combined with three wind turbines mounted on the roof. The renewable energy is designed to top up the heating, as well as the mechanical ventilation heat recovery unit (MVHR). The total floor area of the home is 116m^2 and the predicted primary energy use for heating and lighting is 85 kWh/m^2/year or 14 CO_2/kg/m^2/year carbon dioxide emissions rate as calculated using the Standard Assessment Procedure (SAP) 2005.
The monitoring process commenced with a co-heating test and then utilised a variety of sensors, and meters recording every minute on wireless dataloggers. All of the information from the monitoring was transmitted to a website. Readings were also taken at the end of the occupancy to determine any noticeable off-gassing in the home using a gas PID portable monitor. The first family occupancy period ran from 6th -20th April 2008, and included a family interview, a review of the induction process and home user guide book, a walk-through and a self-made video by the family. They also completed a thermal comfort survey and weekly log sheets to record any deviation from their normal occupancy patterns.

3. Combinatory Process of Evaluation

The comprehensive nature of the process used to evaluate the Sigma Home marks it out from the usual monitoring and post-occupancy studies that have been conducted for other housing projects. The combination of a wide variety of monitoring techniques with innovative post-occupancy techniques such as video analysis and user induction process evaluation enabled a wider range of factors to be considered when evaluating the prototype. The triangulation of the all the techniques utilised allowed a particularly rich evaluation to be compiled which led to further exploration and deconstruction of the design assumptions made. At the same time, the various innovative techniques used presented a number of challenges in their own right, which are discussed below.

3.1 Co-heating Test and Thermal Imaging

The co-heating technique, pioneered by Lowe et al. [3], involved sealing up and heating the home to a set temperature against a varying outside temperature over seven days to establish the actual heat-loss of the external fabric as opposed to that predicted. The test can only be effectively carried out when a significant temperature difference exists between indoor and outdoor environments, ideally during the coldest months of the year. Initial results indicate a heat loss of 144 W/K which is higher than the predicted heat loss coefficient by SAP (98 W/K), This may be attributed to the real heat loss from the construction and ventilation compared to simplified SAP prediction, although this has still to be verified in terms of thermal bridging calculations and party wall conditions where a thermal bypass may exist.
Major difficulties with the technique included ensuring that nobody entered the building during the test period and taking account of the variations solar gain. The use of thermal imaging during the test period identified significant air leakage around the window frames and under the skirting boards as well as several cold bridges at complex junction points [Fig.3]. These were particularly visible due to the high temperature difference between inside and outside of the building.

3.2 Wireless Monitoring

The wireless monitoring promised several advantages: providing continuous data remotely, being discreet and not disturbing the building fabric unduly. 24 window sensors were set up to transmit back to a central data logger under the stairs, which was also configured to pick up various other sensors and all the meter and circuit readings. 55 individual monitoring channels were set to record initially.

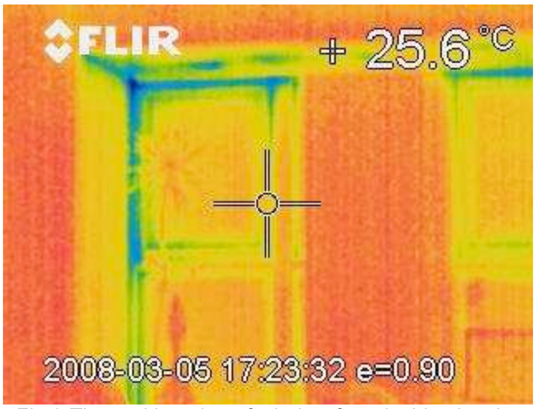

Fig.3 Thermal imaging of window from inside showing air leakage

In reality, a number of the window sensors failed to report, weather station data was lost during a storm and some of wireless transmitters re-assigned their settings during the monitoring. Assigning the electrical circuits and achieving accurate definition also proved more difficult than anticipated because some wiring had not been carried out as planned. Difficulties arose because the home was built initially as a display home rather than a research prototype which would have allowed equipment and wiring to be pre-installed and tested more logically. For future applications, it would be advantageous to introduce the monitoring specialist as part of the sub-contractor team at the pre-production design/specification stage. At the current stage of development, the robustness of the wireless network itself presents the greatest challenge in terms of the monitoring equipment.

Because of the difficulties with the wireless monitoring, the results from it have to be treated with a degree of caution, but early indications are that while the overall primary energy consumption is greater than anticipated (191 kWh/m^2/year for all energy, including appliances), the water usage is within the 80 litre per person per day set by CSH5. The average air temperature in the home varied from the coldest bedroom (east) at 19.3^{o}C to the warmest central bathroom at 21.7^{o}C, with a peak of 24.9^{o}C in one of the bedrooms (east). This first seasonal range of internal temperatures contrasts with the average design temperature for the home of 18.5^{o}C. The average relative humidity in the different rooms varied from 40% to 47%, which is in the range of the normal comfort levels of 40-60%. The carbon dioxide levels internally were an average of 479 ppm with a peak of 588 ppm, which is comfortably within the health limit of 1000 ppm for good ventilation rates. The spot monitoring for off-gassing from materials within the home indicated nothing abnormal.

3.3 Thermal Comfort Survey

The thermal comfort survey was based on an established methodology developed by Nicol et al. [5]. All the family completed the thermal comfort sheets provided. 232 samples were received in total. The globe temperature sensor did not report, meaning that only the indoor air temperatures could be used for comparison. The air movement sensor was functioning, but little air movement registered where it was positioned on the balcony next to the living room on the first floor. The early indications are that the occupants are generally very satisfied with the thermal condition of the house, with the highest number of votes in the category of "comfortably warm" [Fig.4].

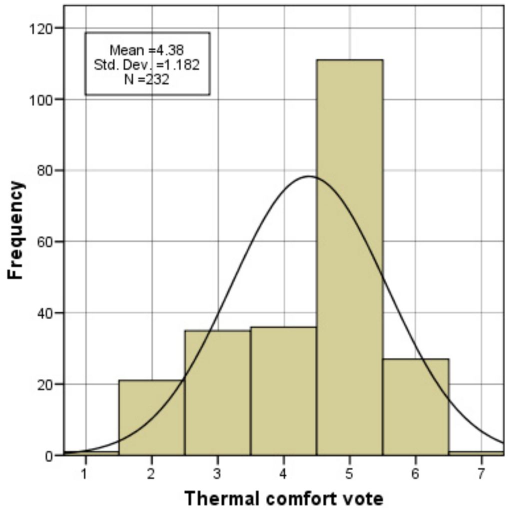

Fig.4 Occupants thermal comfort level (1. Much too cool, 2. Too cool, 3. Comfortably cool, 4. Comfortably neither warm nor cool, 5. Comfortably warm, 6. Too warm, 7. Much too warm)

This finding would appear to contradict the comments made by the family in both the interview and video about the bedrooms being too warm. It demonstrates that the interview process highlights memorable extremes whereas the thermal comfort survey provides a more reliable overall measure of average comfort over time. The thermal comfort survey is also useful for revealing the adaptive behaviour of occupants, who most frequently only wore one layer of clothing in response to the warm temperature of the home [Fig 5].

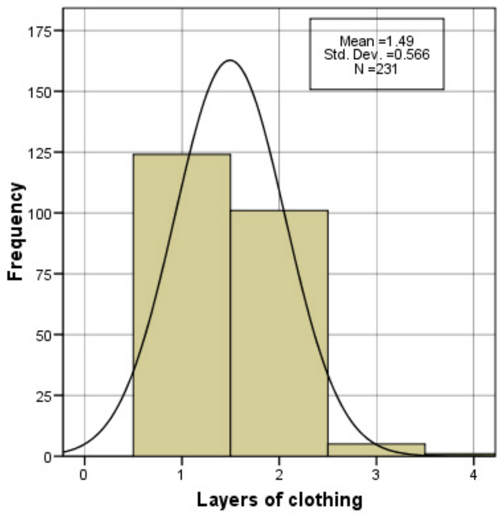

Fig. 5 Layers of clothing worn by occupants

3.4 Logsheets, Interview and Walk-through

The perceptual evaluation techniques used in this study were deliberately designed to compliment and inform the physical monitoring process. The log sheets were completed each day by the mother and these provided insight to the monitoring data by recording any exceptional activity. It was noted that the family, who were sports orientated, made exceptional use of the washing machine because of its relatively small size. They also opened the windows much more often than they usually did in their own home.

The interview in the home with the whole family at the end of the occupancy combined typical satisfaction survey questions on appeal, liveability, flexibility, space standards and maintenance with more detailed ones on comfort and control typically used in post-occupancy evaluation (POE). The interview was digitally recorded and transcribed into notes afterwards. This process was particularly useful for gleaning the reasons behind the monitoring results. All members of the family complained about the bedrooms being too warm at times and feeling unable to do much about it apart from opening the windows. They had very little understanding or control over the heating and mechanical ventilation systems. At the same time, the home was felt to be very comfortable and spacious, providing an excellent quality of day lighting and artificial lighting.

The walk-through after the interview revisited some of the issues already raised but also identified further issues with the home. This involved the interviewer visiting each area of the home and allowing the family to comment on positive and negative features as they saw them and recording this. This is a very useful technique for highlighting small details which may not be recalled during an interview or questionnaire. It also allowed diagnosis and discussion to take place around a particular feature. An example of this was the poor design of the MVHR and room thermostat control dials which showed no indication of what the numerals on them related to (e.g. 1 = hot or cold, boost?) and left the family puzzled.

3.5 Use of Video Recording

The use of video recording was particularly successful and captured why features did or did not work well in a highly visual way. It also helped the family to articulate hidden needs that were not explored in the interview and walkthrough, because it put them in control of the investigatory process. One example of this showed the youngest child going up to a window and describing the pleasure of being able to see through it because of the low cill. It also allowed the family to spontaneously record events as they occurred. The irritating noise generated on the window cill by a loud water drip from above could only be captured this way. The video illustrated the close proximity of the cooker to the smoke alarm, resulting in more opening of the windows to stop the alarm going off every time cooking took place. This led to an uncontrolled loss of heat from the home. It was also used to record the area where the greatest heat differential was felt in the home and helped to diagnose a major overheating problem due to heating pipes not being lagged. Videoing is a technique more often associated with industrial design ethnography [4] but has wide potential in the POE of housing. .

3.6 Induction Process Evaluation

An important aspect of evaluating a prototype home is the degree to which the user is familiarised with its functionality *prior* to occupancy. Evaluating the customer induction process itself is particularly critical for housing developers adopting new technologies because of the significant influence the process can have on effective user interaction subsequently. The family were shown around the home by a representative from the housing developer who was not completely familiar with the complex heating, ventilation and lighting technologies. The tour was logical and a good general overview of the home was provided with clear explanations. However, a significant amount of time was spent describing the more straightforward items such as windows and kitchen units, while the more complex items such as lighting and heating controls were glossed over by referring the user to the induction guide book. The family were not given the opportunity to try out the various features for themselves which might have aided their understanding.

The home user guidebook was issued to the family prior to occupancy. Although it was clearly written and relatively straightforward, the guide book tended to utilise generic information extracted from manufacturers manuals and failed to adequately contextualise these for the particular home the family were occupying. This resulted in confusion as guidance was given in some instances on technology which was not in the home. In the event, the family did not use the guidebook but tended to rely on a trial and error process to find out how features actually worked.

While this worked for the more familiar domestic items such as the cooker and washing machine, the family did not understand how the heating ventilation and lighting systems worked even at the end of their two week occupancy period.

4 Discussion

4.1 Monitoring .v. Post-occupancy Evaluation

The methodology for building performance evaluation has matured over the last twenty years with the recognition that physical monitoring and user behaviour/perceptions are both essential components of the evaluation process. The debate lies in the degree of emphasis and validity placed on each component and the robustness of the methods used. Building scientists tend to favour the former with minimal input from users, whereas social scientists tend to favour the latter with relatively little attention paid to physical monitoring. The best evaluations tend to combine quantitative and qualitative aspects and there is now a portfolio of techniques available for most building typologies [6]. This is not the case for sustainable housing in the UK, however, where the emphasis is tending towards physical monitoring as a priority in an attempt to rapidly address the deficiency of evaluation methods in this area [7]. Resident perception, understanding and interaction with features has a significant effect on energy use in the home, as shown by their willingness to adapt to temperatures higher than those designed for by wearing less clothing and being "comfortably warm" generally. This was achieved however by excessive opening of windows leading to uncontrolled heat loss. The inability of the residents to operate the heating and lighting equipment properly due to lack of understanding also contributed to high energy use. At the same time, the residents are one of the most sophisticated and sensitive instruments we have for evaluating housing performance, as evidenced by the rich findings of this study using multiple methods of user evaluation. This suggests a need for more authentic domestic building performance evaluation methodologies that takes the resident into account in a manner that directly reflects their experience alongside any physical monitoring.

4.2 Prototype Evaluation .v. Post-occupancy Evaluation

Domestic building performance evaluation generally takes place after completion, with modelling and informal tacit knowledge used to estimate performance during the design process. Although there have been attempts to introduce feedback as part of the design process in various sectors [8] this has not extended to employing people to "test drive" a physical prototype of the building during the design process for the obvious practical reason that most buildings are one-off designs and this would be prohibitively expensive. Housing constructed offsite, however, is a product produced on an assembly line, much like a car. To this extent, it becomes possible to test a housing prototype using real occupants for a short period of time to flesh out any operational design issues that cannot be anticipated by modelling, or tacit knowledge. This pre-construction approach has several advantages over the post-occupancy approach. The specific feedback from the process can be used directly to re-engineer the particular product. The evaluation process itself can be tailor made to focus on issues which are pre-occupying the design team. The process can also be contained within the factory site or a designated construction site, with minimal outside interference.

At the same time, there are also pitfalls with the prototype evaluation process: it is difficult to mirror reality for a short period of time, the occupants are in a heightened state of awareness which may bias findings and there are additional costs associated with recruiting occupants to test drive the building, rather than simply asking people who already live in their home to evaluate it. On balance, however, the interrogation of physical prototypes of housing by a user prior to production would seem to be a sensible way forward.

4.3. Refining the Research Design

The combinatory process of evaluation outlined here raises the twin issues of data-overload and redundancy. The physical monitoring was sampled every minute to try and capture precise changes in use and took significant time to analyse. In time, as with non-domestic POE studies such a PROBE in the UK, it should be possible to identify the "killer variables" [9] for housing design and commissioning and focus on these for future evaluation. The use of the interview, walkthrough and video techniques involved a degree of replication of the findings, although the different time modes of these three techniques also revealed different insights associated with each mode e.g. the video showing direct experience and the interview relying on past memory. The interview technique also complemented the video because the former is semi-structured while the latter is completely open in terms of response. This allows the research to cover familiar territory in the interview but open up new areas of interest through the open response. It is debatable whether all three techniques need to be used at once for POE, but for examining prototypes there are definite advantages in triangulating the findings from these methods.

The use of a thermal comfort survey alongside these techniques partially addresses the problems raised by Roaf and Nicol [10] in relation to the retrospective nature of POE studies which fail to address people's perceptions as and when they occur and the ensuing adaptations that take place over time. The use of video also partly overcomes this "partial memory" factor in relation to people's identification of other functional successes and failures as these can be captured in the moment.

4.4 Ethics

This study is unusual in that a family were effectively living on a test site rather than in their own home and raises a number of additional ethic issues. In many non-domestic POE studies no consent has been necessary as the completion of a user questionnaire has been deemed as consent, and any other physical information has been obtained from the building manager or owner. Housing is a more complex and intimate area, however, and it is important that the research design follows an ethical procedure which ensures that privacy and dignity are maintained. The more intimate the techniques are, the greater the potential for violation of these rights. This is particularly the case where families with children are involved and video or walk through techniques are being deployed. When recruited users are living in a prototype that is not their own, extra care has to be taken with the recruitment process itself to ensure there is no bias in the selection (e.g. using employees associated with the prototype) and that all health and safety factors have been taken into account as far as possible. For this study, the research design was presented to a University Ethics Committee for guidance and approval.

4.5 Cost Effective Evaluation

In this study, a family of four occupied a prototype home for a full fortnight and will do so for each season over a whole year, which is an expensive proposition for a housing developer. It may be possible to reduce this to a week for the Winter and Summer seasons, to capture the extremes over a six month period, but any less will not capture the weekly routine of living or the seasonal variation, which are seen as the strongest pattern indicators for home living in relation to energy use. It may also be possible to build the prototype within a large climate chamber in order to rapidly test different seasonal regimes, although this type of accelerated testing cannot fully mimic the natural processes that take place over longer periods of time, such as shrinkage, thermal storage etc. It is also difficult to know how temporary occupants would respond to this.

5. Conclusion

This paper has discussed a variety of techniques for use in the building performance evaluation of housing in a study that has attempted to develop the use of POE and monitoring methodology in the pre-construction phase. The data itself is still subject to verification after the overall research is completed. The initial findings show, however, that the combinatory method outlined has distinct advantages over more traditional POE and monitoring methods but is still very much in the development stage, given that evaluation in housing is still relatively undeveloped. It is clear that for both mass new build and mass retrofit housing, the testing of a prototype by users in addition to physical monitoring has distinct advantages. Given the demands of new policy drivers in housing in response to climate change, design is changing rapidly with the use of innovative materials, planning, energy technologies and construction techniques. This makes it imperative that potential housing products are tested in authentic life-like conditions prior to mass production if we are to avoid the mistakes of housing that took place in the 1960's in terms of the user interface with the technologies. One of the key findings from this study so far is the need to evaluate the proposed user induction process as much as the proposed building itself. Findings will be taken forward in a proposed research project situated in a 353 unit "Sigma Village" as part of the developer's next steps in taking their product to market.

6. Acknowledgements

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