THERMAL PERFORMANCE OF BUILDINGS AND THE MANAGEMENT PROCESS

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From the limited information that exists on the thermal performance of dwellings there is growing evidence of a significant gap between that which is predicted and the built product. Such differences between the intended and actual measured performance are not accepted nor tolerated in other industries. The differences in the performance can be considerable, with some buildings experiencing deviation from designed thermal transmittance resulting in twice the heat loss expected. This does not bode well for the industry when new dwellings are expected to achieve zero carbon standards by 2016. Although some of the problems are related to inadequate design, many are attributable to construction processes. Using the technical reports and feedback from researchers engaged in forensic investigations of building performance, this paper presents some general observations and some re-occurring problems associated with the management of the construction process. Specific areas of concern include the interface between design and construction, sequencing and planning of works, quality of workmanship and build, and lack of quality control systems. Due to current environmental and energy concerns, emphasis has been placed on improving the efficiency of the building system to ensure the gains expected are delivered. Much of this relies on the production of quality building fabrics that provide passive solutions, which maintain thermal comfort and reduce the level of service intervention.

Keywords: building quality, coheating tests, thermal performance, workmanship and zero carbon standards

INTRODUCTION:

Producing Zero Energy buildings

Meeting the standards set across Europe to deliver low and nearly zero carbon buildings is not going to be easy. The building stock in Europe is substantial, with 22 million homes in the UK alone (CLG, 2011a). And although recent production of new homes has fallen from the 2009-2010 output of 128,689 to 121,200 units during 2010-2011, the production of 120,000 units per year in the UK is substantial (CLG, 2011b; UK Statistics Authority, 2011). Thus, any changes to individual elements of the new building stock can have a significant impact on CO_2 emissions and energy consumption. For example, by reducing the party wall heat loss to values close to zero giving savings in excess of 10,000 tonnes of CO_2 per annum are not unrealistic. The party wall research and observations by Lowe *et al.* (2007), Wingfield *et al.* (2009; 2010) and general observations by the CeBE group reports would suggest the

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reductions in CO_2 could be much greater (LSi, 2012). Achieving zero carbon in reality means heat loss mechanisms need to be identified, accounted for, reduced or eliminated.

Identifying the less obvious areas of heat loss and close the gap

It should be noted that the areas of significant heat loss are not always obvious; prior to the discovery of the party wall bypass the general assumption was that heat energy was not lost within or through the party wall. Thus, the recognition of unknown heat loss mechanisms can significantly reduce the energy required to heat the building. Furthermore, producing buildings to enhanced thermal performance standards without knowing the building's actual ability to resist heat flow is like using a bucket for carrying water without checking if it leaks. It is essential that heat loss mechanisms and building behaviour are properly understood, if buildings are to be produced that perform.

The general nature of the building fabric remains relatively unchanged for most of the building's life. Thus, improvements to the building fabric have greater longevity than most other energy saving measures. As long thermal barriers perform, the savings are continuous, operating throughout the building's life. Thus, it is important that the building actually performs.

Underperforming buildings will only achieve desired thermal comfort by consuming more energy than expected. Currently, the additional costs due to underperformance are transferred and accommodated by the consumer. Although, the enhanced energy efficiency measures, that are now promoted when selling buildings, must be changing client expectations, the complaints about a buildings actual ability to reduce energy demand have not yet manifest. The 'grand designs', which stress the importance of thermal performance, must be also be contributing to the general awareness of how buildings should or could perform. It cannot be long before the public ask whether there buildings are working and question whether they have been given what they have paid for. It is questionable whether the industry can offer 'energy efficient buildings' if few of the designs are tested to see if they work. If the industry is to adhere to its own low and zero energy mantra then there is much work to do to ensure performance is achieved in practice. Building designs should be tested to ensure functionality is achieved. Quality control systems should be extended to cover thermal performance and feedback mechanisms introduced to improve building standards and ensure client satisfaction is achieved and maintained. The aim of this paper is to highlight some of the reoccurring construction problems encountered that affect thermal performance.

AS-BUILT PERFORMANCE AND MANAGEMENT

Generalising about the building stock can be problematic with dwellings varying in age, design, size, characteristics, components and materials to name just a few factors to consider. Whilst there is much to learn about the building stock and the effects of the different factors, there are some overriding issues that can affect buildings, almost regardless of type and design. The management and control processes are known to influence the nature of the building product and the way it performs (Fryer, *et al.* 2004). While there is considerable focus on the design of low carbon buildings relatively little attention is being placed on the processes necessary to realise the low carbon product, with some very noticeable consequences.

Figure 1 shows some of the studies conducted by Leeds Metropolitan University over a six year period. The seminal work that emerged from Lowe, Bell and Wingfield (Lowe, Wingfield, Bell and Bell, 2007; Zero Carbon Hub, 2010) has developed into a growing body of evidence of underperformance.

The team have now conducted more than 40 co-heating tests on 25 individual buildings to determine actual thermal performance of the dwelling compared with that intended. Most of the tests are on new builds, however in some cases multiple interventions were introduced to existing buildings, with performance tests before and after the change in order to determine the effectiveness of the change.

The graph below shows the results of 33 tests (conducted on 21 individual properties), identifying the percentage difference between the intended performance and that measured using the coheating tests. In the studies of new build and modifications to existing buildings the research team were able to observe the construction process and consult with site operatives. Thus, the feedback from those directly involved in the management of the construction process and the observations from site visits were useful in identifying potential contributions to difference in performance. While, it is not possible to determine the extent that the process contributed to the variation in performance, what is apparent is that the actions, changes and events on site are directly linked with performance.

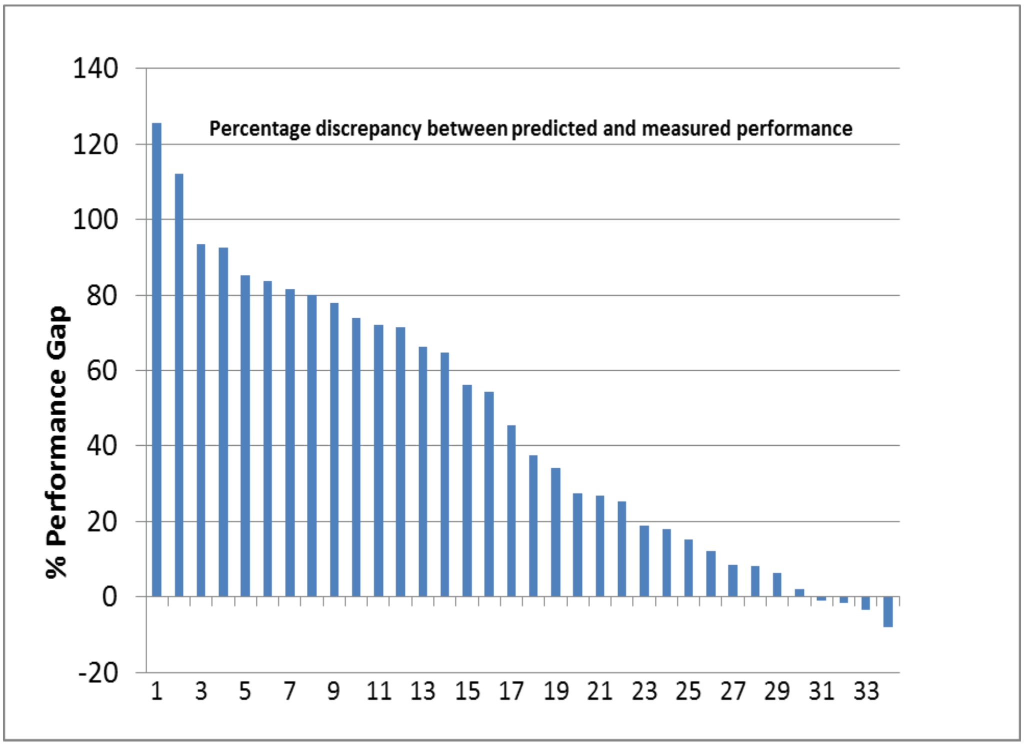

Figure 1. Whole House Heat Loss data – Percentage discrepancy between Measured and Predicted Heat Loss (built on the initial data set reported in the Zero Carbon Hub, with additional tests 2010; Stafford et al. 2012b. 21 individual buildings studied)

Supporting Information for figure 1

Calculation of designed (intended) heat flow
The predicted thermal performance of the fabric uses the summation of all the heat transfer mechanisms in the building (thermal transmittances together with thermal bridging and unwanted background ventilation losses).

Calculation of actual heat loss coefficient
The coheating test determines the actual heat loss through the structure. This is achieved by heating the internal environment to an elevated temperature and maintaining the temperature at 25^{o} C. As the external temperature changes, the power required to maintain a stable temperature is adjusted. As the outside temperature drops more energy is required to heat the dwelling and as the outside temperature rises the energy is required. By monitoring the 'power in' against temperature change outside, the heat transfer through the building can be calculated. Losses due to ventilation, heat gains from solar and variations due to the wind are also considered within the calculations.

The results represent the culmination of many observations and tests. While these tests provide measures of heat flow as well as the difference between intended and actual performance, much more information can be gained from the studies. To understand the reason thermal performance is higher or lower requires investigation of designs, supporting documents and photographic evidence. For example:

- Records of changes, component assemblies and construction operations are important.
- Exploring the differences between the design and that built on site is essential to understanding the deviation in performance.
- By pressurising and depressurising the building under heated conditions, at the same time as undertaking thermographic surveys helps to trace and identify air movement, circulation paths and cold bridges.

When results are obtained for designed and actual performance, a forensic investigation can be undertaken to explore differences found. The information supporting each project is considerable and necessary to understand the building's behaviour. While the focus is on the measured level of building performance, clearly the observations provide much supporting data about the construction shortfalls.

Extent, representative and useful nature of performance data

It is noted that concerns have been raised over the sample size of the Leeds Metropolitan University (LMU) data (The Futures Group Think Tank, 2012). Although the reports from the Leeds group make no claim over the representative nature of the research, the Think Tank in their criticism provide an interesting observation, "this [LMU] sample relates to only 0.0064% of the housing stock constructed…", it would appear that the Think Tank is critical that such a small sample is influencing Building Regulation. Unfortunately, the work of Leeds Metropolitan University is the only sizable unit of information that the industry has with regard to the actual building fabric performance. However, the knowledge that so little research has been undertaken should be of concern for such a substantial industry, especially considering the contribution that the built environment makes to CO_2 emissions (the built environment accounts for 40% of the UK's CO_2). Failing to test or gather a representative sample, when 120,000 units roll out each year, is of considerable concern, especially when such high expectations are aimed at the industry with regard to reducing emissions.

Tolerance and control

Looking at the percentage difference from that intended to that achieved and the distribution (Figure 1), the results show that few of the tests on buildings are within +/- 15% of their intended (design, specified or expected) criteria. For commercial reasons, a low tolerance threshold is always preferred by industry, but is only gained by good quality control in both design and management. The figures in excess of 40% deviation from the standard designed are unacceptably high, yet this represents most (12/21) of the buildings studied (21 individual buildings were tested). If companies claim to provide buildings with specific performances, but know that their standards vary, the deviation needs to be considered and an element of over design or thermal tolerance should be introduced. The accepted tolerance would need to be added to the design to ensure the operational standard is achieved. Such tolerances will incur additional costs. However for the industry to operate efficiently and economically, it should attempt to meet the targets without over specification.

Although the government targets for low energy buildings are incremental they are very ambitious, especially since the evidence, however little, of buildings meeting less stringent targets is not good. The work of Bell *et al.* (2010) found that buildings constructed to 2002 and 2006 Building Regulations failed to achieve the requirements. The statutory regulations have significantly advanced yet little has been done to improve construction and control the process. Although many zero carbon prototype buildings exist, a serious concern is that most of the buildings remain untested (Bell *et al.* 2010), as the Think Tank suggest less than 0.0064% of buildings are tested. At best, buildings are limited to the laboratory information that is supplied with the building components, and although useful, the tests of materials in isolation do not reflect their performance when assembled (Hens *et al.* 2007). For buildings to operate effectively, the construction process should be managed and products must fit and function together to produce a building system that performs as specified.

RESEARCH METHOD

This paper reports findings of projects conducted by the Centre for the Built Environment research team at Leeds Metropolitan University. The information available on each project was reviewed and information from the researchers operating on the projects was obtained. The technical reports provide additional information to that reported in the academic journals and published research. A review of the reports with specific consideration to the points associated with the management process were considered. The technical reports and relevant links can be found on the Leeds Sustainability Institute web site (LSi, 2012), in addition to a review of the technical reports further information has been gathered through discussion with the research teams. The review provides an observation of the findings and re-occurring themes that would not otherwise be available. A further more detailed review of such information is also encouraged. This would become increasingly more important as more technical reports emerge from the Centre and the results from Technology Strategy Board's Building Performance and Evaluation Programmes.

FINDINGS AND RESULTS

The key observations from the reports relating to issues associated with the management of the design and construction processes are listed in Table 1 below.

Table 1: Thermal Performance: Management, Inspection and Supervision Issues

Problems with design and sequencing of operations

Issues identified which could have been rectified by correct installation or inspection

- Insulation was displaced or incorrectly fitted due to obstructions, such as debris, or protrusions through the fabric, such as vent and service penetrations. Where rigid partial fill insulation was used it was pushed off the surface of the wall creating voids around the insulation, allowing free flowing air. With changes in weather, internal environmental conditions and other phenomena that affect air pressure, the movement of air and heat energy bypasses and circumvents the insulation.
- Failure to inspect and correct errors
- There were a number of notable observations that could have been picked up by inspection. These included mortar build-up over fabric penetrations such as vents and between insulation causing continuous cold bridges.
- Debris was allowed to build-up resulting in discontinuity of insulation. The obstructions meant that there were gaps in the insulation. The irregularity of the surface to which the insulations was placed against prevented a close fit.
- Insulation was not fitted under and between some joists. Construction interfaces, that required cuts to the insulation to ensure a complete covering were often overlooked or poorly fitted.
- Gaps were found in party wall cavity socks thus failing to provide an effective continuous seal.
- Some of the insulation was simply not placed properly, not butted up together and not built up to the correct thickness.

Planning and sequencing

- Air, moisture and vapour barriers were installed and then punctured to put services through them, effectively removing the ability of the barrier to function properly. Failing to re-seal the barriers allows air movement within the fabric. Uncontrolled air movement leads to thermal transfer, bypass and moisture movement within the fabric.
- Insulation was sometimes removed to fit services. Once the services were installed the insulation and barriers were not properly reinstated.

Design control and interface management

- Some designs were complicated and difficult to build and due to these difficulties a poor end product was produced.
- Modification were sometimes made to the design. Changes to that which was specified sometimes had the effect of increasing or decreasing the size of components. Fitting components with different sizes to that specified meant they were either too small, resulting in gaps, or too large needing to be cut.
- Air barriers and vapour control layers were sometimes fixed in the wrong positions making them ineffective. The interface between the air and thermal barrier is important.
- In some cases instructions were not provided on how to seal barriers around fittings, penetrations and junctions. Folding and layering of building fabrics, such as vapour barriers, is problematic. Multiple layering to make up joints around corners and junctions needs some thought to make an effective seal without excessive build up.
- Incorrect use of tapes and sealants was common, specialist tapes are needed for different surfaces. Some jointing materials may need pressure between materials to make them effective.
- Pressurisation tests and smoke puffers revealed gaps around RSJs and service pipes.
- Loft hatches were sometimes specified and used that did not effectively seal.
- Services were positioned too close to the wall making it difficult to seal behind them.

- Services that were hidden or boxed-in were rarely sealed.
- Often the penetrations made to house some services become inaccessible once the main piece of plant is installed.

Workmanship

- Mortar beds were not filled and the gaps in the fabric were sometimes not sealed.
- Parging was often only applied to open easy to access faces. To provide an effective seal the parging should extend across the whole surface providing the air barrier, including behind fittings such as, stairs, partition walls and services.
- Sealants were applied at surface level rather than properly fed into the gap.
- Incorrect lifting and moving of structurally insulated panels caused damage.
- Incorrect expansion strips were sometimes used, making an ineffective seal.
- Junctions were not sealed. Points of air-leakage and infiltration were found around thresholds, windows and doors, between frame and breather membranes, around and through roof lights, roof panels, at the ridge, eaves and between roof panels.
- Air leakage was found around light roses, electrical sockets and other service fittings.
- Air leakage occurred through flooring panels that were damaged and poorly sealed.

EVALUATION

Many of the observations relate to a failure to deliver the work as specified or provide the necessary information, instruction and checks to workmanship. Construction works should be planned and sequenced to ensure thermal performance. To deliver building products that are thermally efficient requires a level of understanding of thermal performance that is currently overlooked in many aspects of construction practice. If developers and contractors are producing multiple units a quality control system which checks to ensure thermal performance complies with that specified should be used, such practice is common and regulated in other industries. Quality systems must be capable of checking that the performance specified is achieved. Once there is confidence that a building can be delivered to specification, sampling and control checks should be used to ensure the processes are working, where deviation occurs information should be fed back to enable correction. To improve the product new and existing knowledge should be fed to and through the team. Figure 2 provides a simple control and improvement loop for feeding information in and controlling the process. It is surprising that an industry of such scale does not employ such measures; however, the draft proposals for the next revision to the building regulations propose a ‘Publically Available Specification’ or an equivalent Quality Assurance scheme. It will be of public and economic interesting to see that the industry embrace this.

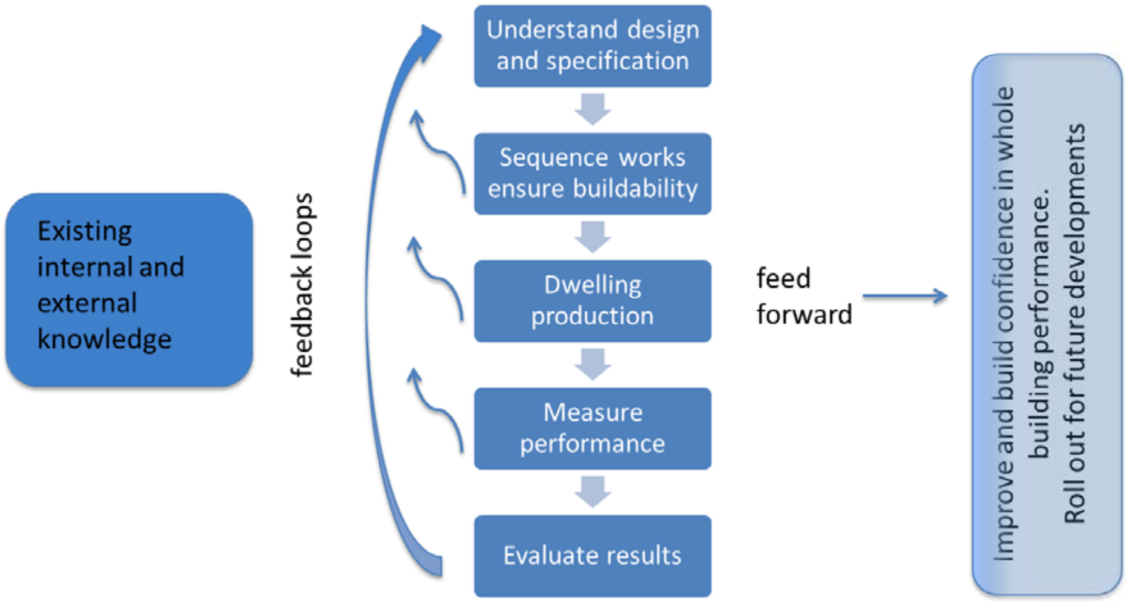

Figure 2, Improving building performance: A simple control loop

SUMMARY

The work has revealed problems with the design and construction processes and the sequencing of construction operations. Where the design information is incomplete or the design process overlaps with construction and change management is not used to control alterations, the building product is susceptible to performance deviation. As few buildings are tested for performance and compliance the profession has little information on the nature and extent of such problems.

Many of the problems observed are occurring in many house types studied and on different sites. The observations seem to suggest that where construction becomes complicated insufficient attention is given to design and construction processes. In some cases design issues are not resolved meaning that the site staff make the decisions regarding selection or assembly of products. Ad hoc decisions that are not properly informed by relevant expertise will have an effect on thermal performance. The results shown would tend to suggest that uninformed decisions are having an adverse effect on performance. The unstructured assembly of different components causes problems and there is evidence that function and fit of components is not being achieved. At each material interface the design needs to be examined and the process and sequencing of operations must be considered.

Training is required to ensure the industry is informed; however, further research is required to ensure that an informed knowledge base is developed. Emmitt and Gorse (2003) suggest that professionals generally select products from their favourite set of products, those which are tried, tested and previously used. We are entering a new arena where building performance needs to be considered differently. Currently, construction professionals may be selecting preferred products rather than those that they know perform, as the knowledge on actual performance is very limited. As professionals obtain feedback through effective monitoring, their ability to select and specify should improve. Currently, some details are not possible to build, it is important that such details are questioned so that effective and buildable solutions are found.

CONCLUSION

Low carbon buildings do exist and can be built. The challenge of mass produced buildings, is to provide the right processes to ensure buildings are reliable and consist with the specified standard. Getting the process right requires good management and supervision, as well as understanding issues that need to be considered.

In some cases the industry is attempting to develop low carbon buildings without a real understanding of the construction process and the performance of components used. Due to the lack of research, there is little information available on the thermal performance of the final building, thus little is known with regard to the issues that are affecting the overall performance. A better understanding of components, their assembly, design and the need for improved sequencing of operations is required. Managers and designers are overseeing and supervising tasks that they may not understand, therefore further research is required and the findings need to be quickly fed back to professionals and site staff to inform and improve practice.

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