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Why advanced buildings don't work?

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Abstract

The intent of policy is to achieve robust comfortable low energy buildings. However there are obvious policy disconnects and, where there is evidence, it appears that in general advanced buildings do not achieve their intended performance. There are many industry and policy initiatives aimed at improving industry processes such as: Soft Landings, BREEAM, LEED, Green Star, AGBR and BIM.

In this paper the performance of buildings likely to be promoted by current policy is investigated and a number of significant and recurring problems identified. The possibility that these problems will be resolved by current initiatives is discussed and it is concluded that important gaps remain to be addressed.

Keywords: Building performance, Policy, Advanced buildings, Monitoring, POE.

1. Introduction

There have been a number of historical studies with the aim of understanding building performance which focussed on buildings intended to be low carbon.

In the UK, the 'Probe' studies carried out in the 1990s have informed policy, regulation and technical guidance for professionals (The Carbon Trust, 2001). These have since been extended by the Useable Buildings Trust (UBT) to provide performance targets and benchmark data for both offices and schools (UBT, 2012). Office buildings in these studies are grouped into 4 categories: naturally ventilated cellular; naturally ventilated open plan; air conditioned standard; air conditioned prestige. Naturally ventilated building types best practice and typical energy performance benchmarks are significantly lower than for air conditioned types.

From the Probe and UBT outputs one might have expected regulations to favour naturally ventilated building types. However analysis using the UK Governments regulatory calculation tool SBEM indicates that the performance of air conditioned buildings in future is predicted to be equivalent to that of naturally ventilated buildings: in combination with the higher allowed emissions for air conditioned buildings and additional requirements to be met by non air-conditioned buildings the regulations tend to encourage buildings with mechanical cooling. There does not yet appear to be significant evidence to support this (Tuohy, 2009).

The naturally ventilated BRE Environmental Office (EOF) was designed and built to be an exemplar building. It is widely referenced as an example to be followed (RAE, 2010). Post occupancy evaluations of the building however identified that the energy used was around 90% higher than the expectation of the designers (Ni Rian 2000).

Office buildings investigated in the Probe and UBT studies included the award winning Elizabeth Fry and ZICER buildings at the University of East Anglia (Tovey and Turner, 2006). One of the key recommendations from the studies was that buildings require up to a 3 year 'sea trials' commissioning process to achieve optimal performance. This requirement reflects the fact that the initial performance of the buildings did not meet with expectations.

The introduction of the requirement to display actual energy use as part of the English Governments EPBD driven Display Energy Certificates (DEC) initiative for Government owned buildings over 1000m2 has led to the publication of a database of energy use for public buildings that highlights many disconnects between expected and actual energy consumption (Booth, 2008).

German Government research into performance of exemplar office buildings found many disconnects between intended and actual performance, particularly where new building and system types are deployed and concluded these were common across the industry (Voss et al, 2007).

In Australia the ABGR energy performance rating system (incorporated in NABERS and Green Star) has been in place since 2000 and while this system is based on actual building performance for existing buildings, developers can use predicted performance in their marketing. In 2007 experience of generally poor or no correlation between predicted and actual performance ("Damn Lies and Simulation"; Bannister, 2003) was highlighted.

The above experience was generally based on commercial building types, for domestic buildings there appear to be similar problems and disconnects.

The UK Governments SAP calculation method and the EU Passive House method used on the same dwelling give differences in predicted space heating of 80% (Tuohy, 2009a), and there are large differences in predicted performance of systems such as solar water heaters and ventilation units etc.

The UK Governments Energy Savings Trust (EST) with support from the UK Technology Strategy Board (TSB) has recently begun to carry out 'field trials' to investigate performance of new technologies in dwellings, these involve monitoring performance of systems in operation and reporting on results (EST, 2012). There have been field trials of micro-CHP systems, gas boilers, micro wind turbines, heat pumps, solar PV and solar thermal systems. In general the results have been poorer performance than expected, for example the solar hot water field trial found variations in solar fraction between 7% and 70% across installations, the heat field pump trial found COPs in practice were often 50% less than predicted. These trials while highlighting poorer than expected performance do not provide a clear understanding of the reasons for these disconnects or corrective actions to be taken. Other systems now becoming advantageous within the regulatory calculations have not yet been subject to extensive field trials.

The importance of understanding these disconnects is fundamental to the decisions and processes required to create low carbon buildings. Here these disconnects and root causes are investigated and whether these disconnects are likely to be addressed by current industry initiatives is reviewed.

The approach followed was to:

1. Investigate the performance of buildings promoted by current policy and identify any problems.

2. Review to what extent current policy and industry initiatives address these.

2. Performance gaps for future building types.

To understand actual performance v. intended for advanced building types, a series of investigations were carried out and overall conclusions drawn. The investigations consist of necessarily opportunistic studies of advanced buildings where direct or indirect access to these could be arranged; augmented with a critical review of the work of others. The scope of investigation depended on the situation: in some cases full plans and design documentation was available together with access to carry out physical investigation and monitoring, in other cases there was more restricted information or physical access available.

2.1. The Environmental Office Building, Garston, England

The Environmental Office building is an assisted naturally ventilated (ANV) office building over three floors situated in Garston, England (figure 1). It was intended as an exemplar for future buildings and is still frequently identified as an example to be followed (RAE 2010).

The design intent had been to achieve similar environmental control to an equivalent mechanically cooled building but with energy use 37% better than a best practice naturally ventilated building, (referencing ECON19 best practice standards). The building was monitored after completion and found to perform reasonably well for occupant satisfaction and energy use compared to other office buildings of the time but the energy use in operation (corrected for weather) was reported to be 90% above the design target (Ní Riain et al. 2000).

An exercise was carried out to revisit the building after around 5 years of operation, review its performance, identify opportunities where further improvements could be made, and generalize these findings to other similar building types.

Figure 1. Environmental Office.

There existed a high level building control ‘concept’ document (Stevens, 2000) and a controls manual from the controls contractors (BMSi, 2000). As a first step the concept was reviewed and then the controls manual analyzed. This proved to be difficult due to the complexity of the 84 page control manual with sections on individual control elements but no overall strategy description.

To allow analysis the control manual was mapped into a one page summary document which allowed the controls to be comprehended but also allowed some observations to be made. The next stage of the investigation was to observe the building during operation. This highlighted further issues. Many significant learning points were observed which if acted on would allow reductions in energy use and increased occupant comfort, these should be viewed as further improvements to this exemplar building which had been operating successfully (although not optimally).

Key findings from this exercise are summarized as follows:

1. The controls documentation was poor and not well understood by occupants, building managers or controls sub-contractors leading to changes to fix immediate issues or complaints that then caused other issues.

2. The control implementation was based on a concept design document. The operation of the controls in conjunction with the building, systems and environment had not been specified or analyzed in detail. The controls engineers implemented the controls on a best-guess basis and commissioning was simplistic.

3. The control strategy as implemented was not optimum from an energy consumption viewpoint e.g. mechanical borehole cooling was being applied at a lower temperature threshold than free cooling by window opening.

4. The control strategy did not include response parameters appropriate to the slow response heavy mass heating and cooling elements which reduced control effectiveness.

5. The control system was too simplistic and coarse e.g. night cooling mode was triggered by external conditions at 4pm only. Afternoon rainfall could mean that night cooling would not be triggered despite extremely high internal temperatures and overall high external temperatures. Control of the windows was much too course all windows opened simultaneously once a threshold temperature was reached, leading to drafts, noise and ratcheting.

6. Incorrectly implemented controls of bore-hole cooling led to incorrect operation. Analysis of the hardware showed that a temperature compensation valve for winter heating was still active in the summer cooling mode leading to the boilers being triggered when cooling water flowed and the cooling water being heated resulting in both systems operating to no effect. This had been undetected since the controls implementation during construction.

7. Fault conditions were not optimum. It was observed that pumps were running and gas being used when there should have been no demand for heating. It was found that a spurious fault condition had caused the non-condensing backup boiler and the hot water feeder circuit to fire indefinitely.

8. Building performance and energy use was not generally visible. There was no display other than on the BEMs PC (inside a rarely visited locked control room). The sub-meters had not been correctly implemented, the only visibility on energy use was to the finance department who paid the bills and as the building was generally performing better than typical for the estate no action was triggered.

9. The building pattern of use was different to that assumed in the design calculations (computer energy use higher than planned).

10. To address the issues identified required hardware and software changes to support improved controls and sub-metering. Implementation of improvements was initiated but stalled due to financial and logistical constraints. This highlights the difficulty of trying to resolve strategy, design and implementation issues after building handover when only an operation and maintenance budget is in place. Also the building was tenanted and in full operation with tenants who were not interested in having their business interrupted to allow works to be carried out. Further research was then directed at investigating whether these more fundamental problems were unique to this building or to what extent they were more widespread.

2.2 The Great Glen House, Inverness, Scotland.

To gauge more recent practice a similar exercise was carried out at the Scottish 'Great Glen House' office building completed in the summer of 2006. The building was built to be as sustainable as possible and achieved a BREEAM 'Excellent' score of 84% ("best BREEAM ever") (Carbon Trust, 2007).

Many building features are similar to the Environmental Office building. At the time of the investigation the building was going through the initial post commissioning 'snagging' process and the findings should be viewed in that context. Key observations were as follows:

1. There was great pressure to complete and sign-off the building so that financial milestones could be met and penalty charges avoided. Many of the project team from the design and build phases were no longer formally involved once sign-off complete.

2. There was poor visibility at this time for the operations staff and occupants of the energy design targets or actual energy use for each of the sub-meters provided throughout the building. The building was consuming higher levels of energy than expected.

3. The control strategy was documented in a comprehensive but complex operations manual and was not clearly understood by operations staff or occupants.

4. The commissioning engineers worked to the control strategy developed during the concept design stage which gave somewhat coarse step function control e.g. "when temperature rises above set-point open both the high level office and the atrium windows" which would activate all high level windows on all three floors together with the atrium opening at the same instant. The control strategy did not take into account wind direction and speed in the calculation of window open extents.

5. There was debate between designers and clients as to what areas the design targets should apply to and whether areas such as server rooms were to be included in the building energy use specifications and design targets etc.

6. The BREEAM and best practice guides stated that seasonal commissioning should take place but there was at that time no plan in detail for how this would be approached.

7. The operations staff responded to occupant feedback by altering set-points to fix immediate issues without necessarily comprehending the impact of these changes on the overall control strategy and building performance at other times of the year etc.

Many of the issues found in the Environmental Office were also present in the Great Glen House. Discussions with facilities management and controls commissioning engineers confirmed that working practices especially in the design and optimization of controls had not been addressed.

2.3. City Hall, London, England

City Hall is an iconic local Government building completed in 2002 on the banks of the river Thames close to Tower Bridge. It was designed and is still promoted as "sustainable and virtually non-polluting" (Fosters and Partners 2012). This public building was visited and investigated through review of public domain information.

The buildings energy performance was monitored and it used 376kWh/m2 in 2003/2004 compared to its design target of 236kWh/m2 (Bennet 2005) with the discrepancy stated as being primarily due to being occupied by 650 people rather than the 440 person occupancy designed for. The energy performance has resulted in the building being awarded an 'E' operational rating under the EU Energy Performance of Buildings Directive leading to it being referred to as one of the 'Halls of Shame' (Booth 2008).

This building illustrates again the gap between design intent and actual building energy performance (236kWh/m2 v. 376kWh/m2). Another gap exists between the marketing of the building "sustainable and virtually non-polluting" and its design intent of 236kWh/m2; the 1997 ECON19 good practice level for naturally ventilated office was 112kWh/m2 (Carbon Trust, 2001).

2.4. Elizabeth Fry and ZICER buildings, Norwich, England.

Both the Elizabeth Fry and ZICER office buildings feature prominently as UK exemplars and are well documented (Probe14, 1998), (Ingham, 2010), (Tovey and Turner 2006).

The Elizabeth Fry is one of a number of buildings on campus built using the TERMODECK construction system where ventilation air is routed through cavities formed in concrete ceiling panels, the concrete construction system also provides excellent construction air-tightness of approximately Passive House standards (Probe14, 1998). The ventilation operates with regenerative heat recovery with stated efficiency of 75%. The building in its first year consumed 60 kWh/m2.a electricity plus 70 kWh/m2.a heat from district heating. The facilities are managed very closely and new optimised heating and ventilation control updates were installed after this

first year which reduced the energy for space and water heating to 37 kWh/m2.a., the building has been operating since at about this level (97 kWh/m2.a delivered energy, electricity + heat).

The ZICER building at the UEA campus was designed to use the same TERMODECK construction system as the Elizabeth Fry but has improved insulation e.g. glazing U-value = 1.1 W/m2.a (Tovey and Turner, 2006). The design expectation was that the ZICER would perform 10% better than the Elizabeth Fry at 30 kWh/m2.a for space heating; however during its first 6 months of occupation the energy use was double this target. Again investigation into controls operation was carried out and revised control algorithms put in place which resulted in the building performing similarly to the Elizabeth Fry (fig. 3). In both buildings control has been implemented based on the temperature of the thermal mass of the TERMODECK construction rather than through the air-temperature sensing that was originally implemented by the contractors.

Both of these buildings have been recognised as exemplars of good performance.

In a large part this good performance has been achieved through the high level of visibility and the motivation and efforts of the facility management team led by Keith Tovey (Tovey and Turner 2006; Ingham, 2010). Without this effort in the first year of operation both buildings would have had much poorer performance with possibly 2x the heating energy demand that has now been achieved.

The importance of controls and the poor performance of the initial control implementations were again highlighted.

The fact that these buildings are part of ongoing campus re-development with 5 buildings of this type constructed has meant that the professional team has maintained engagement longer than in the one-off situations of the BRE and SNH buildings.

2.5. German Low Energy Government Buildings.

The German Federal Ministry for Economy demonstration program covers 22 non-actively cooled buildings; the program has been running since 1995 and involved monitoring energy use, environmental conditions, occupant behavior and comfort. The literature published as output from the study was reviewed earlier. Here several resonances found with the more direct investigations detailed above are highlighted.

One observation was that the monitoring and high focus on these buildings highlighted many system operation errors similar to those seen in the BRE Environmental office case and they draw the conclusion that these types of problems are common practice in the building stock: “In many cases, detailed analysis of the electricity consumption helped to identify weaknesses in the system operation and aid their correction: operation of the heating system pumps outside the heating season, heating of pre-cooled air by an earth-to-air heat exchanger during summer, etc. In large buildings operational faults cause energy consumptions and energy costs in an order of magnitude which is not negligible. From the experiences it can be assumed that these kinds of faults are common practice in the operation of the building stock as a whole.” (Voss et al, 2007).

It is interesting that similar faults to those seen in the other case studies were reported:

- Heating and cooling systems both operating with no positive effect.
- Operation of heating systems when not required.
- Higher energy consumption than intended due to these faults.
- Weaknesses only visible due to the high focus created by the monitoring process.

Their conclusion that these kinds of faults being common practice in the building stock as a whole is consistent with the findings in the other buildings studied here.

2.6. Useable Buildings Trust (UBT)

The Useable buildings Trust (UBT) has been active in the field for the past two decades (Usable Buildings Trust, 2012). While the UBT initiatives have been previously mentioned, a few points are highlighted here which have resonance with the findings of the more detailed studies carried out in this work.

The useable buildings trust 2010 publication 'Design Intent to Reality' (Usable Buildings Trust 2012a) identifies that there are inherent problems with the buildings processes as they exist today and propose that there is a need to "make follow through and feedback routine".

They summarize their findings of recurring problems in buildings:

- Problems with interfaces between work packages.
- Problems with control systems, management and user interfaces.
- Handover processes too abrupt.
- User dissatisfaction.
- Energy use higher than anticipated.
- Unmanageable complexity.

One conclusion is that "Controls, manageability and usability need much more attention at all stages". Their findings mirror those presented here.

2.7. 1st Scottish Passive House and Low Energy house, Dunoon.

In co-operation with the housing developer and social landlord a monitoring scheme was established to gather data on temperatures, air quality and energy use in the Passive House (fig. 4), an adjacent Low Energy house (labeled Code 4 by the architect) and an adjacent 1950s dwelling (Tuohy et al 2011).

The Passive House ventilation is through a whole house mechanical ventilation heat recovery unit, space heating is through an air to air heat pump and hot water is provided through a solar thermal system with a 180litre vertical tank with solar coil in its bottom half and an electric immersion heater above the solar coil as backup.

The monitoring equipment was installed and the Passive House was inspected against the critical points of Passive House specification and design (PHI, 2012). There were many fundamental problems identified through the POE and monitoring exercise.

Key findings from the post occupancy evaluation and monitoring:

- Initial inspection revealed missing and insufficient insulation on the outside air intake and exhaust ducts (insulation missing in sections and where present only 19mm v. PH spec of 140mm). These aluminium ducts bring cold outside air into the building and have 6m length, insufficient insulation leads to a cold radiator effect, condensation risk and significant heat losses.

- The heat pump in the Passive House did not have a remote thermostat control to enable it to perform a whole house heating function. The system failed to deliver enough heat in cold conditions. The system suppliers had originally quoted a seasonal performance factor of 2.5 but when asked for performance data at 2^oC, 0^oC and -7^oC including defrosting they could not supply it. (more on heat pumps in next section).

- The solar hot water system and the immersion heater controls were independently set. The immersion heater had been set to come on 3 times each day including midnight to 8am and 1pm till 4pm meaning that solar contribution was limited and electricity used when there was potential for solar input.

- The solar portion of the tank was not being sterilized. This situation does not comply with legionella guidance and constitutes a potential risk to health (HSE L8, 2012).

- The solar system operation was very difficult to quantify – to monitor performance needed external monitoring equipment to be installed. Initial indications are that the yield from the solar system will be much lower than the 55% solar fraction assumed in the design calculations.

- The occupier was confused by the overly complex manual for the ventilation system, heat pump and immersion heater system.

- The Passive House was not on a reduced off-peak electricity tariff compromising the financial benefit of low energy use.

This study has highlighted issues seen in other buildings such as overly coarse controls, incorrect implementation of systems and controls, lack of visibility to occupants and owners, disconnects between vendors, specifiers and installers, overly optimistic specifications, intended performance not being met, prolonged period of TLC being required to achieve good performance. The difficulty of fixing problems once design and construction phase is over is again highlighted, these issues were highlighted in December 2010 and were finally fixed in March 2011 (14 months later) despite general agreement that this needed to happen.

2.8. Performance of CO_2 Heat Pumps in Scottish Dwelling Retrofits.

Heat pumps in general are being promoted by policy as a Low Carbon option for retrofit or new build (Tuohy, 2009). Traditional heat pump refrigerants have high global warming potentials (e.g. 1400 x CO_2) and so heat pumps using CO_2 refrigerants have been proposed as beneficial and are now entering the marketplace.

The investigation involved literature review and then monitoring of the systems in operation. The outputs from the review and the monitoring were then used to create a

DSM model which could be used to predict performance in practice for any situation (Petinot, 2011).

There were many interesting observations and potential improvements these include:

- For optimal heat pump performance there should be a large delta T across the tank (i.e. good stratification).

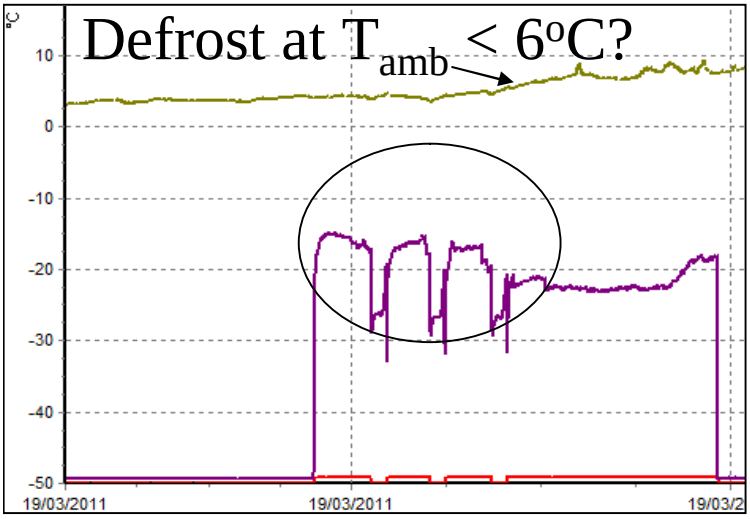
- The system was programmed to sterilise (for legionella) the tank every 4th heat pump cycle which meant that at random times (approximately twice a day) the entire tank was heated to 60°C, significantly reducing heat pump performance.

- The energy spent defrosting the outdoor unit was significantly higher and reduced the unit output more than expected (up to 25% rather than the 10% expected). Defrost energy use was a maximum at outdoor temperatures of 5°C and high humidity i.e. normal Scottish conditions (figure 2).

- The overall COP observed was around 2 compared to the predicted performance of 3.

- The electricity used was at a standard rather than off peak tariff, negating the financial benefit of reduced electricity use.

Figure 2. Air source heat pump performance showing defrost at 4 to 5°C.



3. Performance in practice: performance gaps to be addressed.

Many problems that form potential barriers to the creation of ultra-low energy buildings in practice have been identified and can be summarized as follows:

1. High esteem scores based on predicted and not measured performance. (e.g. BREEAM, Passive House)

2. Marketed performance is not based on actual performance or appropriate benchmarks.

3. Building types promoted by current policy and regulations are not well justified by measured performance data (the opposite may be the case i.e. HVAC measured to have higher energy use c.f. Natural Ventilation but regulation favours HVAC).

4. Current policy and regulations are not based on actual performance in use.

5. Current policy and regulations exclude equipment and appliance energy uses.

6. Building performance often doesn't meet intent or expectations.

7. Optimum operation only after re-engineering in operation phase.

8. Remediation requires large effort, very difficult (or not done) after project team dispersed.

9. Actual performance often unknown or visibility and awareness poor.

10. Scope of design and design targets often too narrow.

11. Design assumptions not robust e.g. fixed patterns of use.

12. Over optimistic performance assumptions.

13. Every project a 'start from scratch' no learning process.

14. Performance of new technology systems difficult to quantify.

15. New technology systems do not work as well as predicted.

16. Controls are poorly designed (coarse, not optimum, conflicting, poor fault coverage) and implemented (incorrect, confusing, unclear, unexplained, and overly complex).

17. Building managers and occupants often don't understand the building.

18. Visibility and awareness of design targets is poor.

19. Faults often occur and often undetected.

20. Lack of user controls, imposed conditions frustrating to building occupants.

21. No accountability for poor performance or poor quality.

Resolving these problems will take a large change in the way buildings are implemented.

4. Will current industry initiatives address these problems?

Problems in buildings industry processes are widespread and have to some extent been recognized. There are a number of initiatives funded or driven by Governments and other organizations intended to address various aspects of these problems such as

the commissioning requirements in LEED and BREEAM, Soft Landings (BSRIA, 2012), AGBR (NABERS, 2012; Bannister, 2005) and BCVTB (Haves et al, 2007) approaches. The BIM initiative may provide a framework within which improved processes could be integrated (Succar, 2009).

The Soft Landings method promotes collaborative working and cohesive processes and could be integrated with or within a BIM process flow. The Soft Landings process has some areas of weakness with regards to the problems seen in the earlier investigations. The investigations found that remedial works can be extremely difficult or impossible to achieve on a building that is already operational; in some cases problems of design may not be able to be fixed - with only a sub-optimal work-around possible. This 'sea-trial' period of monitoring and re-engineering could be viewed as an acceptance that the industry is incapable of achieving a building that performs as intended straight 'out of the box'.

The AGBR (Australian Greenhouse Building Rating) which underpins the energy section of the Australian NABERS and Green Star rating schemes is based on actual performance of buildings. The actual energy data is required to be recorded and submitted in order to obtain a rating; the rating for the actual building is compared to a benchmark building of the same type and adjusted for climate and patterns of use factors such as occupant density and occupied hours etc. The scheme is increasingly being used for new developments and it was identified that preliminary ratings based on simulations were overly optimistic and did not correlate with measured data on completion. The findings were that the scope of the design simulations, and the assumptions made especially for the modelling of HVAC and controls were often idealised and not realistic. To address this they have established a commitment which must be followed this requires an expert review process and the use of simulation in compliance with a simulation protocol. There would appear to be much to commend the AGBR method however it does not directly address the issues of implementation which were found to have such a large effect in the building investigations.

The US Government controls initiatives including the Berkeley Building Controls Virtual Test Bed (Haves et al, 2007) are beginning to create a software environment for developing and testing controls in synergy with building and systems models and then use the simulated controls as a template for both commissioning and operation but their methods are still in the research and development phase and not yet formulated to allow routine industry use.

It is interesting that a motivation behind the BIM initiative is the need to improve productivity in the construction sector. It is suggested that productivity has stagnated compared to that of other industries and identifies the adoption of modern processes and technology as a key enabler for improvement: "If we look at the retail, automotive, electronics and aerospace industries, transformation in these sectors could have only come about through the adoption and continuous development of modern processes and technology" (BSi, 2012). In essence this initiative is driving an industrial engineering approach into the building sector (Tuohy 2009). Processes to address the performance gaps identified here do not yet appear to be defined or even a focus within the current BIM roadmap (Succar, 2009, BIS, 2012).

This more 'automated' and less 'hand crafted' industrial engineering approach is already evident in the some specialist areas of the buildings industry such as off-site modular construction and large apartment blocks, hotels and large cruise ships where

bedroom, bathroom kitchen, cabin or apartment modules are prefabricated and connected together on site; construction of modular buildings or kit houses etc.

5. Conclusions

Several case studies representative of buildings and technologies likely to be promoted by current policy were investigated and multiple issues identified that caused poorer than intended performance. Review of similar studies of others identified these problems as common in the industry.

A selection of relevant current industry initiatives was then reviewed and it was concluded that these alone were unlikely to address these gaps.

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