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Innovation in low carbon construction technologies: an historic analysis for obviating defects

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ABSTRACT

Purpose

This paper evaluates the risks of building defects associated with rapid advancement of 'green' construction technologies. It identifies the methods adopted by the sector for the determination of pre-construction defects that are framed within the context of, traditional; scientific; and professional design approaches. These are critically evaluated and utilised in attempts to mitigate defects arising from diffusing low carbon construction innovations.

Design method

The paper takes the form of an evaluative literature review. Polemic in orientation, the paper critically compares two periods of time associated with rapid advancement of innovation. The first, the post World War II housing boom is synonymous with a legacy of substandard buildings that in many cases rapidly deteriorated, requiring refurbishment or demolition shortly after construction. The second, is today's 'green' technology 'shift' with its inherent uncertainty and increased risk of latent building defects and potential failure to deliver meaningful long term performance. Central to this is an exploration of the drivers for innovation, and subsequent response, precautionary measures initiated, and the limitations of institutionalised systems to identify and mitigate defects. Similarities and differences between these historical periods frame a discussion around the theoretical approaches to defects and how these may be limited in contemporary low carbon construction. A conceptual framework is presented with the aim of enhancing the understanding for obviation of defects.

Findings

Sufficient commonality exists between the periods to initiate a heightened vigilance in the identification, evaluation and ideally the obviation of defects. Design evaluation is not expressly or sufficiently defect focused. It appears that limited real change in the ability to identify defects has occurred since the post war period and our ability to predict the performance of innovative systems and materials is therefore questionable. Attempts to appraise defects are still embedded in the three principle approaches: traditional; scientific; and professional design. Each of these systems have positive characteristics and address defect mitigation within constrains imposed by their very nature. However, they all fail to address the full spectrum of conditions and design and constructional complexities that lead to defects. The positive characteristics of each system need to be recognised and brought together in an holistic system that offers tangible advantages. Additionally, independent design professionals insufficiently emphasise the importance of defect identification and holistic evaluation of problems in design failure are influenced by their professional training and education. A silo based mentality with fragmentation of professional responsibility debases the efficacy of defect identification, and failure to work in a meaningful, collaborative cross professional manner hinders the defect eradication process.

Research limitations

Whilst forming a meaningful contribution to stimulate debate, further investigation is required to tangibly establish integrated approaches to identify and obviate defects.

Practical Implications

The structured discussion and conclusions highlight areas of concern for industry practitioners, policy makers, regulators, industry researchers and academic researchers alike in addressing and realising a low carbon construction future. The lessons learned are not limited to a UK context and they have relevance internationally, particularly where rapid and significant growth is coupled with a need for carbon reduction and sustainable development such as the emerging economies in China, Brazil and India.

Social Implications

The carbon cost associated with addressing the consequences of emerging defects over time significantly jeopardises attempts to meet legally binding sustainability targets. This is a relatively new dimension and compounds the traditional economic and societal impacts of building failure. Clearly, blindly accepting this as ‘the cost of innovation without development’ cannot be countenanced.

Originality

Much research has been undertaken to evaluate post construction defects. The protocols and inherent complexities associated with the determination of pre-construction defects have to date been largely neglected. This work attempts to rectify this situation.

Keywords:

Building defects, Low carbon construction, Building detailing, Innovative technologies, Pre-Construction evaluation methods, Historic analysis

Article Classification: Polemic literature review and conceptual framework

1.0 INTRODUCTION

Today’s necessity to radically alter traditional construction technology has many similarities with the post World War II housing boom. The design and construction of many non-traditional housing systems and innovative materials were a defining characteristic of this era. Unfortunately, this period is synonymous with a legacy of substandard buildings that rapidly deteriorated, requiring refurbishment or demolition shortly after construction (Harrison *et al*, 2004; Lovell *et al*, 2010; Wolf, 1999). The identification of pre construction defects in these structures were unforeseen even with a well established building regulatory framework, research testing facilities (such as Building Research Station [BRS]) and attendant professionalism throughout design and construction activities (Yeomans, 1997). Despite long term planning, foresight about events, and advancements in testing technology, significant and substantial problems associated with designs and material deficiencies in these new build systems emerged (Yeomans, 1997; Cook & Hinks, 1992). There has however been significant time and opportunity for the industry to learn from this period of history. Despite this, a fundamental question remains; are current regulatory frameworks, testing facilities and other institutions, such as professional bodies, powerful enough, and sufficiently developed and interconnected to avoid the ‘mistakes of the past’? This question comes into sharp focus as the industry re-enters the chartered territory of radical alterations to construction technology.

The enormous struggle for the industry to meet significant housing demand after WWII resonates considerably with contemporary concerns and challenges. Housing demand has recently been estimated to equate to 232,000 more homes per year (ONS, 2010a). This challenge of delivering significant homes year upon year is compounded by the need for these homes to meet performance standards rooted in ever stricter and ambitious energy efficiency and low carbon targets. The challenge in the UK is however only a small part of the global challenge to satisfy the growing market for net zero carbon homes and more specifically, the ‘*new low carbon*

cities initiative' proposed by the World Wildlife Fund (WWF) in collaboration with the Chinese government (WWF, 2011; BRE, 2011). The size of the expanding international market is significant and is matched by the extraordinary challenge to develop and consistently deliver cost efficient, low carbon homes at scale that actually perform as predicted. The question is how and indeed, if their delivery can avoid a future legacy of economic and environmentally costly defects on a global let alone a national scale.

Innovation in the built environment is arguably the key to addressing the challenge with many indigenous or international domestic buildings likely to have a greater reliance upon more non-traditional, highly innovative construction designs, build systems, technologies and materials. Export markets for these innovations are limited as they are largely developed within, tested and certified for-use in specific climates. The relevance of nationally controlled testing institutions and the legitimacy of how, why and what they test is thus, not necessarily universally applicable or viable across disparate climatic and political boundaries. Low Carbon construction innovations are thus not necessarily wholly capable of 'going global' and questions surrounding how such innovations cross climatic, and by extension a myriad of regulative, cultural and institutional boundaries are critical to understanding innovations' performance-in-use.

Central to such performance is the mitigation of defects. Whilst the protocols for the pathology and investigation of post construction defects are well established in the UK (RICS, 2011; Watt, 2003; Prieser, 1995; Jaunzens *et al*, 2003), the same cannot be said for pre-construction defects. Regardless of protocols and technologies, designs continue to exhibit significant levels of defects during a building lifecycle (Constable & Lamont, 2007; RICS, 2011). Rapidly diffusing innovative technologies and designs that draw legitimacy from these protocols would arguably only act to increase both the level and severity of defects (Hunt, 2009). Indeed, the severity of defects is exacerbated when the analysis of the carbon costs to put defects right are fully considered (Forster *et al*, 2011). As innovative technologies, materials and designs are empirically tested in use (drawing on live data), disparate levels and severities of defects will undoubtedly be identified and solutions mobilised in the long term. Predominantly relying on a reactive strategy to 'learning from the past' would appear to differ little from the past. Such reliance also assumes that contemporary protocols and testing regimes are 'fit for purpose' and reflect the rigour necessary to predict performance and clearly identify potential defects in diffusing innovations-in-use pre and post construction. Little research has explored the development of protocols and testing regimes in the last two decades and questioned the extent of their rigour, relevance and reliance in mitigating defects.

Adopting innovative designs, technologies, materials and build systems is an integral and unavoidable strategy to achieve the UK's long term, legally binding sustainability targets (DECC, 2009; HM Government, 2011). The attendant need to rapidly diffuse these innovations will undoubtedly have unforeseen consequences in building performance and, without greater attention, may lead to significant and severe building defects or, in worst case scenarios'; necessitate unintended and unplanned premature property stock replacement. The carbon cost associated with addressing the consequences of emerging defects over time also significantly jeopardises attempts to meet legally binding sustainability targets. Blindly accepting this as 'the cost of innovation without development' (BBC 1984) cannot be countenanced. A pro-active and holistic evaluation of approaches to defects in the context of stringent sustainability and carbon reduction targets requires greater and immediate scrutiny.

2.0 METHODOLOGY

To provide a starting point for such scrutiny, the research approach adopted largely relies upon an extensive literature review and a considered historical analysis to provide what is essentially a position paper. Polemic in orientation, the paper compares two periods of time associated with rapid advancement of innovation. A critical reading of relevant literature and associated assumptions are mobilised to develop structured discussion, perspectives and research questions for future investigation. Evaluation of subject specific literature is framed around the historic context, and traditional, scientific and design approaches. Central to this is an exploration of the drivers for innovation and the limitations of institutionalised systems to identify and mitigate defects. Similarities and differences between these historical periods frame a discussion around the theoretical approaches to defects and how these may be limited in contemporary low carbon construction. The structured discussion and conclusions highlight areas of concern for industry practitioners, policy makers, regulators, industry researchers and academic researchers alike in addressing and realising and low carbon construction future. The lessons learned are not limited to a UK context. They have relevance internationally, particularly where rapid and significant growth is coupled with a need for carbon reduction and sustainable development such as China, Brazil and India.

The analysis is structured in four sections. The first presents emerging themes from both the historic and contemporary periods of innovation being studied. Secondly, an evaluation framework is used to map the causal conditions for defects found at the key stages of a construction project from pre construction drivers to post construction result. A conceptual framework is presented with the aim of enhancing the understanding for obviation of defects. The final section discusses the challenges and opportunities for transforming practice.

3.0 PARALLELS WITH THE PAST AND A FAMILIAR PATH

Clearly, technologically altering construction systems have been a feature of the basic need for shelter and climatic modification to satisfy human expectations (Jacobs, 1974). This has occurred throughout history at different points for different cultures (Bronowski, 2011). The need for innovation and change may also be a response to complex socio-economic and socio-political pressures resulting from multi-faceted drivers (Hunt, 2009; Lovell, 2010). During periods of significant pressure, the rate of innovation arguably rises and consequently the risk and potential for defects increases (Cook & Hinks, 1992).

The post World War II drivers for innovating and change are complex to analyse but were primarily associated with materials and labour shortages, financial austerity, and insufficient supply in the domestic housing market. This necessitated rapidly developed and diffused radical innovations to meet unprecedented demand and political expediency. Today's situation is similarly complex with carbon reduction targets, energy efficiency designs (passive design etc.), fuel poverty, insufficient supply in the domestic housing market, trade skill deterioration, and financial austerity arguably driving and impacting upon the rapid development and diffusion of radical innovation. To understand these drivers more deeply and their impact, it is necessary to explore and discuss them in greater depth.

3.1 Post World War II construction innovation

A post World War II imperative to home a mass dispossessed population and those living in slum conditions created significant societal stress (Nuttgens, 1989; Quiney, 1986; Crawford, 1975). Housing demand was a particular issue for the war time government, but their strategy for tackling the evident housing shortage was inadequate and necessitated a shift away from traditional approaches, materials and construction methods:

'even during the war it had been clear to the government that once the hostilities were over it would have to tackle a housing shortage of a scale beyond the capacity of the traditional building industry: as a result alternative methods of construction needed to be examined'. Clearly this placed the construction industry *'under intense pressure (social, economic and political forces alone were not inconsiderable) to produce without adequate resources an unprecedentedly large number of buildings with quite different performance requirements from those previously encountered'* Yeomans (1997:18).

The demand for social housing and the intense government pressure to deliver upon the pre-war political rhetoric focused single-mindedly on the sheer quantity of units that could be produced by both public and private sector housing providers (Crawford, 1975). Between 1945 and 1951, 1,016,349 new dwellings and 157,146 temporary dwellings were constructed (ONS, 2010a & 2010b). The volume and expediency of delivery rested upon the successful diffusion of radical technological innovations. These were manifest within prefabricated and mechanised (i.e. framed construction and composite materials) housing designs and systems such as Airey, Orlit and Blackburn (HMSO, 1987; Ball 1988) that typically used non-load bearing walls (i.e. cladding systems). The designs and systems could be subdivided into 2 forms; framed (including, BISF, Blackburn, Orlit, Weir etc) and unframed (Pre-cast panel, Pre-cast block and insitu, such as no fines), and were adopted in two historical phases: (i) the post war - low rise stock (approx 1945-1950s) and (ii) the 2nd post war building boom – multi storey flats (approx 1960-1970's).

Testing, validation and evaluation of these new systems, techniques and materials was delivered by the public sector organisation Building Research Board (BRB). The BRB had a specific remit to investigate, *'problems of durability and manufacture, the development of new materials, housing problems and fire prevention'* (Yeomans, 1997: 18). Evolving from the BRB was the Building Research Station (BRS) which included an additional division entitled *'intelligence and special investigation'*. This division was responsible for instigating investigations via requests from external organisations and through building failures. Its function was important as trade bodies who could not typically afford their own research, were able, through this division, to sponsor specific research projects. More broadly, the BRB and the BRS widely embraced a scientific approach to testing prefabricated and mechanised technological innovations. According to Addelson (1992: 3) *'with hindsight it is*

now patently obvious that, during the post-war period, far too many new materials and building techniques, most of whose shortcomings were not necessarily understood were adopted'.

The rate of innovation adoption, the testing approach used and perhaps the way it was employed resulted in a legacy of latent defects and performance deficiencies (Yeomans, 1997) including inadequate thermal insulation, cold bridging, surface and interstitial condensation, penetrating dampness, inadequate fire protection and structural movement (Hunt, 2009; Hollis, 2005). These buildings were in many cases demolished shortly after construction (Wolf, 1999) or required significant refurbishment to bring them up to a tolerable standard. Described as a '*costly failed experiment*', costs to correct defects ('*design errors*') associated with this period of '*industrialised housing systems*' was estimated to be £10 Billion pounds in 1984 (Ball, 1988). The impact upon social housing was most acutely felt due to the variety of domestic systems, the volume of units constructed and greater expectations in performance. The deficiencies in design were compounded by operative unfamiliarity with the innovative systems and poor on site quality control (BRE, 1985; See also Ronan point disaster). Buildings rapidly fell into technical obsolescence due to poor performance, which indirectly led to economic obsolescence as the cost of undertaking the upgrading of the housing stock was so significant that it was economically unviable to retain them. Clearly, once wide scale physical and perception degradation had started, the tenants and wider public were in many cases reluctant to occupy them (Wolf, 1999). Furthermore, such degradation retains a strong association with prefabrication and mechanisation (Lovell and Smith, 2010).

In summing up attempts to diffuse technological innovation in the construction sector in this period, Ball (1988) asks why radical innovations were diffused within a design and construction system already known to be associated with design and construction defects. Arguably, diffusing these radical technological innovations rested upon the assumption that technology would simultaneously address ongoing concerns of design and construction defects as well as optimistic ambitions to improve efficiency. Coupled with this was an assumption that design and construction defects were purely technological in nature and thus resolvable by diffusing radical technological innovations. The legitimacy for their diffusion also drew upon powerful technological institutions (such as BRS, BRB and BBA). This dominant technological framing of problems, innovations and legitimising institutions proved limited and provides a very useful point of reference for the contemporary diffusion of technological innovations.

3.2 21st Century innovation

An estimated 232,000 dwellings per year are required in England alone by 2033 (ONS, 2010a), equating to 4.6 million buildings. The insufficient supply in the domestic housing market is clearly a significant problem and is the basis for much current political discussion. Lack of supply is a fundamental motivator for construction. This is coupled with a vision for the construction sector to deliver projects 33% cheaper, 50% quicker and with a 50% reduction in greenhouse gas emissions (HM Government, 2013). There are clearly parallels with the post World War II era regarding the necessity to mass deliver houses within cost and time parameters. This provides arguments for, and a fresh drive towards adopting radical innovations such as prefabrication, off-site manufacturing, panel systems and new build systems. Modern Methods of Construction (MMC) are being revisited. Notably, 21st century innovations are also largely driven by the zero-carbon agenda, the Energy Performance Buildings Directive and the code for sustainable homes (Communities and Local Government, 2006). These political pressures have consolidated and reinforced arguments for adopting radical technological innovations that present significant risks and potential outcomes remarkably resonant with innovations adopted in the post World War II era. Indeed, early innovative low carbon structures are in many cases neither performing nor, delivering on their low-carbon promises (Bell *et al*, 2010; Gorse *et al*, 2012 a & b).

Despite this, rapid advancement of radical technological innovation is set to continue although resting upon contemporary views that the industry continues to deliver buildings *per se* which are too expensive, too slow to build (HM Government, 2013) and, typically associated with poor designs (Halliday, 2008). This early failure to deliver defect free innovative buildings resonates with that experienced in the post World War II period. The greater emphasis on increased carbon loss from the building and the embodied carbon cost to rectify defects amplifies the potential of these failures into the future. Notably, contemporary attempts to diffuse radical technological innovations are also done with clear knowledge that the industry remains intransigent to change and consistently fails to perform. As Ball (1988) broadly questioned during the post war era, why diffuse radical technological change in a context where significant problems already exist; technological or not.

Central to the ongoing uptake of innovative low carbon designs, technologies, materials and build systems is confidence in their ability to deliver performance as '*New methods of construction may be regarded with suspicion if only because the unknown brings with it risk*' (Yeomans, 1997: 14). Such confidence is in part

provided via the robust and reliable testing, monitoring and reporting of LCC innovations through development and into use; essentially a coherent, connected, historic and rigorous system for testing. Currently, building regulations and BBA certification form an integral component of this system. BBA certification operates via specialist teams understanding the function of the product under assessment, identifying its attributes and evaluating its fitness for purpose (BBA, 2009). The certificates are argued, in *specified circumstances to gradually fill some of the gaps in knowledge, thereby helping to assist in the prediction of the risk of failure in particular cases* (Yeomans, 1997: 6-7). Certificates are limited to providing confidence in the use of innovations only within specific circumstances. It is obvious that an expansive testing regime also correlates with ever increasing cost and this is clearly borne by either the client or the testing institutions. A well-meaning company, or indeed the BBA, may be amenable to large scale experimentation but unwilling or unable to bear the cost. This reduction in the breadth and scope of testing is problematic and certainly highlights further limitations in testing systems to provide confidence in the performance of innovations. Indeed, legitimising the adoption and diffusion of technological innovations predominantly via these technology orientated institutions (such as BRE and BBA) differs little from the post World War II era.

These limitations aside, even when a technology is superior, operative resistance to the uptake of low carbon construction innovations is high (whether real or perceived) and failures in design solutions can be, without evidence, blamed upon the innovations regardless (Halliday 2008). This resistance to change in the construction industry is a function of the considerable investment (sunk costs) in existing methods via training of operatives and management structures. Further investment in training is also problematic as *'there is a disincentive within the industry to invest in training to accommodate new technologies because the labour force is highly mobile'* (Yeomans, 1997: 14). The successful diffusion and ongoing legitimacy of adopting and diffusing further technological innovations clearly cannot be provided solely by technologically orientated institutions. Compounding this, modern systems may prove to be relatively robust in terms of performance if they have been built in strict accordance to manufacturer and designer specifications. The recent emphasis on addressing the apparent significant gap between design and 'as-built' performance would appear to have significant resonance with the post war era the gap led to significant technical (and latterly social) failure of entire buildings.

4.0 A COMPARATIVE DIAGRAMMATIC REPRESENTATION OF TWO PERIODS

There is a remarkable symmetry between the post World War II and 21st century eras. An evaluation framework established in figure 1 captures these symmetries. It is used to map the causal conditions for defects chronologically, firstly through an understanding of those pressures placed on the industry to innovate and what are considered to be the broader problems. Secondly, the 'Pre construction response' highlights areas of innovations placed centre stage as those prioritised in order to address broader problems and placate those applying political and social pressure for change. Thirdly, 'pre and on-site construction precaution' portrays the process by which specific innovations achieve legitimacy and provide innovators with the confidence to diffuse them in practice. At this point, the risks of defects are considered to have been mitigated if only hypothetically. Fourthly, 'on site and post construction defects' attempts to paint a picture of how and to some extent 'how and where' defects emerge. The fifth and last aspect of the figure presents a litany of consequences arising from risks poorly mitigated and thought through. From top to bottom, there is an assumption in the model that certainty of innovation performance and propensity for defects are reduced.

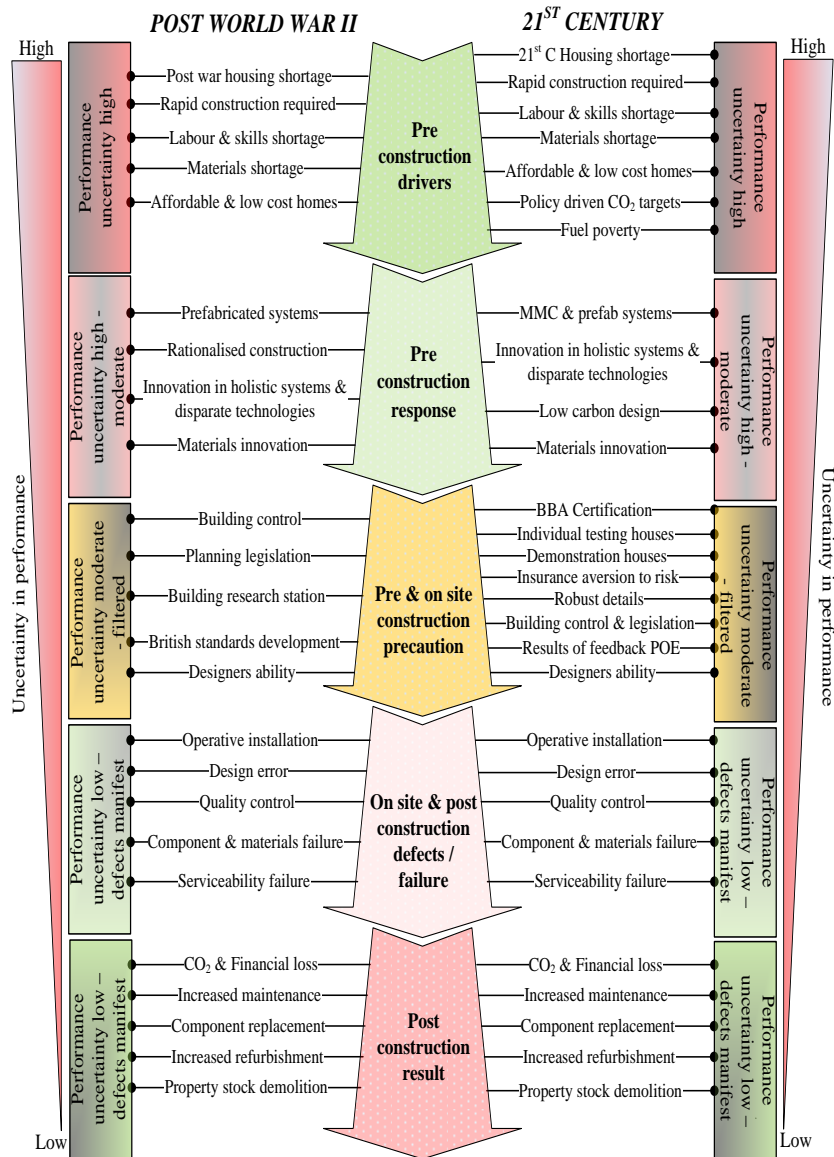


Fig 1: Illustrative representation of the parallels in innovation between WWII & 21st Century

4.1 Pre-construction drivers

Pre-construction drivers are similar in both periods, however, relative energy cost, and CO₂ reduction targets are significant new issues. Fuel poverty is also significantly new driver for radical technological innovations targeted at reducing heat loss and by extension financial hardship for many in British society. These factors have become central themes in design with insulation playing (RIBA, 2011) and remaining a key feature in applying low carbon design principles. Insufficient housing supply is surprisingly similar with approximately 200,000 new dwellings per year required in 1945 and 2013. Post World War II materials shortages led to rationalised components and in many cases the holistic redesign of traditionally built structures. Similarly, current resource depletion and growing global demand for materials (i.e. metals) is stimulating technology substitution and innovation. The imperative to initiate green procurement and utilise greener construction systems and materials is a privileged contemporary argument connected with the adoption of radical technological innovations.

4.2 Pre construction response

Pre construction response across the two era's is also remarkably similar. Innovation in materials and their associated construction technologies are privileged above other important avenues of research and activity such as training, quality assurance and social and environmental behaviour. Post World War II interest in materials

reflected new solutions to problems rather than enhanced or better understanding of existing materials. In the 21st century ‘blue sky’ research into new materials (i.e. graphene) is complemented by revisiting existing traditional materials with good environmental credentials (i.e. lime and earth) [eg. Limesnet]. A new paradigm of low carbon design is now a significant force for change in preconstruction concept and technical design processes, encapsulated in the RIBA 6 core principles: thermal efficiency; air tightness, efficient service and fuels; and a better understanding of the influence of form and fabric of the holistic structure (RIBA, 2011: 3) These are to greater or lesser degrees embedded into the design stage and pre contract agenda and have a tendency to draw upon prefabricated systems and off-site manufacturing similar to the post World War II era. The increased thermal performance, and improved air tightness set out in the building standards, have resulted in design solutions that meet new performance requirements. Sophisticated energy modelling offer architects detailed predictions of energy demand associated with building occupation, that enable design solutions to be tested prior to construction. However there is a clear difference between the designed and actual energy being used in many new buildings (Carbonbuzz, 2013). Innovative approaches to detailing and low energy design adopted to achieve energy efficiency may be contributing to the poor performance of these new buildings.

4.3 Pre and onsite construction precaution

Pre and onsite construction precaution exhibits similar features in both periods. A higher level of sophistication in control, legislation and testing are noted but potential failure associated with fragmentation and enhanced complexity cannot be discounted. Evaluation of pre construction defects ostensibly follows the same process. The pre construction precautionary measures should act as a defect filter, reducing risk and giving comfort to all involved. The use of ‘robust details’ forms a significant part of defect obviation. A notable difference here is the privatisation of government’s technical expertise between the two periods which culminated in the privatisation of BRE. A lot of the institutions and services concerned with control and testing are now market orientated and private sector interests. There are few studies which have explored what this means for the sector. Notably, the professional bodies have not dramatically changed although the RIBA is arguably significantly weaker given the reduced role for architects in the build process.

Skill shortages in both periods have led to rationalised construction and greater use of pre-fabrication. Many traditional skilled operations are now semi-skilled in nature. The ability of the operative to respond to change on site is diminished. The operative understanding in the performance of the technology is also reduced as they do not understand the systems from first principles. This is the opposite of the traditional craft based ‘stick-built’ approach in which the operative understood the elemental and material layer build up and its functional importance. Wide scale operative familiarity with technology could be argued to be currently diminishing with the large scale introduction of unfamiliar disparate ‘eco’ products. The first of any of the new ‘eco’ designed houses may suffer from operative unfamiliarity and as a result a higher incidence of defects may be prevalent.

4.4 On site and post construction defects/failure

On site and post construction defects/failure exhibits significant commonality in both periods. A higher degree of separation is noted between design and construction process, which automatically increases communication complexity and confusion. Problems also exist in the communication between designer and operative in so much as the architect does not tell the builder how to construct it. As Douglas and Ransom (2006: 12) state ‘*the client, via the designer, tells the builder what is required – he does not tell the contractor how to go about it*’. This process can also be reversed with inadequate feedback between installer and designer being common place. This situation is further exacerbated by the unique nature of the product as every project is different. Compounding the problems of site construction quality is the absence of a ‘clerk of works’ who would have traditionally undertaken continuous assessment of the build. Today, overseeing professionals periodically visit sites potentially missing quality assessment on pivotal stages in the construction phase. Additionally, Atkinson (1995: 29) believes that quality in construction cannot be guaranteed unless ‘*the design, and resulting construction works, follow acknowledged rules of technology*’. It is unclear what the acknowledged rules are and this statement poses the question, does innovation in technology alter the rules and if so how would they differ? The defects and failure phase have identical features with both periods. Little appears to have meaningfully changed. Once the works are on-going, certain features of performance will manifest themselves both during and upon initial completion. New defects associated with innovative technology and materials will however manifest themselves reflecting the changing nature of construction employed (eg. a prevalence of buildings over-heating and air quality reduction associated with insufficient air changes are becoming evident). This issue would typically be associated with ‘snagging’ with identification of minor defects. It is clear at this stage that there is no significant reversal potential of the process as the physical asset is created. Uncertainty is reducing as performance is becoming tangibly evaluated. The result of user behaviour and longer term technical

performance are manifest. Therefore virtually no uncertainty exists but irreversible damage may be already done.

4.5 Post construction results

Post construction results are comparable in both periods, however, CO₂ loss features alongside speed and cost of delivery. The resulting performance traditionally measured in terms of social, economic and technical obsolescence obviation can now be overlaid with a new environmental facet (CO₂ loss, materials depletion, and lost carbon sink). There continues across both periods a paucity of rigorous post occupancy evaluations that focus upon the use of buildings as a socio-technical system and thus emphasise equally technology and social systems as well as their interdependency. Notably, post occupancy evaluation systems will have limited effect in aiding better design in the short / medium term.

Professional institutions have developed incrementally in parallel with the traditional approach to managing defects noted previously. The ability of these institutions to effectively operate during periods of rapid advancement in periods of increasing socio and political pressure is however questionable. The determination of problems in design and construction resulting in defects reflect the relative ability or inability to identify issues. Similarly, in both periods there is no incentive for designers and contractors to publicly provide evidence of defects in the products they provide given the continuation of contractual arrangements designed to separate and package work. It really poses a question what evaluation mechanism currently exists and are they sufficiently robust and defined to obviate defects.

In summary, the way defects are approached is fundamental in both framing the way innovations are diffused and the way risks are argued to be minimised regardless of era. The pre construction responses and precautions are however imperative points in time to initiate attempts to obviate defects. The following therefore discusses in more detail the contemporary approaches to defects and whether they have developed over the last 40 years to address rapid advancement of innovation for low carbon construction.

5.0 DEFECTS: A CONCEPTUAL FRAMEWORK

The chronological evolution of a building project results in a fragmented approach to the identification and obviation of defects. A conceptual framework is presented to enable a better understanding of the systems that exist in which defects are considered. The aim of this framework is to consider how effective these systems are in responding to the causal conditions for defects.

Essentially, all forms of construction and associated materials will start to degrade even before the construction phase is complete. Deterioration is largely encapsulated by 'entropy' that is characterised as an increasing disorder in a system. The efficacy of design, detailing and construction of a building correlates with the severity and occurrence of defects and by extension may accelerate or decelerate entropy. Building related entropy clearly has a financial, social and more recently a carbon cost. The factors leading to entropy have been termed the 'Agencies of change' and are broadly characterised as, climatic agencies, and user activities (Watt, 2003). It is evident that recognition of problematic construction and design issues are rooted in antiquity. Alberti (1452) historically, documented these '*climatic agencies*' terming them as '*engines*' that include, damp, frost, and storm. Alberti (1452), broadens this evaluation of defects indicating that failure in buildings is associated with '*error of the mind and error of the hand*'. These could be overlaid today onto preconstruction and onsite construction issues. The evaluation of the performance of any (especially low carbon) innovative material, technology or build system must relate to agencies in order to minimise defects and carbon costs. Approaches to managing defects are thus important in helping to mitigate risks under different societal and political pressures. Defects also occur at different stages and present disparate challenges to alternative approaches. Furthermore, during periods of rapid advancement, it is necessary to understand the opportunities and limitations of alternative approaches mobilised at different stages. Approaches to identifying and managing defects can be classified as: traditional; scientific; and professional design approaches.

5.1 The traditional approach

The traditional approach to identify and rectify defects draws upon a history where construction designs, materials and build systems advance incrementally and are underpinned by evolutionary iterative processes (Addleson & Rice, 1991). Advances are thus small and slow. The approach is indulgent of lengthy trials where learning and development of innovations and change are incremental (Cook & Hinks, 1992). Consequently, the severity and impact of defects are low and empiricism enables easy and ongoing rectification of defects at source and within subsequent designs. The greatest advantage of this approach is that robust designs, materials

and build systems evolve slowly and are more readily and easily embedded in professional practice – principally because they do not disturb the dynamics of power to any great extent and thus are not contested and resisted. Strike (1991: 177) indicates that the *‘story line for each material or technique is never identical, but the recurring stages often include; inception of the idea, testing of the prototype, trial use, failure, gestation on the shelf, reinvention, retrieval, success through the construction of a seminal building, adoption, misuse, rejection due to failure or a change of fashion, introduction of legislation to control its use, gradual improvement of the material or technique, and finally general acceptance’*. This convoluted process is clearly unacceptable in any period but is especially concerning for the current technology shift that require rapidity and efficacy. This lengthy approach is problematic with time taken to learn and to correct defects at source and within subsequent designs incurs large wide-scale financial and carbon costs to society. Such costs run contrary to current policy objectives. Some of the risks and limitations of this approach during periods of rapid advancement can arguably be mitigated through a more scientific approach to the testing and evaluation of innovation in materials, designs and build systems. During periods where innovations are rapidly introduced at scale the risk of severe defects occurring at volume are clearly pronounced.

5.2 The scientific approach

The scientific approach manifests itself in the testing of products and designs (Yeomans, 1997) and draws upon scientific methods as *‘a means of predicting the likely performance of certain combination of materials ..., under given conditions, thereby reducing the time necessary for trials* (Cook & Hinks, 1992: 6). The approach however rather assumes that useful and reliable data is readily available within the sector (Yeomans, 1997) and that organisations in the sector can afford to embrace or commission sufficient science testing for accurate prediction. Construction defects borne of designs adopting innovations have been correlated with inadequate scientific research (Crocker, 1990). Incentivising the commissioning of minimum level testing to satisfy requirements of systems or materials accreditation schemes whilst relatively cheap, does create risk, as it does not extensively evaluate in-use permutations.

Reinforcing the scientific approach are the well-established research institutions such as the Building Research Establishment, the BBA, and a plethora of independent university research facilities. These organisations may investigate materials and technologies properties following British Standards but it is fair to say that conformity to the Building regulations and by-laws are no guarantee of defect free construction or satisfactory performance (Addleson, 1982). Additionally, technologies that have been tested in isolation (BBA) may perform less favourably when they are incorporated into wider design and construction systems. Indeed the inherent reductionism within the scientific approach and associated accelerated testing methods leads to research that *starts with the materials and components and progresses to the study of functional elements and then of the building as a whole* (Lea, 1959: 5). This creates the opportunity for poor evaluation of the holistic system as the complex build-up of components and elements risks losing sight of the ‘whole’.

5.3 The professional design approach

The professional design approach draws upon design expertise and professional judgement to manage the risk of defects arising from adopting innovations. It relies upon input from both the traditional and scientific approaches. Designer’s knowledge (explicit and tacit), largely a function of education and experience, is thus assumed to inform decisions to adopt innovations and underpin judgements about the risks inherent in predicting the severity and occurrence of defects. Notably, the impact of these decisions taken by designers transcends single professional and disciplinary boundaries (Yeomans, 1997). Such decisions are thus limited by the extent of a designer’s holistic understanding of construction technology, building performance and environmental and materials science. Effectively, building professionals do not currently offer a joined up service to deliver sustainable low carbon construction (Twinn, 2013).

In part, this limitation can be addressed by the use of design or design & construction teams that collaboratively make decisions and can more confidently predict the risk of defects. This assumes of course that such teams are afforded time to rationally and holistically predict risk and carefully consider the impact of decisions on defects. It also assumes that the commercial arrangements underpinning team members motivation, available resource and scope of work do not impact upon and shape professional judgements and by extension the risk of defects. Indeed, the extent to which professionals are currently incentivised to focus on long-term goals such as defects over the life of a building rather than short-term goals is questionable (Aho, 2013). These assumptions and limitations have previously prompted calls for formally incorporating defect eradication and a *‘design freeze’* as integral components of design decision processes (Davey *et al* 2006; Koskela & Huovila 1997; Koskela, 2003). The identification of defects at a pre-construction stage will slow the design process down and potentially

delay the diffusion of technological innovation. These tensions will always be present especially if project time scales are tight.

The recognition of the need for inter-connectivity between scientific method and professional design approach is clearly established. It is however, understandably difficult for a design professional to readily digest and implement the findings of often complex and disparate results of scientific analysis relating to products and broader assemblages within design parameters. This has also prompted an emerging debate in the literature questioning the nature, legitimacy and ability of professionals and professional institutions to, for example, facilitate innovations and deliver low carbon construction (see Hughes and Hughes 2013; Janda and Parag 2013; Duffy and Rabeneck, 2013).

5.4 Methods to obviate defects

Tried and tested methods of construction are responsible for detailing and details that have evolved into the development of what are today termed, 'robust details' (Zurich, 2005: 159). Robust details are in many ways a reaction against the uncertainty of innovation and are produced to mitigate risk associated with defects (BRE, 2002). It is logical that insurers such as Zurich will initiate a new set of 'robust' details using the new technologies, but this will require redesign over the longer term, bearing the cost of failure. This reliance on well established design and detailing appears well founded when considering that it has been estimated that the cost to remedy a defective detail is three times as expensive as the construction of the original (Atkinson, 1995). It is therefore clearly obvious that 'getting design right' is far more effective than 'putting it right' (Atkinson, 1995) and strengthens the argument and necessity for well considered, rigorous defect focused design. As a result of this situation, Wigglesworth (1976: 252) believes that '*there is less indulgence of untested innovation*' and '*far more reliance is (now) placed on available recommendations for good practice*'. Today this may be less pronounced as technology and science are used to validate new technology. In addition, it could be argued that robust details 'dumb down' the designer's ability to evaluate performance from first principles as the analytical skills have not been regularly required with the copy book method. However, they are effective at obviating defects within known technological boundaries. The difficulty is that rapid advancement goes beyond these established and accepted boundaries.

The potential for the occurrence for defects is increased with the use of individual, somewhat disparate technologies. However, failures may also be grouped relating to whether they are 'systems' and / or 'material' failures (Heckroodt, 2002). The use of these requires an excellent understanding of construction technology, detailing and aspects of environmental design performance. This mix and match of technologies may create increased complexity and therefore difficulties in terms of modelling the performance of the technologies. Addelson (1992: 3) indicates additional lessons for designers in so much as it is imperative that they understand the combined use of materials, and pay particular attention to the appreciation of multi-layer construction. This problem is exacerbated as the '*materials and components do not necessarily come from the same source for all contracts*' (Douglas and Ransom, 2006: 12). The technological permutations would be extremely large and could not be evaluated prior to certification. Conversely, it could be argued that new systems would reduce this situation with bespoke and relatively robust details being an integral consideration at the design stage and subject to high levels of scrutiny. This approach is reflected in holistic testing offered by the BBA. It is evident that operative and designers know the weaknesses and limitations of well tried materials and accommodate for this in their designs (NBS 1964). Conversely, an unfamiliar technology or material will be susceptible to these limitations and increase risk of performance failures.

Whilst enhanced experimental procedure and understanding of materials is noted, testing and lab work is costly and in many cases out with the capability of those wishing to develop and diffuse innovative materials. The evaluation of interconnected, holistic performance is difficult to achieve in a laboratory simulated environment and products tested in isolation may perform unsatisfactorily. Regimes specifically focusing on determining complex systems interaction, interconnected materials and multi-layer construction performance may be better equipped to simulate real world environment.

Garau *et al* (1996) have undertaken educational research into the relationship of design and construction highlighting a 5 step approach for analysis and identification of pre construction defects. The core of this work analyses the environmental conditions that buildings will be subject to and the designed fabric. This theoretical evaluation process requires; i) the identification of the theme and context, including, typology, morphology and technologies, ii) determination of environmental characteristics, including topography of the site etc. iii) evaluation of current regulations, codes of practice and standards and the proposed projects compliance to, iv) comparative analysis of similar existing structures, v) synthesis of findings. Whilst important, lessons can be

learnt from this approach, but clearly, the efficacy of this framework is diminished in the case of innovative low carbon construction due to an inability to undertake comparative analysis from existing structures and because the evaluation of current regulations for low carbon construction methods is often ill defined or embryonic in nature. The importance placed by Garau *et al* (1996) on environmental conditions is critical. Understanding and ultimately building to accommodate climatic conditions and exposure, are primary design parameters (BS 8104, 1992). The interrelationship between design, materials and detailing is essential for good holistic long term performance and avoidance of premature failure (Crocker; 1990; Forster & Carter, 2011; Cairns, 1994). Traditional evolved design and weathering features were borne out of the hostility of the climatic conditions that a structure would be exposed to, and were responsible for regional vernacular building aesthetics (Clifton-Taylor, 1987; Brunskill, 1978). Breaking this tradition and altering design towards modernist architectural forms and unfamiliar construction systems has increased the rate of defects (Cook and Hinks, 1992; BBC, 2011; Marsh, 1977) particularly moisture related issues such as penetrating dampness (Oxley & Gobert, 1994)

Another method for evaluating pre construction defects (Addleson & Rice 1991) has the idea of ‘creative pessimism’ at its heart. This concept is based on unfamiliarity with materials, and a difficulty to predict the performance of elements. The purpose in the widest sense is to focus on reality and to mitigate against risk. This method is theoretically more defensible, but only directs the evaluator to the broad aspects to consider, and relies on the investigator to have an extremely high knowledge base and experience. The professional requires the ability to understand, apply and predict the performance of structural and non structural materials, multi layer, highly complex assemblages that are exposed to variable environmental conditions. The approach relies upon the adoption of 5 key concepts (Addleson & Rice, 1991):

- i) **Creative pessimism**: characterised as the ‘*inevitability of variations and uncertainty generally*’. It is a function of almost certain eventual failure in ‘*knowledge of materials, of the performance of elements and how buildings are designed, built and used*’
- ii) **High / low**: associated with thermodynamic principles or driving forces acting upon a structure. These can include heat and mass transfer, pressure differentials and forces creating movement, gravity and materials chemical reduction (i.e corroding metal, or deteriorating stone)
- iii) **Separate lives**: associated with movement in or between materials, due to thermal, moisture, structural instability, differential durability or degradation rates. Incompatibility of materials may also be categorised under ‘*separate lives*’ with chemical reactions causing separation, debonding and unwanted movement.
- iv) **Continuity**: is the concept that ‘*no material can be expected to perform its intended function fully if it is not continuous*’ (eg. insulation).
- v) **Balance**: is the recognition that buildings seek to create rebalance. Rebalance is related to the concept of ‘*high/low*’ and can be practically exhibited in rebalance between internal and external environments.

The principles are clearly interrelated. The principle of ‘*high > low*’ and ‘*separate lives*’ are considered as being constraints, whilst the principles of ‘*balance*’ and ‘*continuity*’ are the objectives. ‘*Creative pessimism*’ acts a control. A change in the high > low parameters will directly trigger a corresponding need for alteration in building performance to achieve balance. A change in ‘*separate lives*’ will alter the materials ‘*continuity*’ and will result in loss of performance and cause deterioration. These direct relationships between constraints and objectives can also be correlated with the remaining principles (Addleson & Rice; 1991). To obviate risk and enhance performance, the principles (the principles never change) should be used in conjunction with ‘*rules and precautions*’. These are continuously changing as scientific knowledge advances (sometimes rapidly). Addleson & Rice, (1991: 20) indicate that ‘*rules*’ are primarily ‘*design oriented*’ and ‘*precautions*’ are generally ‘*site or maintenance oriented*’. An example of rules could include ‘*mortar should not be stronger than the host masonry*’. Whilst an example of the ‘*precautions*’ may include ‘*using cavity battens to avoid mortar droppings*’.

The application of the protocols outlined by Garau (1996) and Addleson & Rice (1991) for use upon innovative technology would be undoubtedly beneficial. It would be logical to focus on the predominant and recurring defective areas of construction that according to BRE housing survey (1982) are manifest as follows; external walls, 20%; Roofs, 19%; Doors and windows, 13%; Floors, 11%; Services, 9%. A targeted, systematic and comprehensive approach may have the potential to yield significant and transformative results.

6.0 DISCUSSION

Sufficient commonality exists between post World War II and today to initiate a heightened vigilance in the identification, evaluation and ideally the obviation of defects. Drivers have modified to include environmental impact and these are resulting in innovation in technology and materials. The urgency for delivering low carbon

volume housing is pronounced with a severe shortage of low cost, affordable, dwellings being a significant cross party political issue. Four key themes that characterise both periods are: i) an emphasis on innovation; ii) emerging defects; iii) an over reliance on scientific research; and, iv) fragmented professional responsibility and a lack of meaningful collaboration.

It appears that limited real change in the ability to identify defects has occurred since the post World War II period and our ability to predict the performance of innovative systems and materials is therefore questionable. The legitimisation of innovative systems is validated by scientific research which does not satisfactorily address the complexity of real world environments. Complex design tools (i.e. energy modelling software) offer a promise of performance. The faith designers place in the output of these becomes enshrined in the building itself. The actual performance frequently falls short of design predictions, and this seems to create an environment for defects to emerge over time. Increased emphasis on the performance of detailing at the design phase, and an active consideration of a building's performance over its life span, offer opportunities to reduce the prevalence of defects. Sharing knowledge on a buildings' performance is not in the culture of building professionals. Failure of a building is never celebrated and the valuable lessons from a building defect are rarely advertised and are therefore lost.

Our approaches to appraisal are still embedded in the three principle methods set out earlier: traditional; scientific; and professional design. Design evaluation is not expressly or sufficiently defect focused. A tacit and potentially haphazard approach for the determination of defects is prevalent within the design approach. This is reflected in an intuitive 'feel' for defect identification as opposed to an expressed evaluation protocol being applied. The application of the five precautionary principles outlined by Addleson and Rice could become an expressed design mantra that may be embedded into practice and education alike. A design freeze required to enable '*creative pessimism*' and consideration of how well details work could be readily introduced. Slowing project time frames down to incorporate a meaningful period for evaluation of defects at design stage is however at odds with the fast pace associated with modern procurement. Creating time has a cost implication that needs addressing robustly within project teams and fee structures. This requires a change in attitude to the concept of value. Value associated with design focuses on the immediacy of creating a piece of architecture, and tends to not emphasise long term performance.

Confidence in the system of deemed to satisfy details has developed from an evolution of historic failure. Uncertainty with innovative detailing and materials relies in the faith that designers put in these systems. Independent design professionals insufficiently emphasise the importance of defect identification and holistically evaluating problems in design fail to be influenced by their professional training and education. A silo based mentality with fragmentation of professional responsibility debases the efficacy of defect identification. Failure to work in meaningful, collaborative cross professional manner hinders the defect eradication process. The creation of a cross construction and design profession platform offers opportunities to the understanding of defects. The war time propaganda slogan '*Combined operations include you*' has never seemed so appropriate!

In a bid to respond to the urgency of sharing information on defects in shorter time frames various systems are available. A move to document the performance of buildings through Post Occupancy Evaluation (POE) is evident in various sectors, including government sponsored research and commercial services (BRE, Arup, RIBA, RICS). Although useful to understand the overall performance of a building, this approach works at a whole building scale and does not necessarily consider the scale of a construction detail. A more suitable mechanism for collating information on defects is the 'defects liability period' associated with contractual requirements. This process is an explicit, time bounded approach to identifying defects. Contractual and financial pressures result in a forensic analysis of a piece of work that is not in accordance with the contract. However, as a means to reduce incidence of building defects, resistance to share the information is entangled in contractual sensitivity.

Although the concept of creating a body of knowledge on defects in innovative building systems holds legitimate merit, the reality of revealing failings in building delivery is at odds with business sense. Even if the process could be anonymised to bypass this systemic difficulty, the ability to collate and share knowledge of defects in a useful manner requires a certain amount of contextual information that means that anonymity could not be reasonably achieved.

Combining knowledge of defects into modelling software is an important step to improving the outcomes of the design process. As software improvements result in greater accuracy in building design the ability to test

building systems becomes possible at the design stage. However, before the software incorporates the array of possible outcomes, reliance on computer generated performance outcomes builds huge error into the predictions. The focus on recurring issues or ‘hazard’ design areas associated with defects, such as wall and roof construction is prudent. The integration of the concept of ‘creative pessimism’ into developing BIM systems and modelling simulations are required.

7.0 CONCLUSIONS

Sequential delivery of a construction project as set out in section four does not offer adequate opportunities to obviate defects. This has been shown through the analysis of the causal conditions found at each stage. The evaluation shows there is very little connection between the practice and knowledge that could be utilised to reduce the frequency and severity of building failure between different phases of a project. The conceptual framework was used to explore the existing systems and their ability to reduce defects.

Approaches to appraisal are still embedded in the three principle approaches: traditional; scientific; and professional design. Each of these systems have positive characteristics and address defect mitigation within constraints imposed by their very nature. However, they all fail to address the full spectrum of conditions that lead to defects. The positive characteristics of each system need to be recognised and brought together in an holistic system that offers tangible advantages. The traditional approach enables wide dissemination of knowledge across the sector. The scientific approach accelerates the development of new knowledge and the professional design approach enables creative solutions derived from both. If these positive attributes were combined in a single project delivery system the benefits would cumulatively result in reduced incidence of defects.

Regrettably, design evaluation is not expressly or sufficiently defect focused and it appears that limited real change in the ability to identify defects has occurred since the post World War II period. Our ability to predict the performance of innovative systems and materials is therefore questionable. Independent design professionals insufficiently emphasise the importance of defect identification and holistically evaluating problems in design fail to be influenced by their professional training and education. A silo based mentality with fragmentation of professional responsibility debases the efficacy of defect identification. Failure to work in meaningful, collaborative cross professional manner hinders the defect eradication process.

The carbon cost associated with addressing the consequences of emerging defects over time significantly jeopardises attempts to meet legally binding sustainability targets. Blindly accepting this as ‘the cost of innovation without development’ cannot be countenanced. The potential for history repeating is significant and clearly society can ill afford the financial and carbon cost to be borne. The war time slogan, ‘*Warning! Our homes are in danger now!*’ could be poignantly rephrased as ‘*Warning! Our proposed ‘green’ homes are in danger now!*’

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