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Designing resilient housing for co-evolutionary adaptivity

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Abstract

Buildings and communities need to be more resilient in the face of increasing weather extremes due to climate change. Current building models lack adequate definition to address this new challenge. This paper defines resilient design in terms of four ecosystemic factors: robustness, redundancy, feedback and co-evolutionary adaptivity. It builds upon previous work on usability and extends this to include resilient performance in relation to three new UK case studies covering retrofit and new build housing. In each case usability studies are evaluated in terms of resilient design. Key areas of concern identified in the studies relate to the vulnerability of centralised ventilation systems and the lack of interactive adaptability in relation to the construction systems adopted. Lessons learnt and recommendations are highlighted for design guidance and policy consideration, including a greater focus on delivering low carbon homes that are able to be more resilient over time through co-evolutionary adaptivity.

Keywords: low-carbon housing, resilience, user, adaptivity

Introduction

The latest contribution to the Intergovernmental Panel on Climate Change's fifth assessment report (IPCC, 2014) confirms the virtual certainty of more frequent hot and fewer cold temperature extremes over most land areas, increased heat waves, occasional cold winter extremes, and significantly increased precipitation. These increasing extremes are already generating significant increases in flooding, storms, wind speeds as well as new temperature records which demand an urgent response from building designers, product manufacturers and occupants. This paper sets out a number of key interrelated issues concerning the performance of environmental controls in UK housing, which need to be tackled in terms of climate change adaptation. It then sets out a definition for resilient design for buildings in terms of four systemic factors: *robustness, redundancy, feedback and co-evolutionary adaptivity*. Three new UK case studies covering retrofit and new build housing are examined to see how well key environmental controls in the home perform in each case in relation to these factors. Usability studies are evaluated in terms of resilient design principles, in order to extract key lessons for improving environmental control in housing over time. The paper concludes with a wider discussion about the direction of research and policy in relation to the issues raised.

The environmental 'control' problem

Future overheating issues in the existing UK housing stock as a result of climate change have been widely discussed and modelled at the level of potential building and neighbourhood interventions which take account of socio-technical and economic challenges (Williams et al, 2013) (Gupta and Gregg, 2012, 2013) (Porritt et al, 2012). More worryingly, *current* overheating in new PassivHaus homes in Belgium has already been highlighted in detailed post-occupancy studies, with summer indoor temperature regarded as too high by up to 50% of occupants, particularly in living rooms and kitchens (Mlecnik, 2013).

There is a clear need for more detailed understanding of how well occupants are currently able to mitigate overheating at the level of environmental control available to them in order to improve predictive modelling as well as closing the actual performance gap (Stevenson and Leaman, 2010). Yet, standard building simulation software and regulations do not take account of climate change, even though data is available (e.g. Prometheus using UKCP09 modelling). While there is some guidance on designing buildings so that they can adapt to climate change (Gething and Puckett, 2013) this tends to be at the level of imposed product solutions (Porritt et al, 2012) rather than designing buildings so that people and buildings can adapt to and learn from each other over time (Brown and Cole, 2009). Equally, the discourse about how 'smart' buildings should respond to climate and occupant behaviour tends to be framed in terms of improving an increasing use of technology (Mlecnik 2013) rather than de-mechanisation (Ford 2012) which would potentially increase the resilience of building systems.

There is growing recognition of the need to deal with probabilities of changing conditions related to our weather rather than assuming any certainty (IPCC, 2014). The optimisation of building solutions provided by current building simulation modelling and building standards is therefore no longer valid in itself, because it does not take into account means of dealing with failure and uncertainty related to environmental control. Optimisation in itself does not provide the breadth of response that is required either in terms of unpredictable heating or cooling, or indeed in terms of 'unthinkable' events which are outside current frames of reference in relation to building design. More worryingly, there is persistent climate change denial both at an institutional and personal level in terms of how people choose to act which permeates through human society, given that two thirds of the UK population disavow climate change (Royal Society of Arts, 2013). This means that people accept the reality of climate change but choose to minimise its importance in their lives. This in turn affects the research and design community given that the environment is still framed as something that can be 'controlled' with appropriate measures, rather than a recognition that we face chaotic situations in the future.

Resilient interactive adaptivity

One response to all of the above is to design buildings and communities to be more resilient – defined here as being able to '*resist, absorb, accommodate to, and recover from unpredictable climate change effects in a timely and efficient manner, while preserving and restoring essential basic structures and functions*' (UNISDR, 2009). There is, however, a wide discourse on resilience with many different definitions of the term (Hassler and Kohler, 2014a). The principles of fundamental resilience used here, drawn from Biggs et al (2012), are based on making environmental services resilient in terms of a 'socio-ecological system' (SES) which takes account of how human communities interact with their environment (fig.1): (P1) maintain diversity and redundancy, (P2) manage connectivity, (P3) manage slow variables and feedbacks, (P4) foster an understanding of SES as complex adaptive systems (CAS), (P5) encourage learning and experimentation, (P6) broaden participation, and (P7) promote polycentric governance systems.

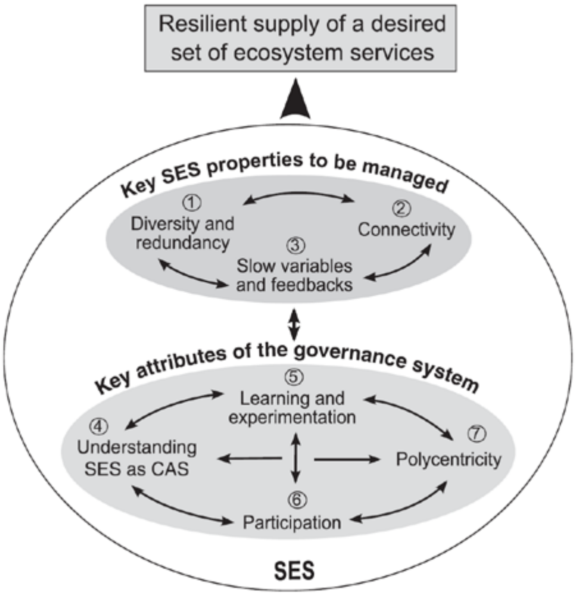

Figure 1. Resilience Properties and Dynamics, taken from Biggs et al, 2012.

Drawing on these principles for SES, this paper reframes resilient building design in terms of four ecosystemic factors which are directly related to the usability of a building: *robustness* – the degree to which a building can withstand the various shocks of climate change (P1), *diversity and redundancy* – the number of different ways in which a building can respond to these shocks, beyond the optimal solution (P1), *feedback* – the ability for a building to provide users with a direct understanding about what is happening (P2, P3) and *co-evolutionary adaptivity* – the ability for buildings and users to mutually develop their ability to respond to changes through time including climate change (P4, P5). P6 and P7, relating to governance issues, are beyond the scope of this paper but need further work to ensure buildings are properly managed.

Existing work on usability (Stevenson et al 2013) is theoretically extended here to include these four resilience factors. In terms of robustness, this includes the ability to maintain and repair any fabric, system or equipment designed to support buildings in delivering safe and healthy environments. The more active technological systems are provided in housing, the more maintenance and care for them is required. Appropriate maintenance also requires awareness of what is required (feedback). The concept of a resilient building should not only cover the features built into a building but also *the quality of interaction a building offers to its users, their understanding of what is offered and expected of them, and their ability to turn the understanding into action as circumstances change.* This has previously been termed 'interactive adaptivity'(Brown and Cole, 2009). Interactive adaptivity, however, has to take on an evolutionary dimension to ensure resilience over a longer period of time, and is thus defined as 'co-evolutionary adaptivity' in this paper. As Briggs et al (2013 p.427) point out:

> *Understanding the relationships between diversity, redundancy, and resilience requires the development of practical methods for measuring diversity and redundancy and for identifying critical processes or keystone entities in different SES. Identifying and managing these vulnerable points may be the most effective way to maintain the resilience of ES (ecosystem services).*

It is the last point that is of crucial relevance to the co-evolutionary adaptivity of buildings - the vulnerabilities in the design of environmental control interfaces and their interaction within a building. If these vulnerabilities can be identified, then suitable diversity and redundancy can be built into the building systems design to ensure that if there is a system failure, occupants have an alternative sub-optimal means of achieving the same effect in terms of environmental control. The use of case study methodology is an excellent way to identify such vulnerabilities in current building design.

Case Studies

Three new case studies (fig.2) have been selected from a spectrum of recent housing developments which represent different building typologies and demographic factors but within a similar climate and culture in Northern England. This allows for a greater degree of comparability (Table 1) (Flyvbjerg, 2006).

Figure 2: LILAC (above) and Saxton west (middle left) and east view (middle right). Photo MBN, Lancaster (below) Photo FS.

The studies have also been chosen to reflect very different housing energy standards operating in the UK. The four resilient design factors are examined in relation to the comparative performance of the housing developments built to each of these standards. Data for the case studies was gathered from March 2012- January 2014.

Case study	Lancaster Cohousing	LILAC Cohousing	Saxton Gardens
Completion	2012	2013	2011
Location	Semi-Rural	Urban	Urban
Size + units	Medium**,** 35 units Owned	Medium**,** 20 units Mutually owned	Large**,** 200 units Owned/rented
House types	New build terrace houses/ apartments in blocks	New build terrace houses/ apartments in blocks	Refurbishment 1950's apartment block
Fabric materials	Masonry and timber frame, clay roof tiles, timber floor	Straw/timber panel system, flat roof, concrete floor	Concrete structure and slabs, SIPS panels, flat roof
Energy, heating and ventilation features	PV panels, MVHR, communal biomass/solar thermal, radiators	PV panels, MVHR, natural gas boilers in each home, radiators	MEV, thermostatic programmed electric heating panels
Energy standards	Passivhaus certified, 'Zero Carbon' Code for Sustainable Homes level 6 (UK)	Code for Sustainable Homes Level 4	2006 Building Regulations for retrofit in UK Eco Homes Very Good

Table 1: Case study characteristics

Methods

In each of the case studies, an evaluative usability sub-study, as developed by Stevenson et al (2013), has been cross-related to commissioning checks on the heating and ventilation systems, occupant guidance, and construction audits, which were carried out as part of wider building performance evaluation studies[1,2]. In the Lancaster case study, supplementary reference is also made to six semi-structured 45 minute interviews as well as a BUS questionnaire on control and comfort. The initial usability study carried out at Lancaster was subsequently developed into an interview-based multiple choice questionnaire for wider use at the LILAC and Saxton Gardens case studies with comment boxes to elicit quantitative and qualitative information. Results for the usability surveys were obtained from one typical house in Lancaster, together with 7 houses and 12 apartments at LILAC and 20 apartments at Saxton Gardens. User 'touchpoints' are defined as anything in the home that the user physically touches in order to provide environmental and comfort control. Although the 'touchpoints' are normally divided into 7 categories, only the heating and ventilation user controls (considered in the widest sense) are considered here in relation to achieving thermal comfort, as these are widely recognised as the key challenge in UK housing at present related to climate change and overheating issues. These are examined in terms of the degree of compliance with the four resilient design factors identified above. The findings from these are set out next.

Heating feedback and user understanding

Heating controls and feedback across all three case studies proved problematic in terms of user understanding. Just under half of occupants in LILAC did not know what the boiler controls were for, although the heating programmers were generally understood. However one LILAC resident commented: *'I don't understand the relationship between the boiler, thermostat and the heating controls'*- an issue that was shared among a number of occupants. In Saxton Gardens, less than half the occupants knew what the programmer on the electric heating panels was for in relation to time settings (fig.3), although nearly all understood how to change the temperature setting on the panel heater, as demonstrated by one occupants observation: *'Electric panel heater control isn't very clear to use. I just use the on/off switch. Electric panel temp control – we always have it on the top setting'*

Figure 3: Saxton panel heater controls - timer (left), power switch and temperature (right)

A significant number of occupants in both LILAC and Saxton Gardens also did not know how to operate the Immersion Hot Water Cylinder with a typical comment from one resident in LILAC summing up the situation:

> *I don't understand how the tanks work or the relationship between the large and small tank. I don't know how to interpret the temp reading on the small tank (thermal) or understand when I would use immersion heater on this system.*

In Lancaster, the main problem was the heating programmer, which was poorly sited in some cases, and the thermostat, which had an unnecessarily complex 'Eco-button'. An issue that compounded the situation at Lancaster was the high degree of thermal mass which resulted in a relatively slow thermal response. This took time for occupants to adjust to and understand. The adjustment was one way, with no co-evolutionary adaptivity present insofar as these building systems did not 'learn' from the occupants and could not be adapted by the occupants to suit their needs.

Ventilation feedback and user understanding

The understanding of ventilation systems presented much more of a contrast across the case studies. In Lancaster, the system was well installed with a good level control and careful occupant induction – something that many PassivHaus developments have achieved. The mechanical ventilation heat recovery (MVHR) unit control panel was found easy to use and a change in air movement, plus a slight increase in the sound of the MVHR system gave a good indication of response (feedback). By contrast in LILAC only two out of 18 occupants understood what the MVHR unit control panel was for or how it worked. Just over half understood what the boost was for, while just over two thirds understood the cooker hood extract. This was despite an induction session (although some occupants missed this) and a home user guide that had been extensively revised following consultation with the researchers. Even so, the guidance on the ventilation system was not particularly easy to understand.

The Mechanical Extract Ventilation (MEV) system in Saxton Gardens should be as simple to control as the MVHR systems in the other two case studies. However, occupants failed to understand the use of the complex humidistat control introduced to meet Ecohomes 'Very Good' certificate. The control located high on bathroom wall allowed them to alter the relative humidity limit from 40-90%. This backfired, because occupants had no idea what the figures meant and in the course of a trial and error ‘learning’ process some occupants turned the dial to maximum and left it at this setting, losing interest in a control that did not respond to any actions taken. The lack of response was also partially due a result of occupants switching off the bathroom MEV fan altogether, allowing these areas to remain unnecessarily humid. This did, however help to reduce the noise level of the MEV system, which was a persistent complaint of many occupants. However, most occupants simply switched the MEV system off altogether. This was despite good written guidance on how to use the system being provided to initial occupants.

Resilient heating and ventilation

Heating systems

A requisite for co-evolutionary adaptivity is occupant understanding of the heating systems installed. In these case studies, it is difficult to see how this can occur, given the poor feedback provided to the occupant in relation to some aspects of these systems. In terms of robustness, redundancy and critical points of vulnerability, the Lancaster heating system currently relies on a communal biomass boiler system with solar thermal pre-heating. While this is very robust in terms of not relying on a natural gas central energy supply grid but having it there as a backup supply if needed, the heating systems in the homes cannot be upgraded with further radiators unless the communal boilers are already oversized to allow for this. However, additional electrical power is also generated through a robust communal photovoltaic (total installed capacity of 1.8 kW per dwelling) and hydro system (160 kW total for the development) which could in future help to provide alternative electrical heating in emergencies. By contrast, LILAC relies on a traditional natural gas supply directly from the grid for individual boilers in each home. This has a critical vulnerability in terms of the security of international gas supplies. Nevertheless, it also has a photovoltaic system (total installed capacity of 1.25 kW per dwelling) that could supplement a small amount of heating in emergency. Saxton relies completely on the national grid to supply electricity to the room heating panels in each home, and while electricity potentially offers the greatest diversity for heating systems, there is a critical vulnerability here in terms of predicted power shortages and failures for the UK in the future.

Ventilation systems

It would appear that MVHR and MEV systems can offer a good degree of systemic feedback to occupants, provided both good guidance and induction processes are in place, but that this can still be compromised due to other issues such as noise from imbalanced ventilation systems or occupants failing to remember what the controls are for. Resilient co-evolutionary adaptivity is difficult with mechanical ventilation systems because the occupant has no easy means of physically altering the installed system should circumstances change (e.g power cuts) – indeed they are explicitly asked not to interfere with the air inlets and outlets – although Lancaster occupants have learnt relatively quickly how to adapt to the system itself.

A key concern with mechanical ventilation systems lies in their degree of robustness and critical points of vulnerability. At the moment these systems do not necessarily switch on automatically after power outages with one Lancaster resident reporting:

> *The MVHR sort of tripped out after a power outage and stayed tripped out which is a bit of a worry because if you were away on holiday or something that happened, then you would be left without any ventilation in the house and you wouldn’t know about it. I don’t see why that unit should do that.*

This lack of robustness is compounded when other information systems also rely on electrical power as one Lancaster resident pointed out:

> *If you get a toaster it comes with an instruction booklet but the house user guide is on the internet...You can't access something with no internet connection and I think that is a failure.*

Windows and Doors

LILAC and Lancaster window and external door openings are roughly 50% of the overall glazed area, and can be opened wide while in Saxton about one third of the window area can be opened, but the opening is restricted to less than 10cm except for the sliding balcony door in some apartments (fig.4). The provision of robust and diverse window openings for night purging ventilation is critical in relation to climate change predictions for warmer summers in the UK – arguable a high degree of redundancy is required in window openings to cope with future conditions.

Figure 4: Windows in Saxton (top), LILAC (bottom left and middle), Lancaster (bottom right)

None of the three case studies have solar shading for the windows and external doors per se, which would help to avoid overheating both now and in the future due to climate change, although the Lancaster and LILAC developments have nominal shading offered by south facing balconies. Saxton has a few internal balconies also facing east and west which offer more solid shading but most windows are exposed to solar gain. Shading provision is increasingly important as temperatures rise as it is one of the most effective ways of mitigating overheating (Gupta and Gregg, 2013). In terms of feedback and co-evolutionary adaptivity, these windows are a very robust mechanism that can be readily adapted and easily understood by the user, providing excellent sensory feedback. They require no electrical power to operate them, unlike mechanical ventilation systems.

Construction fabric
The construction of each development is remarkably different and this greatly affects the overall resilience of the heating and ventilation systems. LILAC utilises the innovative Modcell© timber panel system infilled with straw for its walls and roof, achieving airtightness levels ranging from 1.54 $m^3/h^{-1}/m^{-2}$@ 50Pa to 4.30 $m^3/h^{-1}/m^{-2}$ @ 50Pa. Lancaster has a hybrid construction of double skin concrete block walls with 300mm mineral fibre insulation in between, and a timber frame with mineral fibre insulation on the south side with exceptional airtightness levels of <0.6 $m^3.h^{-1}.m^{-2}$ @ 50Pa. By contrast Saxton is only designed to achieve <7 $m^3/h^{-1}/m^{-2}$ @ 50Pa as per the 2006 Building Regulations for England and Wales. The original 1950's concrete stairs and structural system was retained in Saxton Gardens with columns and floors extended and clad with new lightweight SIP panel envelope punctured by extensive glazing.

Despite the majority of occupants completely switching off the MEV, the relatively poor airtightness of Saxton actually provided the robustness necessary for adequate ventilation even when all the windows are closed and the MEV is cut off. Lancaster has thermal mass which can help to even out excessive temperatures whereas the thermal mass in Saxton is largely isolated, leaving it more vulnerable to temperature swings, should the MEV fail, given the relatively limited ventilation openings. What this shows is that homes which have mechanical heating and ventilation systems need to have a degree of *overall* robustness and redundancy which can cope with unpredicted failures. This is discussed more widely in the next section.

Lessons for Co-evolutionary Adaptivity

1. Future proof our memories
The need to ensure that buildings are future-proofed in terms of sequential upgrades that respond to overheating has been picked up in the non-domestic sector where there is a need for natural ventilation control strategies to be '*remembered and retained*' within subsequent work (Short et al, 2012). Through the promotion of optimised standards and related packages such as PassivHaus, as applied in the Lancaster case study, we are actually witnessing a decline in the resilience of homes in terms of the ability for users to be able to ventilate naturally if mechanical ventilation systems break down. This is due to a tendency to optimise the number of window openings in relation to mechanical ventilation systems for cost purposes, with no allowance for redundancy and over-ventilation options to deal more resiliently with future unpredictable climate changes. Equally people are positively encouraged to rely on the MVHR systems rather than window use – the 'memory' of resilient natural ventilation control strategies is thus lost both to people and the buildings they live in.

2. Create redundancy and diversity in ventilation
A recent MVHR study (NHBC 2013) revealed that occupants were suffering from overheating in the summer of 2011 in the UK due to only being able to open a patio door and no windows in the lounge at night. Understandably, occupants were reluctant to open the door due to perceived security risks. A similar reduction in openable window area was observed in the Saxton case study. Such narrowly focused efficiency necessarily introduces other fragilities into the building system (Anderies, 2014). These fragilities are usually hidden from the user by virtue of the good design of the new MVHR or MEV system and are only exposed when the system fails. In the

same monitored UK housing development less than 1 l/s was delivered through each of the supply air valves in the living rooms due to the MVHR system being almost completely blocked by dirty flyscreens (NHBC, 2013) showing a critical vulnerability of the system. The total exhaust air flow rate, however, was measured as 29 l/s suggesting that that most of the make-up air was being supplied through fabric infiltration or doors and windows. As with Saxton, the housing fabric itself was able to afford the extra ventilation needed to ensure comfort, showing the overall home ventilation system offered some unplanned but essential redundancy and diversity.

3. Stress test for affordance

Introducing stress tests in housing for each good or service provided to make some predictions about how the system might react in extreme situations, could help to overcome some of the heating and ventilation issues highlighted in the case studies (Nicol and Knoepfel, 2014). A key issue here is to ensure that homes with vulnerable technologies such as mechanical ventilation systems are stress tested to ensure that they have other passive means of providing the same environmental control. Some have argued that it is difficult to incorporate such resilient design affordances for many different future climate change options if costs are to be kept within reason (Anderies, 2104) but there are examples, such as the Nottingham Solar Decathalon House (Ford et al, 2012) which demonstrate low cost resilient housing design which can cope with either warmer or cooler climates.

4. Develop passive co-evolutionary strategies

Miller et al (2012) discuss managing comfort related to warmer, subtropical conditions in an Australian context where resilient homes with passive features cope remarkably well. These conditions will increasingly apply to UK and Europe as predicted by climate change and urban heat island experts. Co-evolutionary adaptive strategies such as utilization of internal space (e.g. moving to a warmer/cooler location), using mechanical aids (e.g. ceiling fans) or operating the building fabric itself (e.g. opening and closing windows, doors, adjusting shading, adding reflectance etc) and even utilising outdoor living spaces will become increasingly important in making homes more resilient. It is vital that homes, such as those evaluated in the case studies presented, are future-proofed with a degree of redundancy to allow these features to be added or activated, given that resilience contains both a preventative and a recovery aspect.

Conclusion

This paper has evaluated the resilience of typical UK mechanical heating and ventilation systems in relation to their usability in three housing case studies, with mixed results in terms of feedback and co-evolutionary adaptivity. There are clear concerns in relation to some critical vulnerabilities of these systems which already affect occupants today and will almost certainly affect them more in the future. At the same time, a certain degree of robustness and redundancy has been revealed in the housing developments examined. It is essential that the drive for narrow efficiency does not iron this out in future housing developments or retrofitting of existing stock.

Cultural capital is a critical aspect of building resilience, through ensuring that tacit knowledge and understanding built up over a long time is preserved (Hassler and Kohler, 2014b). As Hassler and Kohler point out (2014a):

> *resilience depends upon sentience and capabilities that must be embodied within people (and not automated systems). The design of any system must provide clear feedback on its performance to allow for learning and adjustment.*

In terms of environmental control for occupants in their homes, we are seeing a memory loss in relation to highly robust controls (openable windows) which are rapidly being replaced by highly vulnerable and relatively untested controls (MEV and MVHR systems) as the ventilation system of choice in the UK, creating a path dependency that locks out significant cultural capital and reduces the existing resilience of homes. This has significant implications for policy making in the UK which is currently moving towards increasing and optimised levels of airtightness and mechanical ventilation in housing as a solution for reducing carbon emissions. It is vital that any new technology for housing is stress tested through the building regulations and equivalent performance standards for future climate change scenarios in terms of the key resilience factors identified in this paper. These stress tests need urgent and rapid development. Equally, legislation should ensure that passive co-evolutionary strategies for heating and ventilation that are already present in existing housing are recognised and not displaced by systems with increased vulnerability.

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Endnotes:
[1]Technology Strategy Board Building Performance Evaluation Programme, UK: Lancaster Co-housing Development: TSB BPE Phase 1
[2]EU FP7 Marie Curie Intra European Fellowship programme: BuPESA project

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