FLEXIBLE BUILDINGS FOR AN ADAPTABLE AND SUSTAINABLE FUTURE

Jonathan Gosling[1], Mohamed Naim[2], Paola Sassi[3], Laura Iosif[2] and Robert Lark[4]

[1,2] *Logistics Systems Dynamics Group, Cardiff University Innovative Manufacturing Research Centre, Aberconway Building, Column Drive, Cardiff, Cf10 3EU*

[3] *Department of Architecture, School of the Built Environment, Oxford Brookes University, Gypsy lane, Oxford, OX3 0BP*

[4] *Cardiff School of Engineering, Cardiff University, Queens Buildings, The Parade, Cardiff, CF24 3AA.*

This paper highlights how a flexible and adaptable approach to construction may contribute to the sustainable construction agenda. It explores the role of the adaptability of buildings in facilitating a realistic response to the challenges of sustainable construction. Techniques for defining the life cycle of an adaptable building are proposed and flexibility in design and construction as a means of facilitating adaptability is examined. A building adaptability system model is proposed as a way to rationalise flexibility and adaptability in the construction sector. In particular, systems dynamics techniques are utilised. A systems model of a facility and its adaptation in response to changes of use and changes in the environment is developed. Further work is required to characterise the life cycle loop and the relationships between different variables. Empirical testing is also required to determine the application of the concepts and models presented in this paper. The models developed herein invite comment on the opportunities and challenges that must still be met to facilitate the exploitation and development of such a concept.

Keywords: adaptability, building, construction, flexibility, sustainability.

INTRODUCTION

A myriad of forces, social, environmental and economic, have ensured that sustainability has crept up the agenda for governments, organisations and individuals. For instance, the UK climate change predictions for high, medium and low emissions scenarios predict increased mean temperatures that vary by as much as 2 ºC (Hulme *et al.* 2002). Uncertainty is also characteristic of the timing and impact of peak oil, which is expected to affect the availability and cost of fuel and consequently all commodities including building materials (Heinberg 2007).

These problems result in numerous challenges for the construction industry, which has wide reaching implications for sustainability. The sustainable construction agenda set out in the UK government document Sustainable Construction Brief 2 (DTI 2004) promotes minimising waste, energy and water use and pollution, while preserving and enhancing biodiversity, respecting people and local environments and doing so by setting targets and monitoring performance. These approaches primarily aim to reduce the immediate impacts associated with building activities. In addition it is increasingly essential to address the impacts that the building stock will have in the future, in fifty,

[1] goslingj@cardiff.ac.uk

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one hundred or more years, linked to its operation, maintenance and disposal. It is also critical for the building stock to continue to provide high quality environments for its inhabitants and that the development, maintenance and operation of such buildings remain economically feasible.

A more recent UK government document (DTI 2007), which aims to develop a joint sustainable construction strategy between government and industry states, the need to encourage the research, development and demonstration of innovative adaptation techniques and more durable systems and components to improve the built environment's ability to contend with the anticipated effects of climate change (DTI 2007: 31). Working towards a sustainable future therefore demands considering a range of building aspects and their immediate and long-term effects. There may be consensus that the future climate and economy will differ from today, but its nature and the timescale of change is uncertain. The challenge is therefore for buildings to perform adequately within the constraints of an unknown future scenario.

This paper explores the role of the adaptability of buildings in facilitating a realistic response to the agenda of sustainable construction. Techniques for defining the life cycle of an adaptable building are proposed and flexibility in design and construction as a means of facilitating adaptability is examined. A building adaptation systems model is proposed as a way to rationalise flexibility and adaptability

LITERATURE REVIEW

The benefits of adaptable buildings

Building technologies and designs that enable flexibility and adaptability have been identified as bringing a number of benefits. These are primarily associated with the requirements for upgrading and maintaining buildings throughout their life and enabling internal fit-out changes in high turnover internal environments such as retail facilities or offices. Slaughter (2001) identified that the cost and time of refurbishments is reduced if buildings are designed for flexibility. This is echoed in respect of building services. Webb et al's (1997) research examining how building services can be designed to accommodate change concluded that 'by utilizing reusable services components, facilities managers may be able to increase the adaptability of both new and existing buildings and reduce the financial impact of change'.

Slaughter (2001) further suggests that the need for changes to a building is increasing with rising consumer expectations, the increasing rate of technological progress and intensifying competitiveness. Some of the needs for adaptability and flexibility are well understood and building design solutions to address these needs are well established. For instance office partition systems designed to accommodate changes required to the internal configuration of offices are ubiquitous. Services and in particular IT systems have relatively short lives and are installed in buildings in accessible floors and ceiling systems facilitating their replacements. However, new needs are emerging, such as the need to provide for an ageing population which has resulted in the development of the principles of lifetime homes involving designing homes to accommodate the changing needs of its aging inhabitants.

In relation to climate change we are seeing changes to building regulations that aim to reduce the building's operational energy requirements. Refurbishments will be required to include an upgrade of the building to improve building performance. Such improvements may require significant changes to the building fabric that could be facilitated by designing buildings to be adaptable. The financial benefits identified could be replicated in respect of the changes needed to improve energy performance and cope with other performance requirements resulting from climate change. In a post-peak oil future these financial savings would be more pronounced as both energy and material costs are expected to rise.

Definitions of adaptability and flexibility

Flexibility is generally perceived as an adaptive response to environmental uncertainty (Gerwin 1993). More specifically, it is a reflection of the ability of a system to change or react with little penalty in time, effort, cost or performance (Upton 1994). Hence, flexibility may be seen as a proactive attribute designed into a system, rather than a reactive behaviour that may in fact result in a detriment to time, effort, cost and performance (Naim *et al.* 2006). Adaptability has also been classified as a capability and flexibility a competence, where capabilities are derived from lower level competencies (Swafford, 2006).

There is little agreement in the construction literature between the concepts of 'adaptability' and 'flexibility'. Edmonds and Gorgolewski (2000) for example, view adaptable buildings as incorporating, at the design and construction stage, the ability to make future changes easily and within minimum expense to meet the evolving needs of the occupants. Rappoport *et al.* (1991) consider that adaptability seeks to establish basic systems configurations that allow expansion and contraction of functional areas, but always within established fixed constraints. According to Edmonds and Gorgolewski (2000) adaptable buildings incorporate, at the design and construction stage, the ability to make future changes easily and with minimum expense to meet the evolving needs of occupants. It means designing a building to allow its hierarchical layers to change, each in its own timescale. Incorporating adaptability into a building during initial construction saves time, money, and inconvenience when changes are needed to designed later in the life of the building.

Addis and Schouten (2004) consider that a flexible building is a building that has been designed to allow easy rearrangement of its internal fit out and arrangement to suit the changing needs of the occupants. Groak (1992) defines adaptability as capable of different social uses and flexibility as capable of different physical arrangements (Groak, 1992: 15). We use the following definitions in this paper:

- adaptable building - a building that has been designed, constructed and maintained with thought of how it might be easily altered to prolong its life, for instance by addition or contraction, to suit new uses or patterns of use (adapted from Addis and Shouten, 2004)
- flexible building- a building that has been designed to allow easy rearrangement of its internal fit out and arrangement to suit the changing needs of occupants (Addis and Shouten, 2004)

Achieving adaptable buildings

Design for flexibility
Slaughter (2001) argues that three general types of changes can be expected to occur, changes in the function of the space, changes in the load carried by the systems of the building and changes in the flux of people and forces from the environment. General design approaches to increasing flexibility and more specific design strategies are also distinguished. The approaches proposed include physically separating the major building systems, prefabrication and overcapacity. The design strategies include reduce inter-system interactions, reduce intra-system interactions, use interchangeable

system components, increase layout predictability, improve physical access, dedicated system zones, enhance system access proximity, improve flow, phase system installation and simplify partial/phased demolition.

Schneider and Till (2007) categorise designs as either 'hard' or 'soft'. Hard designs refer to elements that more specifically determine the way that the design should be used over time. Soft refers to tactics that offer indeterminacy, allowing the user to adapt the plan according to their needs. They also refer to 'circulation', the way that rooms are accessed, and movable elements as key to flexible designs. The Open Building movement has also promoted flexible designs for buildings. Open Buildings seeks to respond to user's preferences by offering flexibility needed for adaptation of individual units over time. Buildings should be designed to enable sub-systems to be installed or changed with a minimum of interface problems. This is usually achieved by the separation of a 'base-building' and its interior 'fit-out' (Kendell and Teicher 2000).

Process flexibility

A process can be defined as any activity which takes a set of input resources which are then used to transform something, or are transformed themselves into outputs (Slack *et al.* 2004). Process flexibility refers to the ability of a process or system to adjust to and accommodate changes and disruptions (D'Souza and Williams 2000). In the context of construction process flexibility has mostly been described at the project level (Gil *et al.* 2005; Olsson 2006), referring to the ability to structure the project process so that it can accommodate late changes. For example, differentiation of works, where building subsystems are designed to be less susceptible to design changes, or offsite fabrication, where more concurrency between fabrication, assembly and onsite construction is offered (Gil *et al.* 2005).

METHODOLOGY

A systems dynamics approach to building adaptability is adopted in this paper (Mohapatra and Mandal 1989; Sterman 2000). A synthesis of the literature relating to flexible and adaptable buildings informs the development of conceptual models to rationalise adaptable building systems. A qualitative formalisation of an adaptable building system is articulated, which maps the dynamic forces that affect building performance and aids understanding of how the variables in this system interact. Coyle (2000) suggests that qualitative systems dynamics has 5 different purposes: to simplify a very complex problem, to facilitate discussion by showing the relationships between the items being discussed, to help to explain behaviour and generate insights, to help to identify the wider context of a modelling task and to provide the basis for quantitative modelling. Love *et al.* (1998) note that system dynamics is especially useful for modelling rework phenomena in construction.

Two models are presented in this paper to help understand the patterns of interaction and the underlying structure of the whole life cycle of a building system: the bathtub curve and a causal loop model. In the system dynamics field, casual loop diagrams (CLDs) are increasingly used as a visual representation of a feedback structure, otherwise portrayed by complex equations or stock-and-flow diagrams. A causal loop diagram can be used to quickly capture the hypothesis about the causes of dynamics within a system. It communicates the important feedback structures embedded in the system that are believed to be responsible for a certain problem. As such, CLDs consist of many causal relations between consecutive variables that combine to form a system.

As a visual method, a CLD consists of variables (nodes) connected by arrows that denote causal influences among the variables. Each causal link is assigned a polarity (positive or negative) to indicate how the dependant variable changes when the independent variable changes. The causal relationship between variables is positive if the effect is positively related to the cause, or negative if an increase in the independent variable causes the dependant variable to decrease. Each arrow could also have equations or rules that formalise how one variable affects another. Until now the technique has been used to understand diverse problems in many fields such as management, environment, socio-economics, medicine and engineering.

MODELLING BUILDING ADAPTABILITY: THE BATHTUB CURVE

A popular way of measuring the performance of a product and failure patterns over time is 'the bathtub curve'. Although the origins of the bath tub curve are unclear, it has been described in many standard reliability and maintenance text books (Klutke *et al.* 2003). Figure 1 shows that the curve is divided into three segments through its life cycle, the infant mortality period, usually marked by a rapidly decreasing failure rate, a random failure period, where the failure rate continues at a steady level, and a wear out period, where failure increases. More recently the bathtub curve has been applied to the reliability of building systems (Wu *et al.* 2006). The bathtub curve provides a useful framework for discussing the literature relating to flexible and adaptable approaches to construction.

Infant Failure Period

The infant period relates to the construction and project delivery process of a building. The aim at this phase of the life cycle is to minimise the time of the infant phase (t_i) and minimise the failure rate (f_i). Gil *et al.* (2005) refer to the importance product flexibility, the ability of the product design to accommodate changes in criteria after the design has been frozen, and process flexibility, the ability to structure the project process so that it can accommodate late changes, for project delivery. Olsson (2006) highlights the importance of project flexibility to the different stakeholders involved in a number of case study projects.

Random Failure Period

The random failure period (t_r) is closely tied up with the facilities management process. The aim during this phase is to maximise the time period of random failure and minimise the failure rate. Hodges (2005) urges facilities managers to consider the total cost of ownership through whole life cycle costing techniques as a route to more sustainable approaches to facilities management. Wu *et al.* (2006) also highlight that reliability analysis leads to an improved whole life performance of a building system. The need for flexibility in facilities management of offices is well illustrated by Patterson (1998). Agre (2005) provides definitions of adaptability types and descriptions of adaptability measures for different building elements in the office environment. The potential of flexible housing has also been well explored by (Schneider and Till 2007).

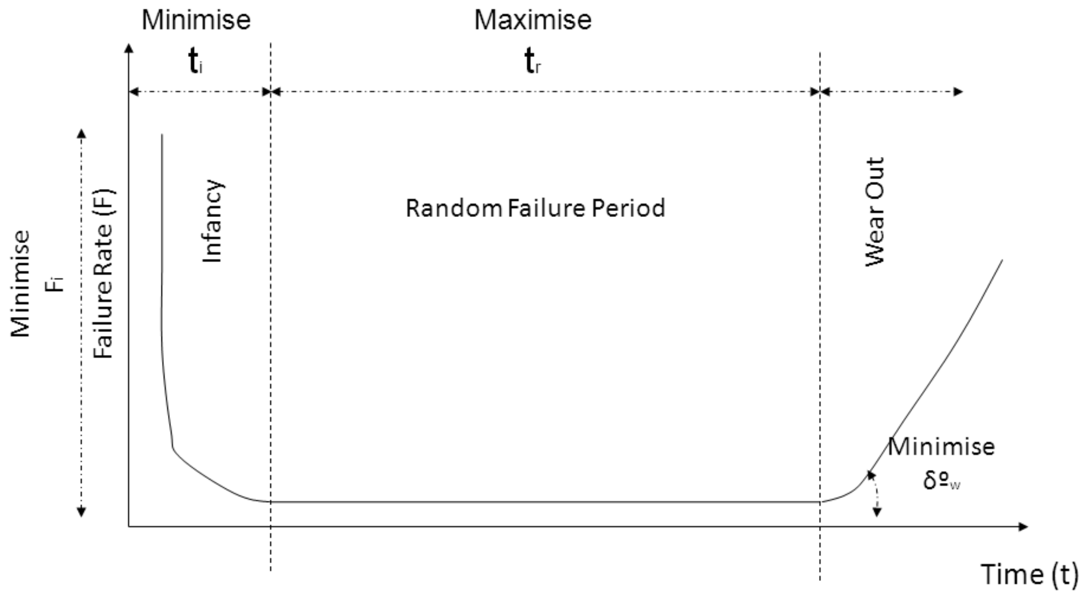

Figure 1: The bathtub curve (Source: adapted from Klutke et al. 2003 and Wu et al. 2006).

Wear-Out Phase

The wear out period refers to the end of life phase of a building. The objective during this phase is to minimise the angle of the wear out failure curve ($\delta^{o}w$). For example, Gann and Barlow (1996) address the possibilities and challenges of converting buildings through case studies of office to residential conversion projects. They conclude that greater flexibility is required to meet unforeseen changes in future use of buildings.

So while failure rate, F, may simply be expressed as a function of time:

Equation 1

Failure rate, F = f (t)

We can postulate that the optimum curve will result when the key characteristics of the curve, namely:

Equation 2

Failure rate, $F \rightarrow F_{optimum}$ as $F_i \rightarrow 0$, $t_i \rightarrow 0$, $t_r \rightarrow \infty$, $\delta^{o}w \rightarrow 0$,

MODELLING BUILDING ADAPTABILITY: A CAUSAL LOOP DIAGRAM

Figure 2 shows the causal loop diagram model we have developed to represent the building adaptation system. Building performance is the major variable of interest but in itself does not represent the building's 'fit for purpose'. That may be represented by two separate variables; user fitness (F_u) and technical fitness (F_t). Both F_u and F_t equate to the bath tub curve and the failure rate, F in Figure 1. Fu represents the difference between user expectations and building performance and Ft is the difference between technical specifications and building performance.

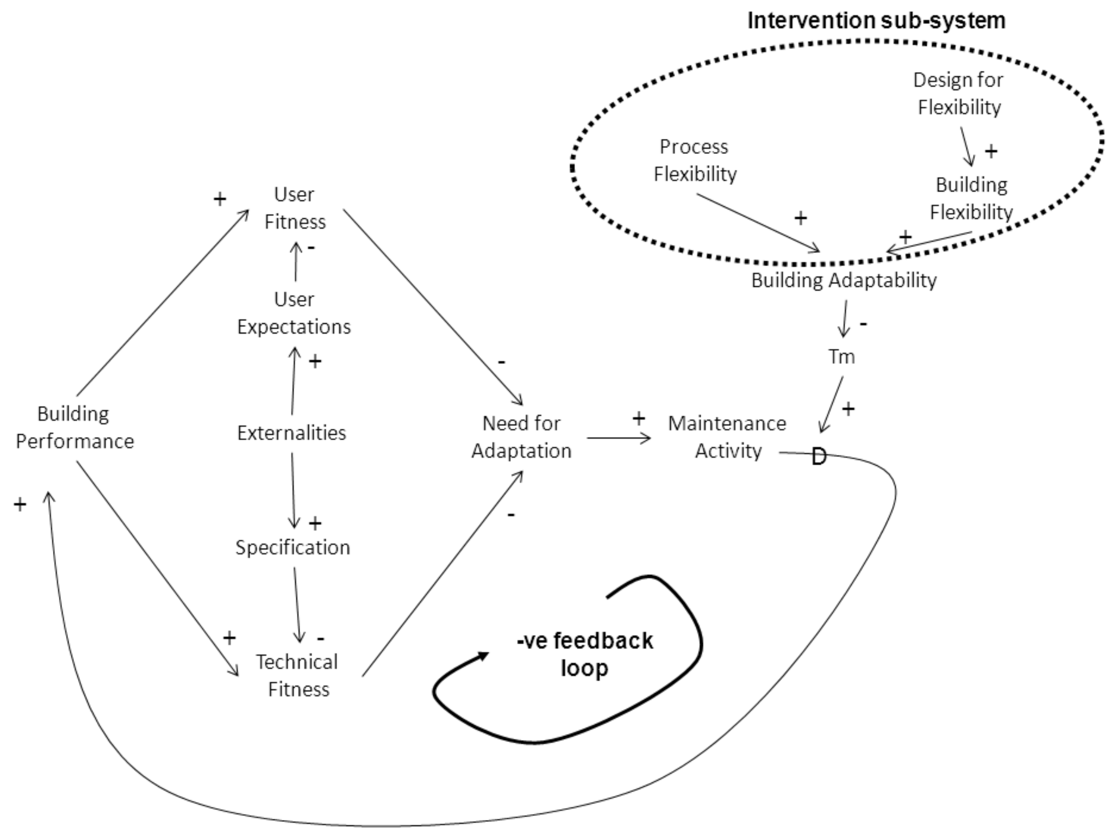

Figure 2: Building adaptation system (Source: Authors)

We postulate that user expectations and technical specifications are generically influenced by externalities, but what form those externalities take may be quite different. Hence, from a user perspective we may see requirements for change of use of the building or perhaps the running costs are too high. Alternatively, from the technical perspective we may find that, perhaps due to climate change, the building no loner conforms to thermal / energy specifications.

Both F_u and F_t then drive the need for building adaptation and hence maintenance, repair or refurbishment of the building. After a delay, defined by the time to undertake the maintenance, T_m, the building will then be brought to the appropriate level of performance. Hence we find a self regulating negative feedback loop in our system which endeavours to correct any detriment in building performance. If T_m is fixed then we have a linear time invariant system whose regulatory behaviour will be deterministic and known.

But how quickly and how efficiently this regulator works is dependent on T_m. As discussed previously, traditionally building adaptability has not been easy; hence we may add a sub-system than intervenes to improve the regulatory properties of the building adaptation system. By reducing T_m we then modify the system so that it is now time varying and we can make it faster in terms of building adaptation.

If a building is totally rigid, i.e. there is no opportunity for any adaptability what so ever, then this will result is T_m being extremely large and approaching infinity. Hence the delay acts as a constraint with no feedback in the system meaning that the building performance cannot be improved. If we were to treat this as a mathematical problem then we could say that the system has an adaptation value of zero. In contrast, for a building that is totally adaptable then T_m will tend to zero and the building performance may be instantly improved. Again, in mathematical terms we may say that the building is 100% adaptable.

CONCLUSIONS

This paper has reviewed the literature relating to adaptable and flexible buildings, which we argue are a realistic response to the sustainable construction agenda. A synthesis of the literature has helped to disentangle the relationship between flexibility and adaptability and has informed the development of a building adaptation model.

The causal loop model illustrated in Figure 2 gives us the ability to understand the influences on the building adaptation system. While the model is conceptual and generic, it provides an opportunity for enhancement of the model by adding other significant variables and/or providing more detail. This may be done at the macro level, to drive policy, or a micro level for individual building units. The model therefore provides a basis for discussion between stakeholders. Furthermore, the causal loop diagram may be translated into a simulation model to allow the testing of interventions under different scenarios.

The model would be used to quantify the variables and model the relationship between them giving a quantitative evaluation of building adaptability. It would allow stakeholders to distinguish buildings with a high potential for a long life with minimal environmental impacts. It could furthermore provide a basis to develop guidance for existing and new buildings for enhancing the adaptability to create long life buildings.

Further work is required to characterise the life cycle loop and the relationships between different variables. Empirical testing is also required to determine the application of the concepts and models presented in this paper. The model could also be extended to include a cost function that could be used to evaluate the cost and effort of different intervention activities. This could form the basis of a decision making tool for building providors. This paper invites comment on the opportunities and challenges that must still be met to facilitate the exploitation and development of such a concept

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