Paper No: 218 Totnes Eco House: interaction between design and in-situ monitoring

Jim Carfrae [1]*, Pieter de Wilde [1], Steve Goodhew [2], Pete Walker[3] and John Littlewood[4]

School of Engineering, University of Plymouth, Plymouth, UK[1]
*jim.carfrae@plymouth.ac.uk**
School of Architecture, Design and the Built Environment, Nottingham Trent University, UK [2]
Department of Architecture and Civil Engineering, University of Bath, UK [3] Shelterre, Cardiff, UK [4]

Abstract
This paper explores the decisions made during the design and construction of an award-winning Low Carbon House, and how these relate to ongoing in-situ monitoring of this home. Analysis of the design process uses the IDEF-0 modelling method, with the objective of investigating the factors that influence design decisions. The building is currently intensively monitored for thermal and moisture aspects. The house studied has been designed by the client/occupant. Important aspects considered within the design process were embodied energy and heating energy demands, which led to the use of local timber, straw bale, loose sheep's wool, lime renders and clay paints for the walls.

Keywords: Eco House, design decisions, process analysis, in-situ monitoring, moisture, straw bale.

1. Introduction

Architects, engineers and clients are increasingly interested in energy efficient dwellings and, in more general terms, structures that are benign to the environment. Depending on the specific properties of the design; the resulting buildings might be named Zero Energy Houses, Low or Carbon Neutral Homes, Passive Houses or, more generally, Eco Houses. Many case studies of this type of building have been described in literature.

In the United Kingdom, one of the original Eco Houses was designed by Robert and Brenda Vale [1]. Their buildings tended to be designed with a view to off-grid living and the virtues of stand alone power supply, with minimal reliance upon off site water and waste removal. Other Eco Houses tend to focus their design and other attributes upon themes, such as the use of site related opportunities/constraints. Passive solar houses such as those exemplified in the Milton Keynes energy park and built in the early 1990s used many design techniques advocated at the time by the AA [2]. If this route was exclusively followed it would be possible to design an Eco House without reference to the environmental implications in the choice of materials and use of low impact construction practices. More modern thinking however relates a raft of more interconnected and additional drivers, including the social and economic elements as well as the environmental aspects of sustainability. A comprehensive guide to sustainable construction has been produced by Sandy Halliday [3].

Eco Houses now often take account of the setting, rural or urban, the level of technology envisaged to be used to drive the comfort and communication related built-in devices. The locality of materials and their embodied energy are also used to potentially place the design in a hierarchy of 'greeness'. Modern methods of construction including the use of Structural Insulated Panels (SIPS), refined heat recovery and low energy lighting can help the designer to achieve level 6 of the UK's Code for Sustainable homes. Although general guidelines for the design and case studies of eco houses are available, (for instance Eco House: a design guide by Roaf *et al* [4]), the actual in-depth design decisions that lead up to Eco House design and its relationship with in situ monitoring are less well explored. An investigation of the reasons for these decisions might reveal important trade-offs and a need for further information and/or design support instruments. The results of these decisions also have implications for other design related decisions.

This paper also explores the early design decision to employ a particular walling system and the subsequent design trade-offs and implications that this choice had for future design choices. It further elaborates an example of how in-situ monitoring can influence this iterative process.

2. Objective

The aim of the research presented in this paper is to analyse the interrelations between specific design decisions, the information used to reach conclusions, the design related implications of the decisions made and the role of in situ monitoring of materials during the design of an Eco House. Through the study of actual design decisions, in their real life context, it is hoped to identify the role of decision making processes and future support mechanisms, such as the role of in situ monitoring.

3. METHODOLOGY

The research focuses on one single case study: the design and construction of the Eco House in Totnes, Devon, United Kingdom. This building has been selected because of excellent access to information about the design and construction processes. Access to the building for monitoring purposes was critical as the scientific implications, particularly related to moisture, were viewed as being central to judging the success of design related decisions.

3.1 Design decisions

The methodology for analysing the design decisions made in defining the case study building is the use of formal process modelling, using the IDEF-0 (Integral Definition) representation technique [5]. IDEF-0 models represent a process as a series of diagrams. In these diagrams the activities that make up the process are depicted as boxes. Interfaces between the activities are depicted as lines with arrows that either enter or exit an activity box. Four kinds of interfaces (called 'concepts' in IDEF-0) are distinguished:

- inputs: information or objects required to perform the activity;
- outputs: information or objects that are created when the function is performed;
- controls: the conditions or circumstances that govern the activity's performance;
- mechanisms: the persons or devices that carry out the activity.

Inputs enter activities from the left, controls from the top, mechanisms from the bottom. Outputs leave activities on the right (see figure 1).

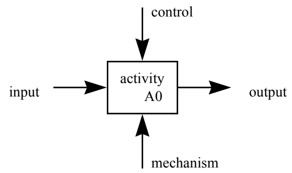

Fig 1. IDEF-0 representation of activities and concepts

IDEF-0 uses a hierarchy of diagrams. One top-level diagram (A0) shows the process as one activity only; this activity is broken down (decomposed) into more detailed diagrams (A1, A2, …) that can themselves be decomposed until the tasks are described at a level necessary to support the goal of the process model.

For an efficient implementation of IDEF-0 the KBSI function modelling tool AI0-WIN has been used. Process models have been developed retrospectively, in close collaboration between the modeller and the designer of the Eco House.

3.2 Moisture monitoring

Initial moisture monitoring was undertaken using a permanent moisture probe based on a Canadian design. This consists of a wooden disc approximately 20mm in diameter and 5mm thick encased in a perforated plastic tube. The moisture content of the wooden disc was measured using a Protimeter 'Timbermaster' electrical resistivity moisture meter. It was assumed that the wooden disc would mimic the behaviour of the straw, as straw and wood are physiologically very similar. In a given relative humidity and temperature they will have a comparable moisture content. Twenty such probes were installed in the walls of the house. However, when the readings were compared to those gathered at the same locations using a Protimeter 'Balemaster' (a professional metal probe used in agriculture to quickly measure the moisture content of straw-bales), it was found that the 'Balemaster' moisture content measurements were higher than the measurements using the permanent moisture probe readings. The 'Balemaster' was proved to be more accurate by the application of gravimetric analysis upon a series of straw samples, which is considered to be the most precise way to determine moisture content [6]. Therefore a new improved wood block probe has been developed, the main change being the removal of the perforated tube, and instead forming a bullet shape for the wood that puts it in direct contact with the walling material. This provides increased contact with the material being measured and was found to more accurately follow the patterns of moisture concentrations in a variety of straw-bale walls. This new design, depicted in figure 2, almost exactly duplicates the readings given by the 'Balemaster' and gravimetric analysis, and can be left in-situ for continuous monitoring.

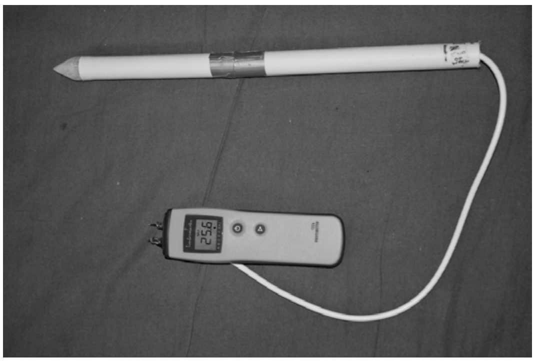

Fig 2. Improved wood-block probe showing 'bullet' shaped wooden tip. Also shown is the wood moisture meter used to record the moisture content.

4. Results

4.1 General description of the case building

The Totnes Eco House was designed to have a minimal impact on the environment both in the construction phase and during its life span. The client felt that he needed to move on from the conventionally built low energy houses that he had previously been constructing and take more account of the embodied energy of the materials to be used, whilst still keeping the budget to within £1100 per m2 of floor area.

Fig 3. The Totnes Eco House

One of the decisions that underpinned the design philosophy was to avoid the specification of construction materials with high embodied energy content, such as cement. This decision also influenced the sourcing of the chosen construction materials, attempting to obtain them as close as possible to the site in order to cut down on transport energy and potentially to support the local economy. It was therefore decided to use timber for the building's structural frame, straw bales for the external walls, loose sheep's wool for insulation and lime based renders for exterior and internal wall coverings.
The main structure of the house is a large section post and beam timber frame made from Douglas fir. This kind of timber can be sourced locally as it is grown throughout the United Kingdom in managed plantations where the relatively fast growing trees are constantly replaced after felling. This is in contrast to the slower growing Oak, the traditional material used for this type of house framing, the bulk of which has to be imported.
In order to minimise the use of concrete, the timber frame sits on individual precast pads. Once the frame was erected, the builders were able to construct the first layers of the roof, enabling the rest of the build to proceed under cover – an important issue when using straw bales, which could be stored and worked on protected from the weather. The main floor joists are cantilevered out from the frame to support the straw bale wall that forms a continuous insulating blanket around the outside of the building's structure. This minimises cold bridging and allows the traditionally jointed frame to be revealed inside the house.
Three coats of fat lime render protect both sides of the straw walls. This render is made from a mixture of sharp sand and lime putty, which is the result of slaking quicklime in water. This material performs better than the more commonly used hydrated lime. As an additional protection from driving rain an untreated cedar rain screen was used on the more exposed sections of the first floor. The importance of these hygroscopic, vapour permeable finishes in the moisture performance of the building are covered later in this paper. The use of a hygroscopic render also has a role to play in improving the inside air quality by moderating humidity and absorbing odours.
The insulation in the roof is made up of a 300mm thickness of loose sheep's wool sourced locally from a company making sheep skin rugs and, along with the straw bales, is the by-product of an existing industry that might otherwise have to be disposed of by burning or landfill.

4.2 Design process of the Eco House

The Totnes Eco House forms one step in a series of developments by the same client. It is preceded by the design and construction of two semi-detached houses on an adjacent site. These have been based on conventional design and construction methods, but with additional attention to their energy efficiency beyond that required by the current UK Building Regulations. It has been followed by a refurbishment project on a remote site, while currently a further project on a nearby site is under development. In all these projects, the client is closely collaborating with one 'master builder', with whom he has a long-term working relationship.
The Eco House project can be divided into three main activities: the actual design, the construction, and (ongoing) in-situ monitoring and evaluation.
The design of the building was divided into two main phases: first the development of an architectural outline design (submitted to obtain planning permission) and secondly the development of a detailed design. An architect carried out the first phase; the client and the builder carried out the second phase. The decisions relating to design or construction features that take the building from a normal dwelling to one worthy of the accolade Eco House are made in the second phase only. This second phase can be subdivided into two main iterative activities: (1) consideration of the choice of materials and use of solar gain, and (2) the development of construction details, captured in a 3D model. The activities in the second phase are strongly influenced by a design philosophy that emphasised maximum insulation levels, minimum embodied energy, and, where possible, use of passive energy systems before recursion to active ones. The IDEF-0 process model on this level is presented in figure 4. Note that more detail is available in decompositions of the activities A212 and A213; these have not been included in this paper due to space restrictions.
In terms of selection of materials, three systems are selected based on the design philosophy; a sedum roof, a timber frame, and straw bale walls. Of these, the timber frame and straw bale walls are closely interrelated: the timber frame allows the straw bale walls to be kept suspended above the ground, without a need for full foundations and the risk of moisture ingress. The straw bale walls influence the wall thickness and the dimensioning of the timber frame. Straw bale walls require large overhanging eaves and so the

choice of wall type influenced the choice of roof design. The design specification of the sedum roof further interrelated with the choice of roofing materials. A sedum roof requires a pitch of 15%.

Design decisions were made relating to the moisture performance of the organic material (straw) used as the main material for the walls, vapour permeable coverings were specified to allow the walls to breathe and mitigate the possible moisture problems associated with the use of straw. Intrinsically connected to the choice of wall components was the perceived need to monitor the moisture content of the straw inside the walls, and the University of Plymouth became involved with the initial placement of the twenty wood block probes installed in the walls.

The development of design details for this building was carried out in a just-in-time manner, while the construction process was ongoing. This way of working was facilitated by the close collaboration of client and master builder, within the context set by the architectural outline design. Both the way of working and the choice for the timber frame and walling materials influence the way the design process and detailed. A 3D modelling tool was used as this enabled the team to construct parts of the building in virtual reality. Before proceeding for real, the different design options issuing from the model's images were discussed.

An interesting design decision was related to the development of one of the construction details: one drip detail was badly executed in a way that allowed moisture ingress into a section of the straw bale wall, due to an insufficient overhang and a gap between a capping material and the render on the top of a projecting wall on the South West corner of the ground floor. The need for in situ monitoring phase was in part proven by result of the moisture ingress allowed by this form of detailing.

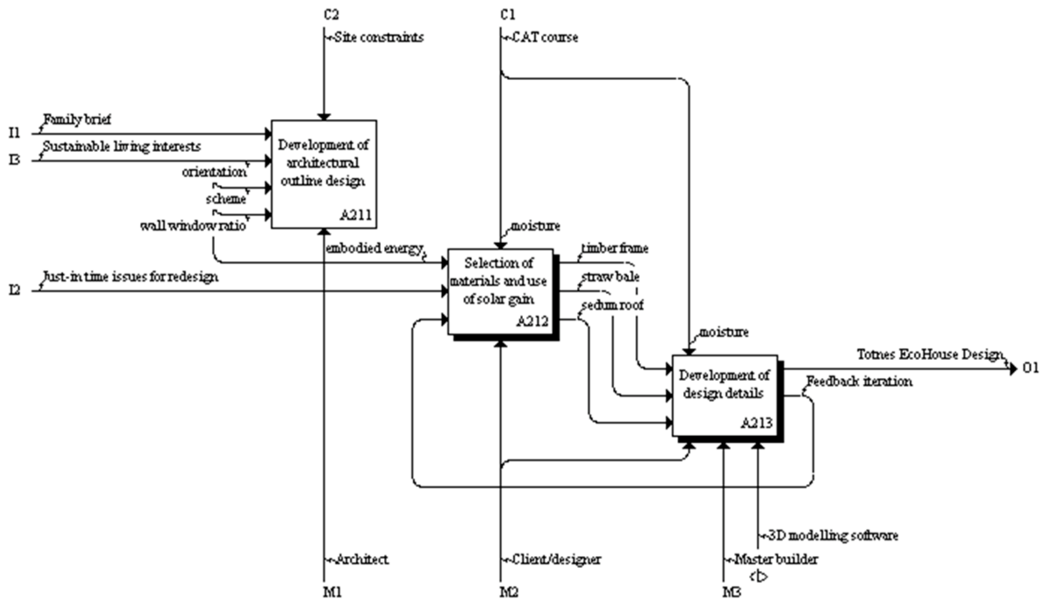

Fig 4. Top level (A21) view of the design process of the Totnes Eco House

4.3 Monitoring process of the Eco House

Because of the interest of the client in the medium and long-term performance of the Totnes Eco House, thermal and moisture related variables have been monitored since the building's completion. As depicted in figure 5, this monitoring takes place at two levels: on a general, whole house level, and by specific monitoring of conditions for sections of the wall. The latter activity helps to establish the point in the design process that changes are required.

Whole house monitoring is mainly carried out by means of readings taken from the house's utility meters. The integrity of the insulation of the building's façade (a comparative measurement that would not be apparent from using energy consumption measurements alone) was investigated by using a thermal imaging camera to capture any unexpected heat losses through the building fabric.

The choice to undertake the moisture monitoring of specific sections of the wall was felt to be important by the client who had visited a number of straw bale structures during the design phase. The impression was quickly formed that one of the biggest potential drawbacks to the use of this material was the potential for problems caused by the ingress of moisture [7]. The moisture monitoring used three instruments: a permanent wood moisture probe, (versions one and two) a