Peter Linnell, B4 Report
The computer simulation of buildings

As the world struggles with combined threats of anthropogenic climate change and diminishing affordability of fossil fuels the need to reduce energy consumption in the built environment is an increasingly vital driver of building design. Two themes emerge from this trend, the incorporation of novel materials and constructions, and the re-examination of vernacular design and materials. There are additional requirements to determine the merit of remedial measures to existing stock without damaging fabric. The twentieth century is littered with building projects of all scales which are both expensive to manage in a high energy cost economy and also critically challenging to retro-fit with more appropriate systems. Examples range from the speculative housing on which this writer worked in the seventies to the UN building in New York.

Computer simulations allow designers to experiment with the properties of their project, from fine detail of glazing through materials in basic structural elements, to orientation on the plot and services . Such trials can reveal implications for the eventual completed project in terms of predicted energy budgets, compliance with regulations, allow cost/benefit analysis of suggested changes and perhaps most importantly reveal unforeseen flaws in the design before it is committed on the ground. Previously confined to research demanding understanding of advanced applied mathematics and computing the recent growth in power of PCs has brought modelling within reach of almost any practitioner.

Any simulation begins with a three dimensional model generated by use of suitable 3D modelling software. This needs to be compatible with the simulation software used, most often contained within the same suite of applications (such IES virtual environment); and able to run on available hardware and operating systems; (this may be challenging for architects using a mac system, or attempting to port research unix systems to PC). Designers need clarity that a model suitable for simulation is *not* the same as a model to show how the project looks ! The essential rule of simulation modelling is to make the model as simple as possible commensurate with the task required of it. (Paul Carey 2010)

Practitioners need to *properly* scope the simulation project by identifying factors which may influence the performance of their building and consider ways in which they may be modelled. Perhaps the most important aspect of this is to identify mutual co-actions and establish a test matrix to assess their impacts. This leads to consideration of applicability of tools to tasks, perhaps requiring more than one suite of applications to obtain the most appropriate match. Finally there is the matter of data quality, both in terms of accuracy of values (eg properties of materials, especially natural stone or vegetable based see eg Valek et al 2000) and relevance to the project such as meteorological reference year data from a nearby site with a different weather pattern (eg a coastal weather station applied to an inland site). These limitations must be clearly understood and stated in any subsequent reports.

> *“To select appropriate MRYs it must be possible to classify weather years according to criteria relevant for the problem at hand. There is probably no one definitive set of MRYs that are appropriate to solve all the hygrothermal problems of interest. Different sets of MRYs should be produced to suit different problems.”*

Cornick et al 2003

Considerable research effort continues to improve modelling methods and input quality with co-ordination offered through the International Energy Agency Annexe 41 (Wolszyn et al 2005). In the UK increasing use of simulation is aiding guardians of the built heritage (Baker pers. com. 4.3.2010 and Cassar & Hawkins 2007)

The Project

For the purpose of studying and evaluating the IES suite the group examined it's applicability to designing energy saving solutions for traditional mass masonry houses typical of the Welsh National Parks (also found elsewhere). Given conservation restraints the study examined solutions used in the Edinburgh World Heritage Site pilot project undertaken by Changeworks (2006) followed by an examination of external insulation and addition of conservatories which would challenge existing policies. The model was based on an existing house in Abergynolwyn, Gwynedd, for which dimensions and material specifications were available. Unusually for this house type the loft had been converted; it was decided to retain this in the model to examine the effect of improving it's insulation to current standards.

Figure 1; IES “Model IT” Textured image of “Stone House”

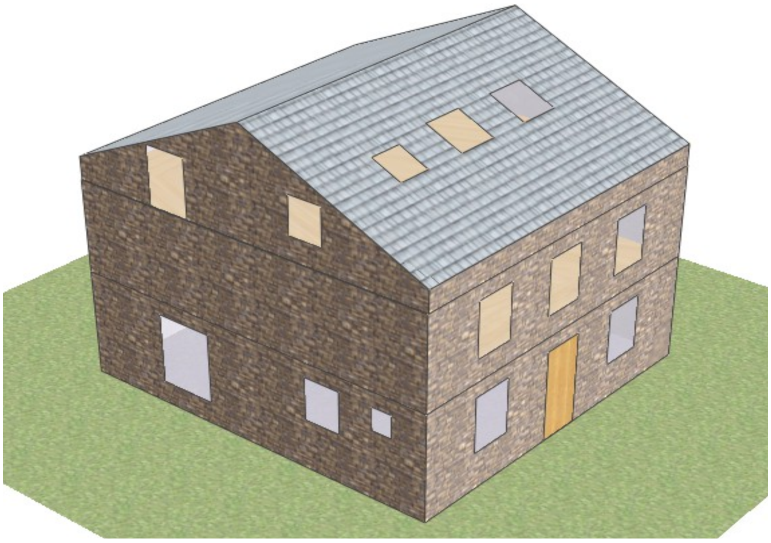


Table 1 Job scope for trial project “Stone House ”		
Task	Requirements	Outcomes
Make model	Dimensions and materials specs. Location data. Software	3D numerical model (simplified for simulation use)
Simulation base case	Define profile (from IES database).Select weather data (decision needed)	Base case outputs for heat load and solar gain
“Low Hanging Fruit” improvements (LHF)	Define each by material/ expected outcome. Check sources	Table/chart in Vista for each separately by heat load and solar gain
Total effect	Add all improvements to the model	As above
External insulation	Decide required u value/ select material; add to model	As above
Conservatories; West	Design and add to model, define profile. Predicted/expected results	As above, include SG for conservatory
Tuning	Adjust openings profile and sizes; seek optimum	Iterative use of outputs seeking best option.
Analysis	All test data	What makes a difference and by how much
Cost/Benefit Analysis	Costings of proposed works	Is it worth doing; in what circumstances?

Following the process tabulated above a number of issues arose. Firstly the IES database does not have values for properties of slate stone in the expected area, values were eventually discovered in the tiles section! This aside, appropriate values were found for all required elements used in the model, however caution is required when using “standard” values for natural / mineral materials (Lanas et al 2004, Valek et al 2000) and traditional constructions like draughty windows (Appendix A). Secondly anomalies arise from selection of a suitable weather database. Of the reference locations available for Wales all are airfields, mostly near the coast. Inland weather, especially in hilly/ mountainous areas like Snowdonia will differ in significant ways. The IES software does not permit use of wind from one location and rain from another. Weather data from elsewhere can be used if appropriate data are available in a suitable format but constraints of time and resources prevented exploration of this. Whilst use of reference years weather data is preferable to averages the advantage of including extreme events that this method allows may be lost in the distance from the reference location. In other words a different type of extreme event may be more appropriate at altitude, inland, or sheltered by mountains than on a coastal site.

Values for pre-improvement conditions, where not available in IES, were taken from initial conditions of the Changeworks project in Edinburgh, as were input values for improved ventilation and window constructions. (See appendix A)

Table 2 Summary of base case

Constructions	
Stone walls	600mm slate; int.plastered
Windows	4mm single. SW frames
Floor	75mm slate over gravel
Internal floors	25mm timber,225 void,plasterboard and skim
Internal partitions	None (ignored)
Roof (attic room)	Slate over felt and battens, 100mm quilt,interior plasterboard,skim
Room and use profiles	
Air change rate	3 Ac/hr
Occupancy	DOMOCC2 (from IES options)
Heating	Unlimited at 19 deg, timed
Ventilation	Natural only
Cooling	Off

Figure 2: Base case; model of heating load and solar gain

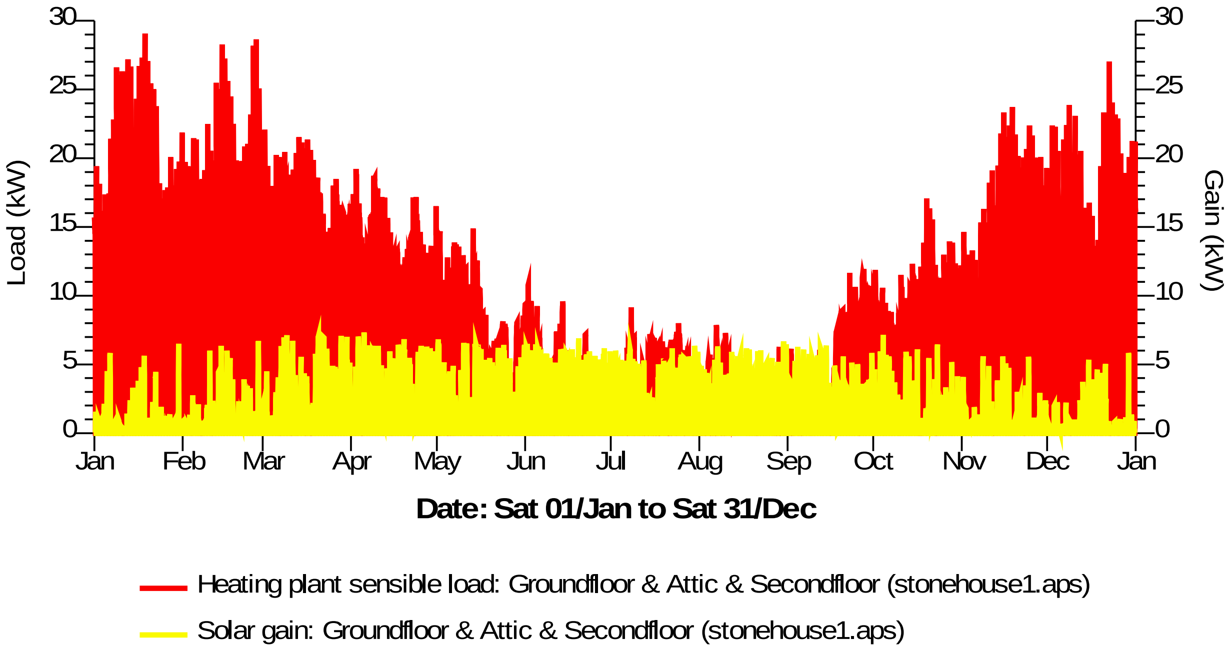


Figure 2 and **table 3** show as expected heat load is seasonal and solar gain is greatest during the summer months; but surprisingly the peak level is apparently capped at about 7kW. Whilst this may be available for longer summer hours, it suggests there may be merit in trying to increase it by

designing to capture more passive heat especially at equinoctial seasons.

Table 3; Base Case Heat Load and Solar Gain

Date	Heat load Mwh	Solar Gain Mwh
01/01/31	8.27	0.29
01/02/28	7.53	0.42
01/03/31	7.44	1.05
01/04/30	6.08	1.29
01/05/31	3.75	1.31
01/06/30	1.75	1.64
01/07/31	1.92	1.34
01/08/31	1.06	1.23
01/09/30	2.26	0.91
01/10/31	4.47	0.7
01/11/30	6.67	0.36
01/12/31	7.46	0.27
Summed total	58.66	10.81

Figure 3 (below) allows a more detailed inspection of building performance around spring equinox, allowing hypotheses to be formulated for later testing. The graph shows dynamic relationships between ambient temperature, cloud cover and solar gains as external factors compared to heating load and indoor temperatures as outcomes. On cloudy days diurnal temperature range is small, solar gain low and indoor temperature drops quickly when heating is off (18th,25th.). In sunnier days with higher diurnal range indoor temperature stays higher during the day with heating working less hard *overnight* despite similar temperatures to dull periods (23rd,24th.). The observable solar gain is apparently impacting internal temperatures. Caution is needed in reading this graph as the apparent effects may be due to increased outdoor air temperature warming building fabric to a higher starting temperature for cooling overnight. Only the capacity to model temperatures *within the fabric* would permit extraction of this level of understanding.

Figure 3 Base case, Vernal Equinox

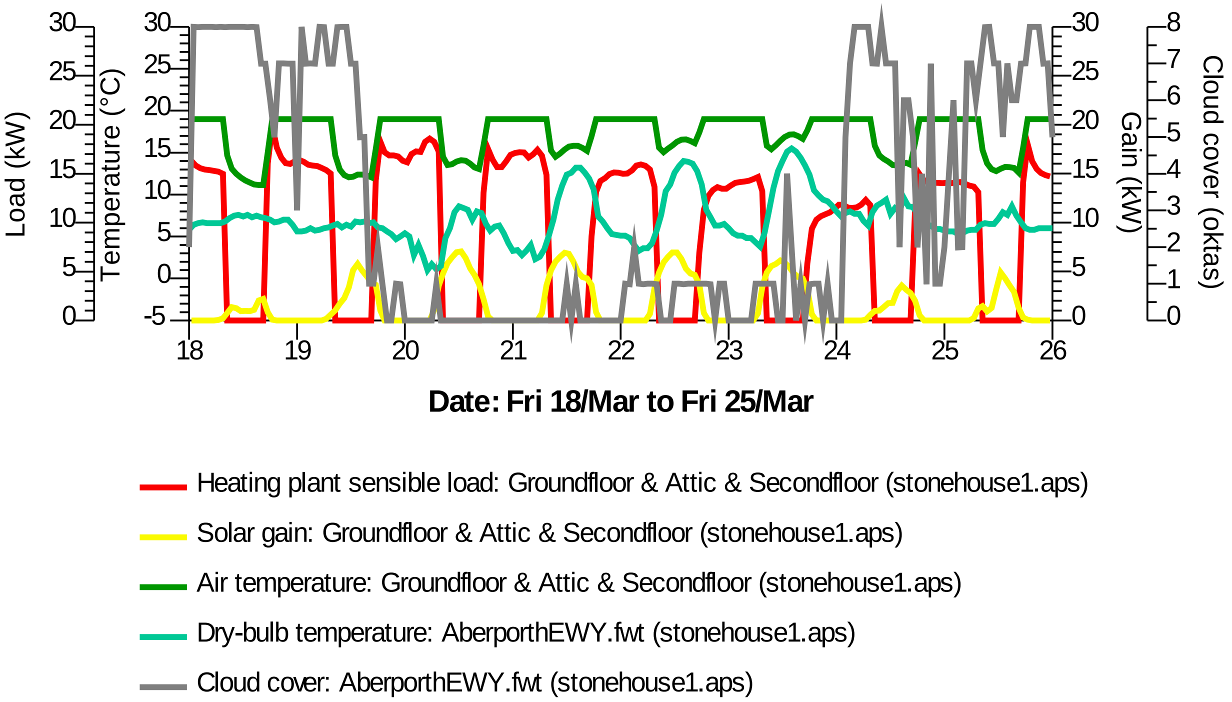


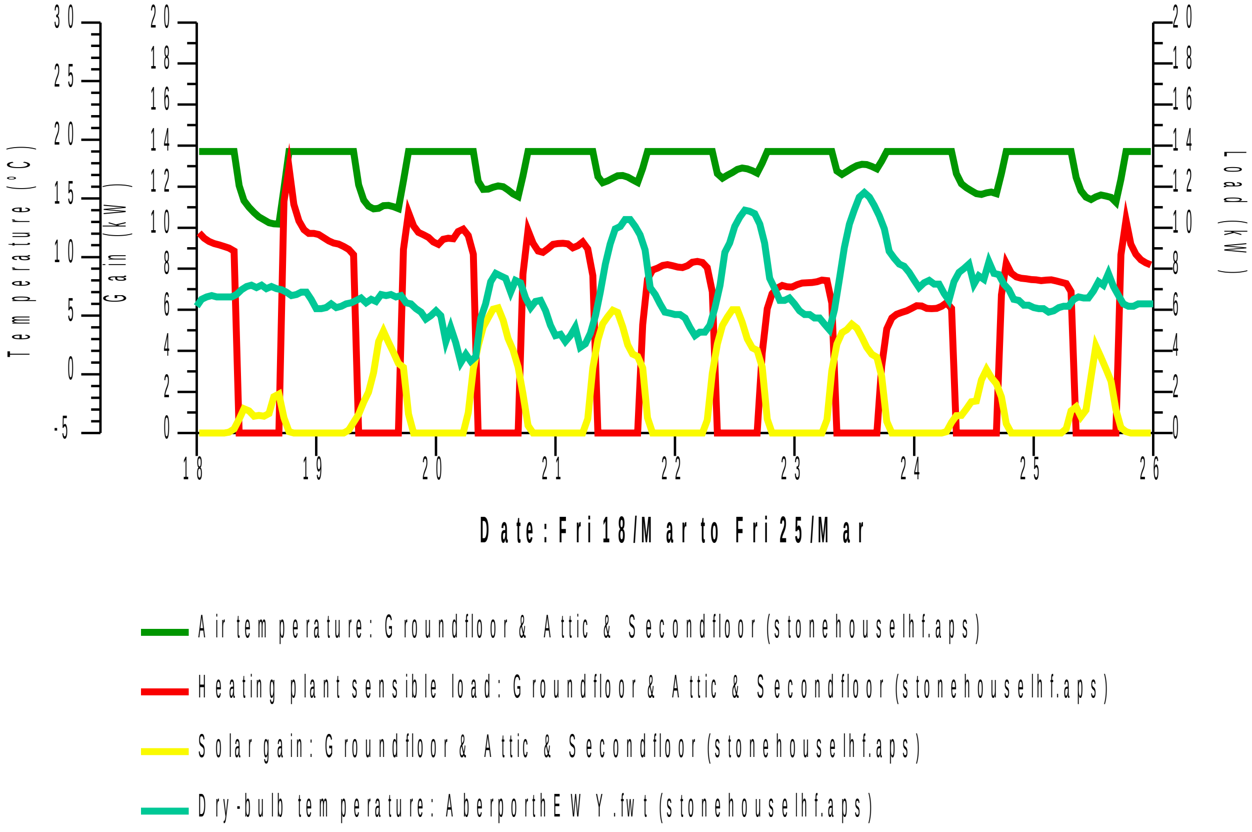
Table 4; Initial results for base case and LHF

Case	Heat load (Mwh)	Solar gain (Mwh)
Base case	58.66	10.81
Reduced Thermostat (16)	38.61	10.81
Draft Proofing	36.58	10.81
Secondary Glazing	34.09	9.37
Roof repaired (2006 adL)	55.52	9.37
Insulated Ground floor	57.57	10.54
Cumulative Total	**32.48**	**9.37**
External Insulation	14.3	9.37

(For details of alterations and sources of data, see Appendix A) NB: thermostat reduction is NOT included in the cumulative total.

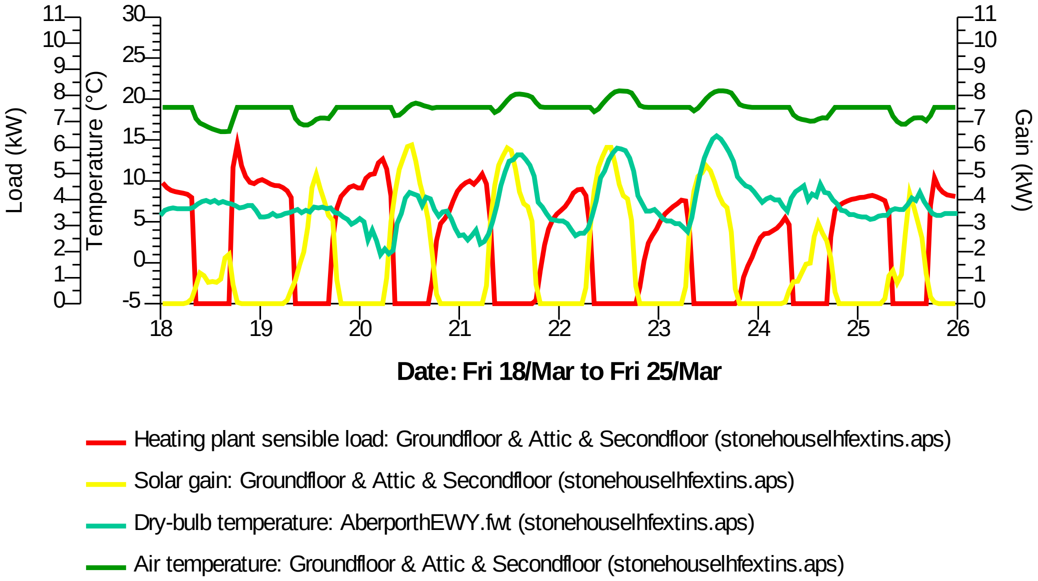
From **table 4,** simply reducing internal temperature to 16 C seems at first blush to be an effective energy saving measure, but the internal temperature graph reveals unacceptably low temperatures during "heating off" periods. Also; at no time did temperature fall to dew point, but it would not be safe to assume this applies in a real case, as hygrothermal effects are not modelled in IES.

Figure 4 After "Low Hanging Fruit" Improvements



The results of “LHF” measures are reduction in overall heating load and smoothing of daytime indoor temperature line. In **Figure 4** the effect of solar gain on heating load is apparent in the data for 19th and 20th . On the 19th there is a load spike when heating restarts, the following days, after some higher solar gain despite falling temperatures outside the load spike is lower and overnight load is no greater. Finally, for the same week, **figure 5** shows the effect of the suggested external insulation.

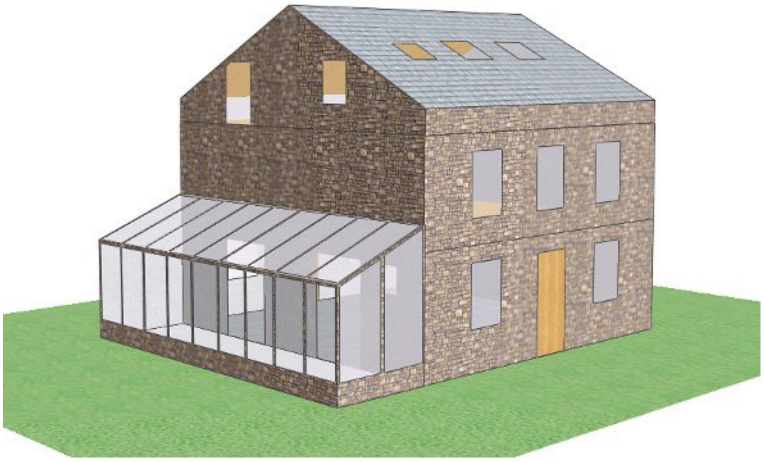
Figure 5; Effect of external insulation



Two effects are apparent from **figure 5**. The internal temperature is smoother, exceeding thermostat during the day when heating is off, which can only be due to solar gain effects. Secondly heating load is now significantly lower than previously (note scale). In this model, the contribution to the energy budget from solar gain is much more significant (see **table 4**)

The case for conservatories

Figure 6 Textured model showing conservatory



A simple way to capture additional solar gain is to add a conservatory extension. As well as the obvious solar gains, this also reduces evaporation heat loss from the wall and reduces the thermal gradient across the wall element. Warmer air “outside” the masonry wall reduces conduction heat loss.

For model purposes, a

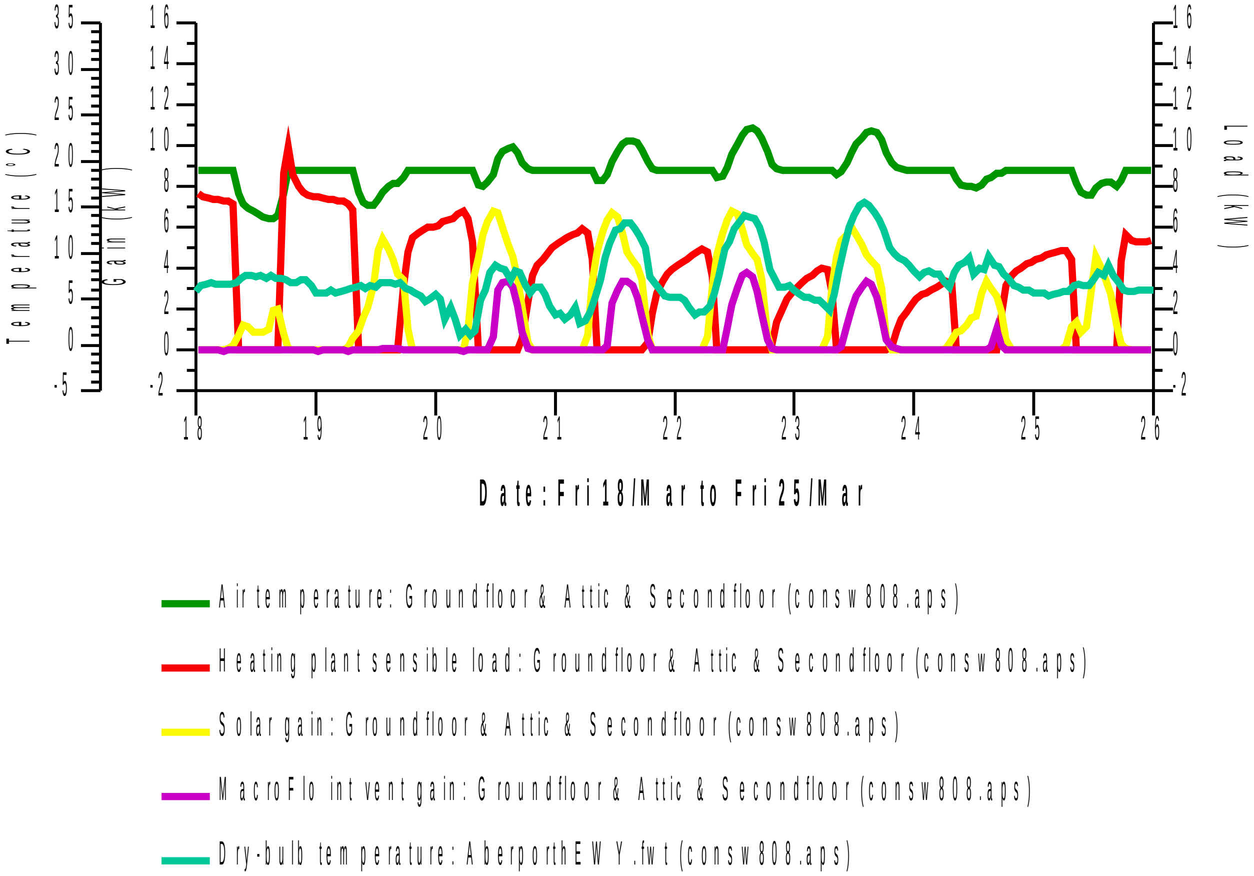
high specification double glazed (“low e” coated glass) conservatory is added along the SW elevation. (Figure 6) This is connected to the ground floor by glazed doors opening according to profile rules when temperature in conservatory reaches 20 C.

Table 5 Overall effect of conservatory

Date	Heat load (Mwh)	Solar Gain (Mwh)
01/01/31	4.16	0.68
01/02/28	3.56	1.03
01/03/31	2.76	2.61
01/04/30	1.6	3.26
01/05/31	0.62	3.22
01/06/30	0.01	4.03
01/07/31	0.18	3.32
01/08/31	0.03	3.04
01/09/30	0.56	2.24
01/10/31	1.74	1.69
01/11/30	3.26	0.87
01/12/31	3.79	0.64
Summed total	22.28	26.63

From **table 5** compared to **table 3** there is a clear saving of 10MWh/yr after adding the conservatory. It must be noted that this is still not as effective as external insulation, but may be more likely to gain favour from a heritage planning agenda. It is also clear that there is still heat available from solar gain which is not being utilised indoors.

Figure 7 Effects on the main building from heated air moving indoors.



Comparing this graph to **figure 4** and **5** a number of effects can be seen.

There is a smoothing of the internal temperature similar to that achieved with external insulation. There is a smoothing of the heating load spikes following days of good solar gain, even with dropping outdoor temperatures (20th.) Even where overnight temperatures drop below half daytime values there is still reduced heating load on nights following good solar gain. The transfer of heat into the main building by air movement can be clearly seen (20th.to 23rd.) Given time, further modelling would be used to test the impact of using mechanical air movement to circulate warmed air from the conservatory to the rest of the building. It would be instructive to model possible use of materials with higher heat capacity (eg water) to achieve the desired effect.

Conclusions

In the model project of “Stone House” the simulation shows clear benefits from all the “low hanging fruit” insulation measures; most benefit coming from simple draught proofing. In addition both a lean to conservatory and external insulation offer considerable additional improvements if permitted. The results obtained suggest much greater benefits than found in the Edinburgh pilot project but the latter included DHW in it's energy use measurements. Comparison of the model energy use with the actual use in the home on which the model is based (14MWh/yr) confirms the cold damp misery in which the sole occupant owner lives and indicates the level of improvements required to live comfortably at this level of energy use. For cost benefit analysis see Appendix B

The IES suite offered a useful entry level toolkit for understanding the main strengths and weaknesses of computer simulations as an aid to designing better performing buildings. During the writing of this report a total crash of the software required intervention by IES support to resolve; not a good thing in mission critical situations. In the context of the project undertaken here the main flaw is the lack of hygrothermal modelling tools, which would severely limit it's applicability in real cases of this kind. Despite this the suite allowed relatively inexperienced users to model simple buildings and to test a range of variations to evaluate their impact.. Attempts at deeper understanding of thermal behaviour of heavyweight structures were impaired by the inability to model temperature gradients within structures. Other modelling software may permit this, but constraints of time and resources prevented further study.

Whilst simulations of buildings using modern engineered materials may give high accuracy, there is variation in properties and uses of natural materials which make simulations of traditional buildings less reliable (valek et al 2000) It is unsafe to treat mass masonry/rubble walls as homogeneous uniform constructions, but for larger structures this may possibly be averaged out. Values for hygrothermal properties of vernacular materials used throughout Wales ought to be the subject of an urgent study as in other parts of the UK (P. Baker pers. comm. 2010).

> *“..we do not yet understand real walls and real buildings well enough to confidently develop models that could take the place of in situ monitoring and measurement”*

English Heritage Stakeholder comment in Cassar& Hawkins 2005

> *"Computer modelling attempted to understand how climate change will affect buildings in future, but suffered limitations including a lack of advanced knowledge of physical characteristics of historic building materials"*

Historic Scotland (ibid*)*

Similarly study into heat and moisture performance of dwellings occupied to modern comfort and health standards is urgently required. Use of modelling *aids* the design of appropriate energy saving measures, but is no substitute for rigorous long term monitoring to determine cost/benefit ratios in real applications.

Notes on group work

For this project a team of three worked on the model, the properties of the original case and improvements and cost benefit analysis. The final group task was preparation and delivery of the short presentation outlining the project.

The small scale of the project lent itself well to a small team, being achievable to a reasonable quality level within the time available. Consequently no conflicts arose and all members were able to contribute materials and ideas to the work flow. Working within internet connected space allowed exchange of draft documents for collaborative editing. Each member contributed according to the relevant skills and knowledge they brought and there were no gaps; everything needed was available within the group apart from easy familiarity with IES VE software. At the end of the project each member had achieved a working understanding of the basics of IES modelling and Apache simulations.

Appendix A

Base Case sources of data and specifications for alterations.

Materials. The thermal properties of slate walls are derived from the values given the IES materials database for slate tiles. Original windows are assumed to be 4mm float glass in softwood frames taking 20% of opening size. The roof is as surveyed with 100mm of glass fibre quilt between rafters for insulation assumed to be airtight and defect free (almost certainly not true in reality). The project construction for internal floors does not consider the different thermal properties of the timber joists, consisting of the layers between timber floors and plaster ceilings with a void between joists.

The Base Case model, although based on a real building takes no account of it's landscape context, so shading and wind shelter effects of nearby mountains are not modelled. The weather exposure is classed as severe.

The air change rate set at 3 AC/hr is taken from the pre-improvement conditions of the Changeworks Edinburgh project (Changeworks 2006). The values used were derived from a combination of test cell data and in situ measurements carried out by Glasgow Caledonian University (with some surprising results – notably the u value of a 600mm sandstone wall is considerably lower than given by ASHRAE database in IES. The difference, between 2.0 and 1.4 W/m2K, may be due to including the lath and plaster facework in the field tests in Edinburgh (Baker, pers. com.4.3.2010))The construction, windows and age of the buildings are considered comparable, the essential difference would be the weather exposure, higher in Wales. For the purpose of modelling the building energy budget it is assumed that the heating plant has unlimited capacity to meet the room profile requirements.

Draught proofing. The Edinburgh project reported improvements in air change down to 0.4 AC/hr. As this is well below the level deemed safe for CO2 concentrations, the adjusted value used is 1 AC/hr (CIBSE 2001).

Windows; In situ measurements of the glazing of the Edinburgh flats showed that the thermal performance of conservation grade double glazed units was effectively the same as secondary units. The values used for the model are based on a model construction of double glazed units. It is assumed that glazing improvements will also lead to improved airtightness, so a level of 1 AC/hr is assumed for this case.

Floor insulation is based on 75mm of Cellular Polyisocyanurate laid below slate flag floor. In real cases this would impact moisture transport from ground to masonry wall fabric and effective countermeasures would be required.

The roof insulation is specified to comply with UK building regulations 2006 approved document L. The thermal bridging effect of the rafters is ignored as the insulation requirement is fulfilled by the additional thickness of uninterrupted insulation below the rafter line. The original quilt is removed and replaced by 75mm of polyisocyanurate with a vented air gap between it and the breather membrane

External wall insulation is based on 50mm of polyisocyanurate with a light render face covering, as applied to social housing in parts of Powys (Linnell 2010). Application in real cases would depend on regulatory consents and adequate moisture control within the masonry.

Appendix B

Cost / Benefit Analysis

Case	Heat load (Mwh)	Cost (£)	£/Mwh/yr saved
Base case	58.66	n/a	n/a
Reduced Thermostat (16)	38.61	0	n/a
Draft Proofing	36.58	5655	256
Secondary Glazing	34.09	12600	512
Roof repaired (2006 adL)*	55.52	2000	637
Insulated Ground floor	57.57	4485	4114
Cumulative Total**	**32.48**	**19085**	**729**
*External Insulation****	*14.3*	*23000*	*126*
*Conservatory*****	*22.8*	*18000*	*186*

*The costing here is just for the insulation element, assuming the rest requires repairs anyway.
** Thermostat setting is not included. Draft proofing is ignored in favour of secondary glazing.
*** Based on a price of £100/m^2 (Green Building Forum: 2010)
**** Based on a price of £2k/m (linear) (lifespacedesign 2010)

Italicised items are potentially controversial for the National Parks Planners, both assume that the LHF items have all been implemented but are not themselves combined. The cost performance is an addition to the cost for LHF measures.

Item	Cost	Life (yrs)	Cost/ year (£)	Value of saving (£/yr)	Payoff (yrs)
Draft proofing	5362	10	536	2200	2.4
Glazing	12600	25	500	2460	5
Roof Insulation	2000	Indefinite (20)	100	310	6.5
Floor insulation	4485	Indefinite (20)	224	110	41
Ext. Insulation	*19943*	*Indefinite (20)*	*997*	*2280*	*8.8*
Conservatory	*18000*	*Indefinite (20)*	*900*	*1820*	*9.9*

Values are based on energy price of 10p/kWh and ignore inflation.
Costs are at 2010 prices and ignore financing cost.

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