# Strategies for low carbon buildings: Assessment of design options and the translation of design intent into performance in practice.

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## Abstract

To deliver low carbon buildings requires: a) Performance assessment and option appraisal; b) Industry process to translate selected options into low carbon performance in practice. This thesis aims to make some contribution in each of these two areas.

Legislation such as the European Performance of Buildings Directive (EPBD) is stimulating the market to put forward many technical options for design or retrofit of low carbon buildings. The need is identified here for a low cost, EPBD compatible, simulation based, real time method for performance assessment and upgrade option appraisal to inform decisions for a range of users with various levels of technical knowledge. The hypothesis is advanced that such a method can be developed.

An EPBD compatible, dynamic simulation based, real time, performance assessment and option appraisal method is then proposed and evaluated. A range of test applications and user groups are considered. Test applications include the generation of energy performance ratings based on a simple questionnaire. Other applications cover a range of individual building, policy or strategy contexts.

A critical analysis is carried out of the applicability, scope and limitations of the method. The proposed method proved useful in a range of applications. For other applications some limitations were identified. How these can be addressed is discussed. The development and deployment examples are for a specific building stock but provide insights to enable replication for other situations. The research provides a foundation for further research and development.

There is much evidence that selection of appropriate options is not sufficient to achieve low carbon performance. Many issues can lead to gaps between intended and actual performance. Problems are identified in the design and implementation of low carbon systems and controls. Problems include poor understanding, errors in implementation, and poor visibility of actual performance. The need for a method to address these problems is identified. The hypothesis is advanced that such a method can be developed.

A Modular Control Mapping and Failure Mode Effect Analysis (FMEA) method is then proposed and evaluated for a range of test applications to buildings intended to be low carbon.

The insights from the test applications are reviewed and the scope and limitations of the proposed method discussed. Overall the applications were successful and the useful application demonstrated. The method was deployed post-occupancy, then applicability at various stages of the design process was demonstrated by using concept and detailed design information.

The modular control mapping and FMEA process proposed leverages in part the approach taken in industrial sectors identified as benchmarks by proponents of the Building Information Modelling (BIM) initiative. The potential application of further processes from BIM benchmark industry is discussed in the context of current buildings industry initiatives.

The performance assessment and option appraisal method, the modular control mapping and FMEA method, and the outcomes from their evaluations are intended to contribute to the realisation of low carbon buildings in practice. The future integration of both methods within a BIM framework is proposed.

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# Chapter 1: Introduction

*The background, focus, aims, and intended outcomes are introduced in this chapter.*

*The thesis is structured in two parts followed by overall conclusions: Part A addresses challenges in performance assessment and selection of design or retrofit options; Part B addresses challenges in translating the intended performance into practice.*

*This thesis puts forward the hypothesis that two methods could be developed to usefully address these problem areas. Both of these new methods are intended to provide a vehicle for expert knowledge to be embedded and made available to a range of users.*

## 1.1 General context and focus

Worldwide there is a drive to reduce carbon emissions. The contribution to carbon emissions associated with buildings is recognised to present a significant opportunity. Many international and regional initiatives are directed towards reductions in carbon emissions from buildings and associated energy systems.

The overall aim of the thesis is to contribute to the realisation of low carbon buildings in practice. The focus of this thesis is on strategies to assist in this overall aim. Two aspects of the current industry process are identified as problematic. The first is the assessment of performance and design options. The second is the translation of the design intent into performance in practice. It is proposed that both of these aspects require to be addressed to enable the realisation of low carbon buildings.

Significant new policies, regulations, methods, standards and processes have been implemented over the last decade with the intent of delivering a reduction in energy used in buildings and the associated carbon emissions. These provide a context for the work of this thesis.

A very significant policy measure which forms a backdrop for the thesis is the EU Energy Performance of Buildings Directive (EPBD, EU 2002, EU 2010). The EPBD requires assessment of building performance and design options for new and existing buildings, both domestic and non-domestic. The EPBD has acted to stimulate activity in the EU building sector driving the market to provide an increasing range of technical options. The increased requirement for performance assessment and increase in technical options to be considered are a challenge for the increasing pool of potential decision makers with various skill levels.

Initially the focus of this thesis was on assessment of performance and design options. However it quickly became apparent that this on its own would not lead to low carbon buildings in practice. There was growing evidence of disconnect between design intent and the actual performance being achieved (Bordass 2011, Bordass and Leaman 2012, Bannister 2009, Voss et al. 2007).

The thesis evolved into a story in two parts: in Part A the focus is the assessment of performance and design options; in Part B the focus is the translation of intended performance into performance in practice.

Methods are advanced in this thesis for: a) Performance assessment and option appraisal, and b) Translation of design intent into practice. In the thesis they are demonstrated for specific case studies. The methods are however intended to be more generally applicable. The scope of potential future application is intended to include: new buildings, retrofit of existing buildings, both domestic and non-domestic.

The research conception underpinning this thesis is aligned with the ‘Domino conception’ of Brew in which research is viewed as “a process of synthesising separate elements so that problems are solved, questions answered or opened up” (Brew 2001).

## 1.2 Part A: Performance assessment and option appraisal.

### 1.2.1 Problem statement *(Part A: Performance assessment)*

A necessary step to achieving the desired low carbon performance is assessment of building energy performance and upgrade options. The requirement for performance assessment and option appraisal can occur at various levels: national policy formulation, investments in new or retrofit building stocks, or the approach taken for individual buildings. While energy and associated carbon emissions are one focus for policy and legislation, other factors which influence decisions include capital and running costs, maintenance requirements, availability of fuels, comfort and health risks.

Option appraisal is made increasingly difficult by the accelerating changes in regulations, standards and guidelines, the increasing range in technical options, and the wide range of buildings to which these options may be applied. Technology options historically applied predominantly in the non-domestic sector such as refrigeration cycle heat pumps, whole building mechanical ventilation systems with heat recovery, and advanced controls, are being increasingly promoted for the domestic sector.

Selection of the calculation method to be used to inform option appraisal and strategy decisions presents another difficulty. Simple monthly methods, while being able to return real-time results, have limited ability to represent detailed building performance, while dynamic methods can be used to investigate performance in detail and give insights into systems and controls operation, moisture, ventilation and indoor air quality, occupant comfort and behaviour. Dynamic methods have however historically been the preserve of building simulation specialists.

Engaging specialists in the option appraisal process generally incurs a logistical and financial cost which may act as a limitation to its use. Where experts are engaged by decision makers in appraisal of options their interactions are often through iterations of: client questions -> simulation expert analysis -> answers provided, with each iteration typically taking of the order of a few days. This slow iterative and costly process is a barrier to the use of simulation. Ideally a real-time option appraisal should be available to the decision makers themselves.

Often a decision maker will delegate the option appraisal entirely to the expert and is uninvolved and must accept the results without direct experience of or influence on the process.

Due to cost constraints dynamic simulation specialists are rarely engaged in domestic projects.

In the timeframe of this research the Scottish Government was interested in a low cost method of implementing the EPBD for existing domestic stock which minimised the need for specialist energy assessor involvement.

In parallel with the work presented here the UK Government put forward its simplified monthly methods SAP, RDSAP and SBEM for EPBD compliance (BRE 2013, BRE 2013a) and also allowed the use of dynamic simulation for the most complex buildings.

There have been many attempts to develop policy and strategy decision support methods based on simplified and dynamic approaches. The dynamic simulation based approaches allow a much richer representation of building performance than non-simulation methods but don’t readily support real-time feedback and generally require a more expert user.

The challenge addressed here is to investigate whether a dynamic simulation based method can be developed to be used directly by non-simulation experts to give real-time outputs for performance assessment and option appraisal. Such a method should usefully inform policy, upgrade strategy, performance rating, or initial design decisions, in the context of the EPBD and other current initiatives.

The need is greatest in the domestic sector due to the lack of simulation and building services engineering involvement and less familiarity with new technology options.

### 1.2.2 Aims, approach and outcomes *(Part A: Performance assessment)*

The research aim was to investigate an effective method to support performance assessment and option appraisal in the context of the EPBD.

After reviewing requirements and state of the art, the research question formed was: *"Can a low cost simulation based method be developed to support real-time performance assessment and option appraisal by a range of users in the context of the EPBD?"*

The hypothesis was advanced that such a method could be developed. A method was proposed and applied to a number of applications in order to test the hypothesis.

An iterative research approach was adopted with a client and user group providing: inputs on requirements, opportunities for testing, and user and technical feedbacks in response to propositions put forward by the author. Both the technical and process aspects of the method were developed in parallel through this iterative process.

The development and test deployment examples of the method elaborated here are focussed on the Scottish domestic building stock. The method is intended for wider applicability.

The outcomes from part A of this work are:

- The elaboration and investigation of a low cost, EPBD aligned, simulation based, real-time method for performance assessment and upgrade option appraisal to inform decisions for a range of users with various levels of technical knowledge which addressed gaps identified in previous work. The research covers technical and user process aspects of the proposed method.

- An example development and deployment process for the proposed method is elaborated to provide research insights, a template for others to follow, and a platform for future work.

- A critical analysis of the performance of the proposed method for a number of test applications. Test applications included: Energy Performance Certificate (EPC) generation based on a simple questionnaire; and more general applications to inform policy and strategy decisions.

- The uses of the method are described and where there are some limitations in the scope of the method for specific applications then these are identified.

- Future work is described that would expand further the scope and address these limitations.

## 1.3 Part B: Translating intent into performance in practice.

### 1.3.1 Problem statement *(Part B:Intent to Performance in practice)*

While the problem described above of selecting technical options from the increasingly wide range of those available is one challenge, overcoming this challenge will not on its own deliver low carbon buildings in practice.

There is much evidence that there are often disconnects between design and actual performance. A particular area of difficulty has been identified as the implementation of low energy systems and controls, issues with which are frequent and often undetected (Bordass 2011, Bordass and Leaman 2012, Bannister 2009, Voss et al. 2007).

The recent Building Information Modelling (BIM) initiative highlighted other industries such as electronics, retail, automotive and aerospace as having higher productivity than the buildings sector due to improved processes in these benchmark industries (BSI 2012).

One technique used in some of these industries as a part of their quality systems approach to design and manufacturing is Failure Mode Effect Analysis (FMEA) where expert knowledge on potential fail modes is captured and then actions are taken to detect and avoid these fail modes (Liu et al. 2013).

Another technique used in some of these industries is a modular approach to design where designs are constructed from libraries of standard components which have been well characterised based on feedbacks from previous use, and have associated information on application range, limitations, potential failure modes, verification tests etc. (Freescale 2012).

Though there are a range of current industry initiatives aimed at improving building and construction industry processes including Soft Landings and NABERS, other than requiring expert reviews in the design process, these do not directly address the identified problems (BSRIA 2012, NABERS 2012). It is the aim of this thesis (part B) to develop a method to directly address these problems. The proposed method will leverage the Modular Design and FMEA process from a BIM benchmark industry.

### 1.3.2 Aims, approach and outcomes *(Part B: Intent to performance in practice)*

The research question formulated was: *"Could a Modular Control Mapping and FMEA approach be developed to address the gaps between intended and actual performance for systems and controls in low energy buildings in synergy with current industry initiatives?"*

The hypothesis was advanced that such a method could be developed and the hypothesis tested through application to a low energy office building and low energy dwellings with various low carbon technologies. The proposed method involves a modular approach to control mapping and the principles of the FMEA technique.

The method is intended to be applied pro-actively throughout the design process but be able to be usefully applied at any individual design stage (e.g. concept design, detailed design, implementation, commissioning, handover, operation). The test applications of the method were post occupancy. This allowed deployment at multiple stages of the design and implementation process to be demonstrated through the use of concept and detailed design information in addition to observation of the building in operation.

The proposed future integration of the method into the overall design flow is also described.

The modular control mapping and FMEA method elaborated here has parallels in the quality systems approach of the electronics industry. Further parallels and potential opportunities for improving buildings industry processes by leveraging those of the electronics industry are discussed.

The work is presented in the following steps: A ‘Modular Control Mapping and FMEA’ method to address gaps between intended and actual performance of low carbon buildings is defined. It is then tested for a low carbon office building. The method is further tested through application to two low energy dwellings. Conclusions are drawn from these test applications and the more general application of the method within the design process is proposed.

The outcomes from part B of the work presented in this thesis are:

- A new Modular Control Mapping (MCM) and Failure Mode Effect Analysis (FMEA) approach is proposed. It is then developed and deployed on a number of test applications to both non-domestic and domestic buildings.
- The application of the method at post-occupancy stage is demonstrated. The method proved successful in providing a useful template for post occupancy evaluation, facilitated clarification of the intended and as implemented operation, allowed clear communications and transfer of knowledge, and led to identification of numerous potential and actual failure modes.
- The modular nature and re-usability of the proposed method was demonstrated through subsequent re-application of selected modules to a further project.
- The applicability of the Modular Control Mapping and FMEA method to various levels of the design process was demonstrated. The method was

applied based on concept design information, detailed design information, as implemented based on observations and monitoring, and to communicate potential improvements.

- The integration of the control mapping and FMEA process in the design flow is elaborated. It is shown how the Control Mapping and FMEA process can underpin the expert reviews called for in initiatives such as Soft Landings and NABERS.
- The potential adoption of the method within a Building Information Modelling (BIM) process is discussed.
- The Modular Control Mapping and FMEA approach in part leverages methods from a BIM benchmark industry. Other methods used in BIM benchmark industries are assessed. Their potential contribution to the realisation of low carbon buildings in practice is discussed and directions for future research advanced.

### 1.4 Discussion and general conclusions.

The option appraisal method, and the Modular Control Mapping and FMEA method, were found to be able to make a contribution to identified areas of weakness in the current buildings industry process and also provide a basis for potential future research and development.

The integration of both methods together within a BIM environment is put forward. Adoption at a company or more public level is discussed in the context of future work.

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# Chapter 2: Literature review, research questions and approach.

*The aim of this thesis is to contribute to the processes for achieving low carbon buildings in two areas: A. Performance assessment and option appraisal, and B. The translation of intended performance into practice.*

*In this chapter some general background context is given. Then for each of the two focus areas the state of the art is reviewed, research question formulated, research method and thesis structure described.*

## 2.1 General background and focus.

Worldwide there is a drive to reduce carbon emissions; international and national policy has been constructed with this intent. The contribution of the carbon emissions associated with buildings is recognised to present a significant opportunity and many international and regional initiatives have focussed on reducing carbon emissions from buildings and their associated energy systems.

This drive for improved performance in buildings and associated energy systems has stimulated (often with EU or other Governmental support) much activity leading to new or improved products and technologies in the marketplace.

The EU Legislation EPBD (EU 2002) and EPBD recast (EU 2010) has established a requirement for energy performance rating of buildings and incremental improvements leading to ‘nearly zero energy’ standards to be applied to new and retrofit buildings in future. Many supporting EU standards (Roulet and Anderson 2006) have been developed including EN 13790 which describes both ‘simplified’ quasi steady state and dynamic methods which can be used to characterise building energy performance in compliance with the EPBD (CEN 2007). Individual EU member state legislation is being enacted to meet the EPBD requirements; in the UK this is being achieved through building regulations.

The EPBD focus is on energy use and cost effective improvements; in the UK carbon emissions and various other aspects of sustainability are recognised in regulations, energy performance certificates for new and existing buildings, and sustainability standards such as ‘The Code for Sustainable Homes’ (DCLG 2010), ‘BREEAM’ (BRE 2012b) and ‘Scottish Technical Standards Section 7: Sustainability’ (Scot Gov 2011).

In parallel with the legislative measures, the EU and UK Governments, Industry, and other bodies have produced a wide range of exemplar projects and guidelines for both new build and to a lesser extent renovation of existing buildings.

These EU and UK activities are mirrored in other countries, states and regions, e.g. in the USA LEED (USGBC 2012) has been established as an energy and sustainability standard similar to BREEAM; in California Title 24 standards (CES 2012) dictate aggressive energy performance to be achieved by new and modified domestic and non-domestic buildings; in Australia the Australian Buildings Greenhouse Rating (ABGR) scheme incorporated within the National Australian Building Energy Standards (NABERS) scheme has been implemented since 2000 (NABERS 2012); in Japan the CASBEE scheme has been established since 2003 (IBEC 2012).

In parallel with the drive to achieve low carbon and low energy performance and sustainability, the Building Information Model (BIM) Initiative (Succar 2009) aims to provide an integrated buildings industry process which facilitates interchange of information between partners in the design, construction and operation of the building. This initiative has been endorsed by several Governments and Government agencies and is seen as key to improving productivity and competitiveness which is perceived to have stagnated in the buildings industry compared to other industrial sectors (BSI 2012).

Concern has been raised that buildings which achieve a high standard or rating based on the predictive calculation methods do not necessarily have the intended high performance in operation (Bannister 2003) (UBT 2012) (Booth 2008) (EST 2012a) (Turner and Frankel 2008).

This rapidly developing and complex situation is challenging to those aiming to deliver low carbon buildings in practice. The plethora of regulations and standards, technical options and their integration, in combination with the wide range of building and construction types, particularly in existing building stocks, makes option appraisal difficult and presents a challenge to the supply chain, building professionals, building managers and building occupants.

Two aspects of the buildings process were identified as the focus of this thesis: the first is methods to support decisions on the most appropriate technical option or combination of options to apply in a given situation; the second is how design intent translates into actual building performance.

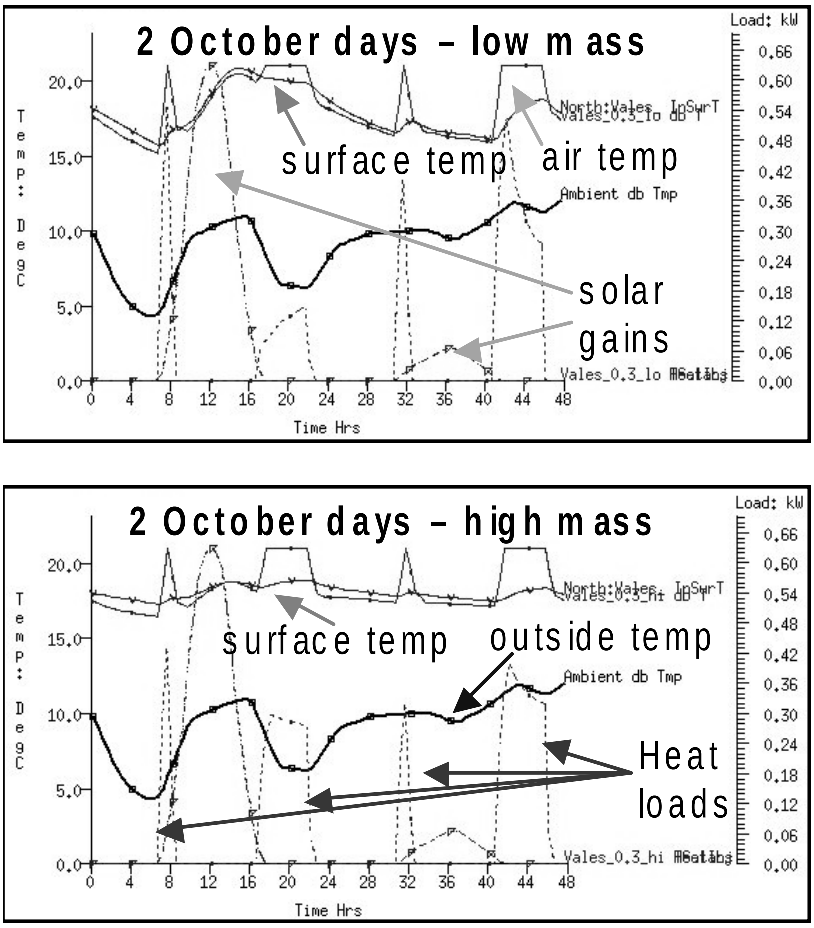
## 2.2 Part A. Performance assessment and option appraisal.

### 2.2.1 Performance assessment and option appraisal – Literature review.

The importance of correctly assessing building performance and appropriate upgrade options has increased in parallel with the increase in difficulty of making these assessments for the reasons highlighted above. Policy makers, building or building stock managers and other building professionals are increasingly required to make decisions based on these assessments.

The calculation method to be used in the performance assessment is one important consideration with a range including simplified (typically monthly) and dynamic (typically sub-hourly) calculation methods available. While the simple methods give only monthly or annual data outputs based on time averaged inputs, dynamic methods can give much more detailed performance insights. Some example simulation outputs are shown in figure 2.1, to illustrate only a subset of the full range of possible rich insight supported by dynamic simulation and not available to the simplified monthly methods.. These more detailed outputs are based on the more detailed physical representation of constructions, systems, controls, climates, occupant behaviour and occupant comfort than possible in the dynamic simulation calculation methods.

***Fig. 2.1 An illustration of dynamic simulation outputs including sub-hourly variations in air temperature, surface temperature, solar gains, outdoor temperatures, and heating load for a building with low thermal mass construction and the same building with high thermal mass construction.***



Simplified monthly methods have historically been used for building standard compliance; dynamic methods have historically been used for investigation of more detailed building performance questions. However this situation has changed over the last 10 years with dynamic methods becoming an accepted method for building standards compliance and energy performance rating and increasingly becoming the mandatory method of performance assessment for more complex buildings.

The UK Government uses the Standard Assessment Procedure (SAP, BRE 2012) for dwellings which is in compliance with the CEN 13790 monthly method. The UK Government has also established the UK National Calculation Method (NCM) for performance assessment of non-domestic buildings for both building regulation compliance and energy performance rating (BRE 2012a). The NCM allows the use of either simple or dynamic simulation methods (DSM) in accordance with EN 13790. The NCM lays down rules for the use of simplified and DSM methods including software tool accreditation. Under the NCM the Governments Simplified Building Energy Model (SBEM) which uses the EN 13790 simple monthly method is allowed to be used for simpler building types while DSM may be used for any building type and is mandatory for more complex buildings that are beyond the defined scope of the simplified SBEM model.

The Passive House standard has been promoted as an EU wide standard for domestic and non-domestic buildings through several EU projects (CEPHEUS 2012); it also uses an EN 13790 compliant simple monthly calculation method known as the Passive House Planning Package (PHPP) (PHI 2012). The PHPP documentation includes the guidance that the simple monthly method has limitations and that where for example gains are concentrated in space or time then dynamic methods must be used.

There is general acceptance that dynamic methods have greater capability to represent building performance, leading to increasing use of dynamic methods in performance assessment. While dynamic methods have the potential to provide more detailed insights they generally require correspondingly more detailed inputs and may require a more expert user than the simpler methods.

Given the policy direction and need for improved building regulations, Government agencies and others responsible for forming revisions in building standards have a critical requirement for a method to assess building performance and appraise upgrade options across their stock in order to inform future legislation and associated standards that can deliver policy aspirations for reduced carbon emissions without having unnecessarily adverse economic, industrial or social consequences. Those with responsibility for buildings that are required to have their performance assessed and upgraded in line with the revised legislation and associated standards then also have a critical requirement for a method of performance assessment and upgrade appraisal to inform the approach they will take. There is also a requirement to educate those in current and future buildings industry on the impact of different upgrade options on building performance so that their knowledge and awareness is raised.

One insight into the current policy and associated regulation setting process is provided by the Scottish Governments 2008 policy document ‘A Low Carbon Building Standards Strategy for Scotland’ (Sullivan 2008) and supporting research contributed by this author that were designed to assess potential impacts of improved regulatory standards (Tuohy 2009, Turner and Townsend 2008). The regulation setting process focussed on standards for new buildings only and the Government mandated the use of the SAP simplified monthly calculation method to predict performance for a subset of exemplar buildings and a limited set of possible upgrade measures. An example of the research output is given in figure 2.2.

***Fig. 2.2 Impact of a range of improvement measures applied individually to the 2007 regulations detached house (Tuohy 2009).***

| Improvement measures beyond 2007 regulations<br>Individual improvement measures applied to 2007 house: | DER kgCO$_2$ /m2.y | CO2 % saving | Percentage CO2 saving (%) [SAP]<br>10% 20% 30% 40% 50% 60% 70% 80% | Rating (EI) |
|---|---|---|---|---|
| 2007 base case (with gas boiler + radiators) | 25 | 0 | | C |
| Infiltration reduced from 10 to 5 m3/m2.h at 50Pa | 24 | 4% | | C |
| Infiltration reduced from 10 to 1 m3/m2.h at 50Pa | 23 | 6% | | C |
| 100% low energy lights (lel) | 24 | 3% | | C |
| Underfloor heating (concrete screed) | 27 | -9% | | C |
| GSHP space heat + lightweight underfloor heating | 20 | 18% | | B |
| GSHP space and HW heat + lightweight underfloor heating | 20 | 21% | | B |
| ASHP space and HW heat + lightweight underfloor heating | 23 | 6% | | C |
| Solar thermal (1000kWh per annum) | 23 | 9% | | C |
| Solar PV (650kWh per annum) | 21 | 15% | | C |
| Biomass boiler space heating (85% eff) | 15 | 40% | | B |
| Biomass boiler space and hot water heating (85% eff) | 9 | 64% | | B+ |
| Gas community CHP space and water heat | 14 | 42% | | B |
| Biomass community CHP space and water heat | -7 | 130% | | A++ |
| 0.15 insulation / 5m3 per m2.h at 50Pa / lel (0.15/5) | 20 | 20% | | B |
| 0.1 insulation / 1m3 per m2.h at 50Pa / lel (0.1/1) | 16 | 35% | | B |
| 0.1 ins / 1m3 per m2.h / lel / MVHR (0.1/1 plus MVHR66/1) | 16 | 35% | | B |
| 0.1 ins / 1m3 per m2.h / lel / MVHR (0.1/1 plus MVHR90/1) | 15 | 39% | | B |
| 0.1 ins / 1m3 per m2.h / lel / MVHR (0.1/1 plus MVHR90/0.5) | 15 | 41% | | B |

This restricted set of results for a small number of selected scenarios involved construction, energy, and cost consultants in a lengthy process. If the policy decision maker required further scenarios to be explored then this required further engagement of the team of experts. A similar process would generally be followed by those responsible for implementing performance upgrades on buildings or building stocks. Several limitations are apparent here, the use of simplified methods, the requirement to engage an expert team, a focus on a restricted sub-set of buildings only, the generation of only a very limited sub-set of the possible upgrade scenarios, the lengthy and costly iterative process.

Worldwide there have been many efforts to provide support for building performance assessment and upgrade option appraisal. A number of researchers have produced non-simulation based methods for use by experts to provide inputs to policy and strategy decision makers. These non-simulation approaches are limited by the use of simplified quasi-static annual or monthly calculation methods and also the requirement to engage third party experts. Examples in this category include: the BREhomes BRE Domestic Energy Model (BREDEM) based model which has been used to model the UK stock and provide analysis of potential upgrade options in the form of regular reports (Shorrock and Dunster 1997). The BMT sub-project of the Carbon Visions project (Staunton 2008) has created stock level models (UKDCM2, UKNDCM) based on the simple UK calculation methods (BREDEM, SAP) in order to provide scenario and policy effect analysis (BMT, 2008). Jones et al (Jones et al 2001, Li, Jones, et al 2007) developed the Energy and Environmental Prediction (EEP) planning support tool based on SAP and a geographic information system (GIS). The tool was applied by researchers to the Neath Port Talbot County Borough comprising 60,000 dwellings and 4,000 commercial properties. Gupta (Gupta, 2008) developed the similar SAP and GIS based ‘DECoRuM’ methodology and toolset.

Other researchers have used simulation based methods in the hands of experts to provide inputs to policy and strategy decision makers. While these approaches have the advantages of using dynamic simulation methods with capability for more detailed representation and analysis than the simplified methods, they have the limitation that they require the engagement of third party experts in the assessment process, with associated cost and time implications. Crawley (Crawley 2007, 2007a) reported on a DSM-based method for the assessment of the impact of climate change and urban heat island effects on future building performance. Heiple and Sailor (Heiple and Sailor 2008) investigated energy supply and heat island effects using DSM and GIS at the urban scale. Their approach employed prototypical models representing 8 dwelling and 22 non-dwelling types. Entire districts were then mapped and the researchers reported agreement with utility data to within 10%. Researchers at Osaka University used DSM models corresponding to offices and

228 residential categories to provide inputs for policy decisions (Yamaguchi et al, 2003). (Hashimoto et al, 2007) (Taniguchi et al, 2007). The UK Technology Assessment for Radically Improving the Built Asset Base (TARBASE) sub-project of the UK Carbon Visions project carried out dynamic simulation modelling for representative building types in order to determine the applicability and likely impact of specific upgrade measures (Staunton, 2008). Swan (Swan, 2009) (Swan, 2009a) created a hybrid database for modelling the Canadian housing stock and supporting policy and strategy analysis. Based on extensive existing survey data, DSM models of 17,000 different dwelling categories based on actual architectural details are being established.

Clarke et al (Clarke et al 2004) developed and deployed a simulation based method for evaluating the impact of thermal improvements on the space heating performance of existing Scottish dwellings and housing stocks. The approach taken was to map a range of thermal performance possibilities into an array of dynamic simulation models with each one identified as a specific thermodynamic class (TC). These models were then pre-simulated and the upgrades of dwellings were then evaluated by mapping the original and the improved dwelling to their corresponding thermodynamic classes and comparing the pre-simulated results. This approach greatly reduced the complexity of the modelling task compared to modelling dwellings by distinct architectural types with all possible thermal upgrades and also allowed dynamic simulation results to be delivered ‘real-time’ to the user. The method of Clarke et al is encapsulated in the Housing Upgrade Planning Support (HUPS) toolset. The main HUPS tool supports space heating demand analysis; further spreadsheet based tools allow simple analysis of renewable energy systems and the impact of energy efficient lights and appliances. While the HUPS method provided some useful concepts with the potential to be leveraged in the proposed research of this thesis, as would be expected from the timeframe and more limited scope of HUPS, many gaps remained to be addressed. The challenges not addressed included: the requirement for specialist input data (e.g. thermal mass and thermal mass position); the many additional factors required to be assessed under the EPBD (specifics of geometry, thermal bridging, range of thermal performance and potential upgrades, range of system and control types and potential upgrades); appropriate thermodynamic classes to represent the range of current and future thermal performance in alignment with survey data; a mechanism to address the discrete nature of the TC method; to encapsulate the method in a single tool for real-time use by experts and non experts; to match with the needs of the range of potential users; to evaluate, demonstrate and deploy the method; to critically review and identify limitations and opportunities for future research and development.

One challenge faced by EU countries in implementing the EPBD legislation was how to minimise the cost burden on individuals and organisations of the EPC ratings process, a common view being that money spent on ratings should be minimised so that money was available as much as possible for the implementation of improvements. Much of the cost historically associated with performance rating has been associated with the need for qualified energy assessors to undertake detailed physical surveys. A challenge for research into a low cost method would then ideally consider whether this detailed physical survey could be avoided through homeowners themselves returning an energy statement (analogous to a tax return) which would allow a rating and appropriate upgrades to be determined.

### 2.2.2 Performance assessment and option appraisal – research question, method and thesis structure.

The specific research question formed as the output from this review of the performance assessment and upgrade option appraisal state of the art was: *“Can a low cost simulation based method be developed to support real-time performance assessment and option appraisal by a range of users in the context of the EPBD?”*

The research presented here then makes the hypothesis that such a method can be realised, proposes such a method and tests the hypothesis through a range of deployments to the Scottish domestic building stock.

Decomposing the research question leads to the following desired characteristics for the proposed method:

- The method should be aligned with the requirements of the EU EPBD.
- The method should be dynamic simulation based to allow the more detailed physical models to provide more detailed performance insights.

- The method should be encapsulated in a single easy to use format that facilitates ‘real-time’ analysis.
- The method should not require dynamic simulation expertise to carry out meaningful analysis.
- The method should be able to be used by building professionals with some limited amount of education / training.
- The method should be capable of being used through data gathered by people who are not buildings professionals with some limited amount of education / training.

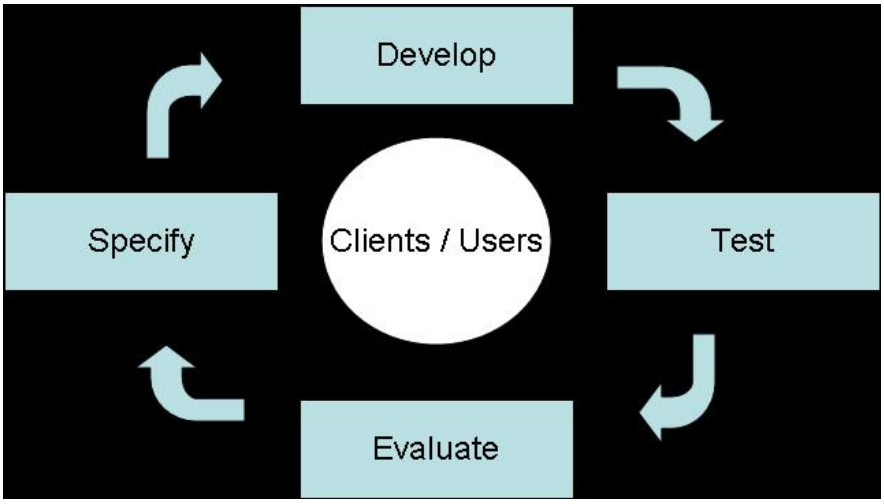
Table 2.1 provides a high level summary of the previous work against the desired specification.

An iterative approach was adopted in this research (figure 2.3) with a client and user group providing a response to propositions put forward by the author: inputs on requirements, opportunities for testing, user and technical feedbacks.

**Table 2.1: Previous work and desired characteristics**

| Method | EPBD aligned | Dynamic simulation based | Single tool with real time results | For use by non simulation experts | For use by building profession | For use by non-building profession |
|---|---|---|---|---|---|---|
| SAP<br>SBEM<br>RDSAP | **Y** | **N** | **Y** | **Y** | **Y** | **N** |
| UK Accredited Dynamic Simulation | **Y** | **Y** | **N** | **N** | **Y** | **N** |
| Non simulation policy decision support | **N** | **N** | **Y** | **Y** | **Y** | **N** |
| Simulation based policy decision support | **N** | **Y** | **N** | **N** | **Y** | **N** |
| Simulation based decision support (Clarke et al). | **N** | **Y** | **N** | **Y** | **Y** | **N** |
| Desired | **Y** | **Y** | **Y** | **Y** | **Y** | **Y** |

***Figure 2.3. Iterative research approach***



Although the technical aspects and the process/user aspects of the method are reported sequentially in this thesis, both were investigated in parallel through this iterative process.

The work on the performance assessment and option appraisal method is presented as follows:

(i) The overall methodology and underpinning calculations are proposed (chapter 3).

(ii) The proposed method is tested through an application for EPC rating based on inputs gathered through a simple questionnaire (chapter 4).

(iii) The method is tested through more general applications in support of strategy and policy decision making (chapter 5).

(iv) The proposed method is reviewed against the original hypothesis, conclusions made, and possible future work described (chapter 5).

The example deployment of the method given here is for the Scottish domestic building stock but the method is intended to have wider applicability.

## 2.3 Part B. Translating intent into performance in practice.

To achieve low carbon building performance it is necessary to make informed policy, strategy or design decisions, but not sufficient. There is a need for these decisions to be effectively translated into low carbon performance in practice. There is much evidence that performance in practice of low carbon buildings and systems is often poorer than intended. As it is an aim of this thesis to address these performance disconnects it is important that these problems are first comprehended,

There are a range of current initiatives aimed at improving industry process. The extent to which these will address the gaps between intended and actual performance is important for the work of this thesis. This thesis aims to address the performance gaps and make a useful contribution that is beyond the scope of these current industry initiatives but with potential for future synergy.

Here the literature review is presented for each of these two areas, first the literature on performance problems for systems and buildings intended to be low carbon, and then the literature on current industry initiatives is reviewed.

### 2.3.1 Gaps between intended and actual performance – Literature review.

Concern has been raised by studies worldwide that buildings which achieve a high standard or rating based on the predictive calculation methods frequently do not demonstrate the intended performance in operation.  A few of these studies are briefly reviewed below, in order to highlight the gaps that have been identified, and the causes proposed.

In the UK there have been a number of historical studies that aim to understand non-domestic building performance, particularly energy and indoor environmental performance. They include low-energy demonstration projects in the 1980s, and case studies, reviews and research under the Energy Efficiency Best Practice and Partners in Innovation programmes in the 1990s.  The results informed policy, regulation and technical guidance for professionals, for example in Energy Consumption Guide 19 for offices (Carbon Trust 2003), first published in 1991.  This guide groups office buildings into four categories: naturally ventilated cellular; naturally ventilated open plan; air conditioned standard; air conditioned prestige. The energy benchmarks for naturally-ventilated buildings are significantly lower than for air conditioned types, so one might have expected regulations to favour naturally ventilated buildings. Instead, there is some evidence that the performance-based specification used in the regulations which take account of performance relative to a reference building rather than absolute performance, with correspondingly higher energy use allowed for mechanically cooled buildings, may encourage buildings that have mechanical cooling (Tuohy 2009a).

Other work included the Probe series of published post-occupancy surveys, which exposed many strategic and tactical issues that made it difficult for even the best buildings to achieve their intended performance. The findings were reviewed in a special issue of Building Research & Information (BRI 2001). The ignorance of the industry, its clients and government to the major differences between expectations and outcomes was also discussed by Bordass (Bordass 2001).

In the late 1990s, the British Government's attention moved away from studying building performance to rethinking construction (DTI 1998) – seeking to streamline the build process to improve efficiency and reduce costs, but failing to provide effective follow-through from construction into operation, or to close the feedback loop. One consequence was the establishment by some Probe team members of the Usable Buildings Trust (UBT) charity, to help provide information and guidance on building performance (UBT 2012). The UBT was influential in the establishment of the UK Display Energy Certificate operational energy performance ratings process (DEC) adopted for non-domestic public buildings over 1000m$^2$ in the UK (Bordass, 2005, Bordass et. al., 2004).

Office buildings investigated in the UK studies included the award winning Elizabeth Fry and ZICER buildings at UEA, the University of East Anglia (Probe14, 1998) (Tovey and Turner, 2006) (Ingham, 2010). Elizabeth Fry was the first building at UEA to use a construction system where ventilation air is routed through cavities formed in concrete structural floor panels. It was also constructed to high levels of insulation and air-tightness, though somewhat short of Passivhaus standards. The ventilation operates with regenerative heat recovery with stated efficiency of 87%.

The building in its first year consumed 60 kWh/m$^2$ electricity plus 70 kWh/m$^2$ of gas, significantly higher than predicted. When performance monitoring revealed considerable scope for savings, the University substantially upgraded the heating and ventilation controls, reducing annual gas consumption for space and water heating to 37 kWh/m$^2$. A recent review (Bordass and Leaman, 2012) showed that this performance has only deteriorated slightly over fifteen years.

The ZICER building at UEA used the same construction system as Elizabeth Fry but with improved insulation and glazing. Completed in 2003, the predicted energy use for space heating was 30 kWh/m2 per year, 10% less that Elizabeth Fry. However, in the first two years of operation it used over twice as much. Another investigation into controls operation was carried out (this time by a research student) and revised control algorithms were put in place, resulting in a similar energy performance to Elizabeth Fry, though with a lower level of occupant satisfaction. In both buildings, the revised control was based on the mass temperature of the ventilated concrete beams of construction instead of air temperature.

Both buildings have been recognised as examples of good performance. In a large part this has been achieved through the high level of visibility, the motivation and efforts of the facility management team, and support from independent monitoring. Without this, both buildings would have continued to use twice as much heat as necessary. UEA has now built five buildings of a similar type, and all have required considerable post-completion input by the university to bring them close to their intended performance – attention that new buildings seldom receive, especially in typical one-off situations.

The strategic review of the findings from Probe including Elizabeth Fry (Bordass et al. 2001), identified inherent problems in the way buildings were procured and proposed making follow through and feedback routine. These and more recent findings are summarised in Bordass (Bordass 2011) which concludes that “Controls, manageability and usability need much more attention at all stages”. Recurring problems with new buildings are summarised as: problems with interfaces between work packages; problems with control systems, management and user interfaces; handover processes too abrupt; user dissatisfaction; unmanageable complexity; and not surprisingly energy use higher than anticipated.

One of the key recommendations from the Probe and Post Probe studies was a 3 year ‘sea trial’ commissioning and review process to achieve optimal performance. This is now incorporated within the Soft Landings process (BSRIA 2012).

CarbonBuzz is a recent initiative in the UK which includes a voluntary (and anonymous if required) repository for predicted and actual energy use data. So far there is limited data but across 9 building types there is evidence of actual energy use being typically more than 50% higher than that predicted (CarbonBuzz, 2012).

Such discrepancies are not unique to the UK. The German Federal Ministry for Economy demonstration program covered 22 non-mechanically cooled buildings designed to be low energy, monitoring energy use, environmental conditions, occupant behaviour and comfort. One observation was that the monitoring and high focus on these buildings highlighted many errors in system and controls operation. “In many cases, detailed analysis of the electricity consumption helped to identify weaknesses in the system operation and aid their correction: operation of the heating system pumps outside the heating season, heating of pre-cooled air by an earth-to-air heat exchanger during summer, etc. In large buildings operational faults cause energy consumptions and energy costs of an order of magnitude which is not negligible. From the experiences it can be assumed that these kinds of faults are common practice in the operation of the building stock as a whole.” (Voss et al, 2007). Their conclusions infer that these faults only come to light through detailed inspection and are invisible in many buildings that are not subject to this scrutiny.

In the USA, a review of the performance of LEED (USGBC, 2012) accredited buildings found those predicted to be most energy efficient had the greatest discrepancies between predicted and actual performance, with actual energy use twice the prediction in some cases (Turner and Frankel, 2008).

In Australia, Bannister (2003), found generally poor or no correlation between the design score and the operational performance benchmarked by Australian Buildings Greenhouse Rating (ABGR) (now incorporated in the National Australian Building Environmental Rating Standards NABERS (NABERS 2012)). In a later paper Bannister (Bannister 2009) identified some reasons why, including poor controls design, implementation and commissioning; poor build quality; complexity; poor maintenance and operations; invisible problems; inoperable or un-maintainable plant and systems; bad design; and over specification. Again these echo the findings of Probe in the UK. To remedy the causes of these disconnects NABERS has developed a “Commitment Agreement” protocol (Bannister 2005) which in order to be able to advertise a building as being targeted at a particular NABERS rating requires expert reviews in the design stages and prescribes the scope and reporting of predictive analysis using building simulation. The NABERS rating is not awarded based on any prediction, only based on actual performance once the building is occupied.

For domestic buildings there appear to be similar problems and disconnects, that may be getting worse as legislation makes the buildings more complicated and technologies traditionally deployed in the non-domestic sector are applied. UK government agencies the Energy Savings Trust (EST) and the Technology Strategy Board (TSB) are undertaking field trials of new technologies in dwellings, monitoring performance of systems in operation and reporting on results (EST 2012). These include micro-CHP systems, gas boilers, micro wind turbines, heat pumps, solar PV and solar thermal systems. In general they have revealed poorer performance than expected, for example with COPs in practice typically 33% less than predicted in the heat pump trials. Other systems currently favoured within regulatory calculations have not yet been subject to extensive field trials. Again the findings echo those of earlier case studies, for example Stevenson & Rijal (2010).

In summary, it would appear that performance disconnects are a common experience in the current buildings industry, that a significant problem exists in the implementation of low carbon systems and controls, and that often these problems are not visible unless non-standard investigations are carried out.

### 2.3.2 A selection of current building industry initiatives – Literature review.

The building industry is going through a period of rapid change. There are many policy and industry initiatives (some of which were highlighted in the previous section) with the intent of improving building performance and building industry processes.

In order to appropriately position the work of this thesis an essential step is to consider to what extent these existing initiatives already address the performance disconnects highlighted in the previous section.

Many initiatives are based on predicted performance leaving actual performance outside their scope and largely unaddressed. A number of initiatives require or encourage post occupancy performance assessment. Some require expert reviews as part of the design and implementation process. There is a suggestion that processes have stagnated in the buildings sector and that processes from other industries could be usefully leveraged.

A range of these current industry initiatives is reviewed here, the range is not exhaustive but was selected to be representative and provide a basis for more general conclusions. After the main work of this thesis is presented, research outcomes are discussed in the context of these initiatives (chapters 8 and 9).

The primary focus here is on initiatives that impact on energy, carbon and indoor environmental performance. The initiatives considered include the UK DEC operational energy rating, Soft Landings, and Australian NABERS processes highlighted in the previous section. The range of initiatives considered is summarised in tables 2.2 and 2.3, brief descriptions and the relevant references are given below:

In its Energy Performance of Buildings Directive, EPBD1 (EU, 2002), the European Union required energy performance-based building regulations, air-conditioning inspections, and energy performance certificates (EPCs). At a minimum, the performance calculation must cover energy use for space and water heating, cooling, lighting and ventilation. The recast, EPBD2 (EU, 2010) identified the need for incremental improvements and targets ‘nearly zero energy’ standards for new and retrofitted buildings in the future. Many supporting EU standards have been developed including CEN13790 which describes both simple and dynamic predictive methods to calculate building energy performance in compliance with the EPBD (CEN, 2007).

Individual EU member states must enact legislation to meet the EPBD requirements. For UK public and commercial buildings this includes: the CEN13790 compliant National Calculation Method (NCM) and the associated Standard Building Energy Model (SBEM). The energy prediction covers the minimum set of end-uses defined in the EPBD, which the industry has come to call “regulated loads”. This predictive method is used in somewhat different ways for regulatory approval and to produce the “Asset Rating” calculated performance indicator for Energy Performance Certificates, EPCs that are statutorily required when a building is sold or let or building work is completed.

***Table 2.2. A selection of EU and UK Policy and Industry Initiatives.***

| | |
|---|---|
| **EU Legislation** | |
| 2002 Energy Performance of Buildings Directive. | o Energy Performance Certificates (EPCs) at sale / rental.<br>o Building regulations updates to improve energy performance for New Buildings. |
| 2010 Energy Performance of Buildings Directive. | o Nearly Zero Energy Standards for New and Retrofit.<br>o Minimum standards for existing buildings at sale / rental. |
| **EU EPBD Implementation - Individual Country Legislation - UK** | |
| Building regulations (England, Wales and Northern Ireland) | o Regulation compliance based on predicted performance.<br>o EPCs based on predicted performance except for public buildings > 1000m$^2$.<br>o EPCs (Display Energy Certificates (DECs)) based on actual energy use for public buildings > 1000m$^2$. |
| **EU Supported Building Energy Performance Standard** | |
| Passivhaus | o Advanced energy performance standard promoted through EU dissemination projects.<br>o Compliance based on predicted performance plus blower door air tightness test. |

*Table 2.2. A selection of EU and UK Policy and Industry Initiatives.(cont'd.)*

| **UK Government supported voluntary sustainability rating systems** | |
|---|---|
| BREEAM | o Sustainability rating system for non domestic buildings (and domestic refurbishment).<br>o Requirement for UK Government projects.<br>o Ratings based on predicted performance.<br>o Commissioning and sub-metering encouraged.<br>o Monitored performance fed back to improve process. |
| Scottish building regs. Sect 7. | o Sustainability rating system for domestic and non domestic (Voluntary).<br>o Ratings based on predicted performance. |
| Code for Sustainable Homes | o Sustainability rating system - domestic (like BREEAM).<br>o Ratings based on predicted performance. |
| **UK Buildings industry process frameworks** | |
| Royal Incorp. of British Architects (RIBA) Plan of Work. Construction Industry Council (CIC) Work Stages. | o RIBA framework for construction process from Architecture perspective; established over 50 years.<br>o Recently added Green and BIM Overlays to RIBA Plan of Work to synergise with Soft Landings and BIM initiatives (see below).<br>o New revision of RIBA Plan of Work due in 2013, to be aligned with the CIC Work Stages. |

*Table 2.2. A selection of EU and UK Policy and Industry Initiatives.(cont'd.)*

| **UK Government supported buildings industry process initiatives** | |
|---|---|
| Soft Landings | o Framework and Core Principles for design, handover and post occupancy to ensure optimal performance.<br>o Participative process in design with expert reviews and the engagement of team through 3 year handover.<br>o Adopted for Government Projects after positive pilots (Government Soft Landings (GSL)). |
| Building Information Modelling (BIM) | o Initiative aimed at improving buildings industry process through use of digital information.<br>o UK BIM policy and BIM Task Force established.<br>o Construction Operations Building Industry Information Exchange (COBie) standard schema adopted.<br>o Development in partnership with industry organisations including the UK Construction Industry Council (CIC), RIBA and CIBSE.<br>o BIM support for existing legislative and voluntary performance standards based on predicted performance.<br>o BIM support for Government Soft Landings (GSL). |
| **UK buildings actual performance benchmarking** | |
| CarbonBuzz | o Voluntary database for anonymous building performance benchmarking. |
| Usable Buildings Trust | o Performance data for case study buildings.<br>o Methodologies and guidance for post occupancy evaluations. |
| UK DEC database | o Actual performance data for public buildings > 1000m$^2$ available on open database. |

*Table 2.3. A selection of Non EU and UK Initiatives.*

| **Voluntary sustainability and energy rating systems** | |
|---|---|
| LEED (USA)<br>GreenStar (Aus) | o Sustainability rating systems for non domestic buildings.<br>o Ratings based on predicted performance.<br>o Commissioning and sub-metering encouraged.<br>o Monitored performance fed back to improve process. |
| NABERS (Australia) | o Energy and indoor environment rating system for non domestic buildings based on post occupancy evaluation.<br>o Ratings based on actual measured performance.<br>o NABERS can be used in pre-completion marketing only where a Commitment Agreement is signed.<br>o Commitment agreement includes expert reviews and specifications for the use of simulations in design and communications of limitations and risks across design team including clients.<br>o On completion of a NABERS project the NABERS rating is given based on actual annual energy use. |
| **Buildings actual performance and benchmarking** | |
| EnergyStar<br>GreenStar (Performance) | o EnergyStar Building performance benchmarking and awards based on comparative energy use.<br>o GreenStar Performance to be launched 2013. |
| NABERS | o Performance data for case study buildings.<br>o Methodologies and guidance for post occupancy evaluations. |

The EPBD also required public buildings over $1000m^2$ to display their energy certificates. Many countries (including Scotland) display predicted EPCs, but in England, Wales and Northern Ireland it was successfully argued that in order to motivate better management, a Display Energy Certificate (DEC) should be based on actual energy use in operation and renewed annually. This “Operational Rating” uses a different, semi-empirical benchmarking procedure, (CIBSE 2008 and 2009), which takes account of all energy end-uses.

Passivhaus is another advanced energy performance standard being promoted across the EU and worldwide (PHI, 2012) and now receiving attention in the UK and beginning to be adopted on a small scale. While concentrating on minimising energy requirements for heating, cooling and ventilation, the standard includes predicted energy for all uses within its criteria. To address quality issues the Passivhaus Institut has developed its own CEN-compliant PHPP predictive software and provides training and accreditation of Passive House Designers and independent Certifiers.

In the UK aspects of sustainability including transport, health, embodied energy and carbon, and ecology are recognised in voluntary standards and rating systems such as:

- The Building Research Establishment’s Environmental Assessment Method BREEAM (BRE, 2012) which was first launched for offices in 1990.
- The Code for Sustainable Homes (DCLG 2010)
- Scottish Technical Standards Section 7: Sustainability (Scot Gov 2011).

These standards are increasingly being adopted as a requirement for UK public funding or in client specifications. They are based on the UK Government’s legislative predictive performance calculation methods described above but give additional credits for elements such as sub-metering and commissioning.

EU and UK initiatives are mirrored in other countries, states and regions, with the LEED (USGBC 2012) sustainability standard in the USA having similarities to BREEAM. The California Title 24 standards (CEC 2012) dictate aggressive energy performance to be achieved by new and modified domestic and non-domestic buildings. These US standards are based on approved predictive energy performance calculation methods. The US also has the voluntary Energy Star (Energy Star 2012) Portfolio Manager building rating scheme based on actual energy use compared with benchmarks for various building types.

The Australian Green Star rating scheme has historically been a sustainability rating scheme similar to BREEAM and LEED with its energy component based on predictive methods. Recently it has announced an operational sustainability rating 'Green Star Performance' (GBCA 2011), for which the energy performance rating will be harmonised with the longstanding ABGR, the Australian Buildings Greenhouse Rating, which now forms part of the National Australian Building Environmental Rating Standards NABERS scheme.

ABGR was first launched for large office buildings in New South Wales in 2000 and is based on operational energy use normalised by building type and use pattern. It is now a national system, is being gradually extended to other building types, and declaration has recently become mandatory for landlords' services in office buildings over 2000 m2. The NABERS scheme also includes water, waste and indoor environment ratings. NABERS energy ratings are based only on operational energy data but NABERS can be used in pre-operation marketing where a "Commitment Agreement" is signed and a protocol followed that includes design review by experts, a rigorous specification for the appropriate use of simulation, and the inclusion of fault tolerance and risk analysis in the design process. There are no ratings given on the basis of design predictions; NABERS ratings are only given based on actual energy performance once in operation.

In the UK, USA and Australia there have been initiatives to improve the design, construction, commissioning and handover processes to achieve better performance in practice. In LEED, similar to BREEAM, there are increasing credits for seasonal commissioning and sub-metering.

In the UK the Soft Landings process has been developed and launched to encourage a collaborative approach to the design process, a focus on outcomes, inclusion of expert reviews, a smooth handover to the building user, a 3 year period of handover, performance optimisation or remediation and post occupancy evaluation of both occupant perceptions and energy performance. (Way and Bordass 2005, BSRIA 2012). Soft Landings is being integrated in synergy with both BREEAM and the RIBA

Plan of Work and is being adopted in an adapted form for projects by central government. Soft Landings encourages the use of standard approaches to the post occupancy evaluation, referencing CIBSE Technical Memorandum 22 (CIBSE 2006) and UBT guidance (UBT 2012) for gathering energy and indoor environmental quality performance data. Soft Landings also suggests the use of CIBSE Code M 'Commissioning Management' as a template for the commissioning process (CIBSE 2003), a main element of this guidance is the appointment of an expert as 'commissioning authority' to oversee the commissioning process.

In parallel with the drive to achieve low carbon, low energy, and sustainability, the worldwide Building Information Modelling and management (BIM) initiative (Succar 2009) aims to provide an integrated building industry process that facilitates interchange of information between partners in the design, construction and operation.

BIM has been endorsed by several Governments and Government agencies and is seen as key to improving productivity and competitiveness perceived to have stagnated in the buildings industry compared to other industrial sectors including retail, automotive and electronics (BSI 2012).

The aim of BIM is to have a common data model for use in the building design and operation by all participants. The UK's BIM roadmap goes from the current mix of paper and electronic 2D and 3D datasets and models through a common 3D model, to modelling that incorporates time, cost and facilities management dimensions (4D, 5D and 6D models respectively). It is also being integrated with the RIBA (RIBA 2011) plan of work. The UK BIM Taskforce has recently announced the intention to support 'Government Soft Landings (GSL)' for the Government estate as a BIM priority after successful trials (GSL 2012).

The identification of industries with higher rates of productivity improvement by BIM proponents suggests a comparison with these industries to be a useful exercise.

In the automotive, aerospace and electronics industries an industrial quality systems approach has been adopted (Pyzdek 2003). Two elements of this quality systems approach may have relevance to the current buildings industry issues. One is the adoption of a modular approach to design, where existing well understood and well documented modules are often re-used with some level of review and customisation

(Freescale 2013). A second is the adoption of a formal risk management process, often through the application of the Failure Mode Effect Analysis (FMEA) (Liu et al 2013) method. The FMEA method is used to capture expert knowledge on what can go wrong, what the impact of this would be, how it could be detected if it occurred, and how the risk can be eliminated so that the problem cannot arise. Based on FMEA reviews with suitably qualified experts actions are determined in the project plans to pro-actively ensure the risk levels are managed i.e. reduced or eliminated, or at worst a failure detected, so that they should not cause a hidden failure in practice.

FMEA's are associated with design modules and assist in the transfer of knowledge pertaining to the selected modules from project to project. The FMEA that has been developed over time for a module will be the starting point for the FMEA analysis for use of that module in the context of the next project and so on, ensuring that learning is captured and transferred.

This review of industry initiatives provides a useful context for the work of this thesis. It was concluded that while some of the current initiatives address some aspects of the performance disconnects, a more direct and systemic approach such as the modular design and failure mode risk management techniques of BIM benchmark industries would be required to enable the effective and routine realisation of low carbon systems and controls with the intended performance in practice. The view was taken however that the outcome of this thesis should be applicable in synergy with the most appropriate of the current industry initiatives.

### 2.3.3 Translating intent into performance in practice – research question, method and thesis structure.

It is clear that there are disconnects between intended and actual building performance particularly in the performance of systems and controls. It is also clear that these are often hidden from building professionals, building managers and building users.

The current industry initiatives encourage a more participative approach to projects with all the project partners and the building manager / user involved throughout the building design and implementation process.

The current initiatives attempt to address the issues which potentially cause the performance disconnects largely through the requirement for expert engagement in reviews at various stages of building design and implementation process and a requirement in some initiatives for actual performance to be assessed.

The current industry initiatives involve consultants and experts as a vehicle for knowledge transfer between projects and to ensure lessons are learned from what has gone before.

The view is taken here that while this engagement of experts is a positive step, this relies on the particular expertise and knowledge of the available experts. It is proposed that a more systematic approach will be required, such as the modular approach and use of FMEA as adopted in some of the BIM benchmark industries, if the industry is to routinely achieve low carbon performance in practice.

The research question formulated was: *"Could a Modular Control Mapping and FMEA approach be developed to address the gaps between intended and actual performance for systems and controls in low energy buildings in synergy with current industry initiatives?"*

The hypothesis was made that a system and control mapping approach based on well characterised modules and FMEA analysis could be developed that would usefully support resolution of the highlighted performance gaps in systems and controls in low carbon buildings, in synergy with current industry initiatives.

The work on the Modular Control Mapping and FMEA method to address gaps between intended and actual performance for systems and controls is presented as follows:

(i) An Modular Control Mapping and FMEA method is proposed. (Chapter 6).

(ii) A test application is made of the proposed method to an office intended to be low carbon, with the focus on low carbon systems and controls. The results of this application are reviewed. (Chapter 6).

(iii) Further test applications are carried out to two domestic buildings intended to be low carbon with the focus on their low carbon systems and controls. The results are reviewed. (Chapter 7)

(iv) The overall performance of the method is then reviewed and some conclusions made. How the Modular Control Mapping and FMEA method can be usefully integrated within the buildings industry process is proposed. (Chapter 7)

(v) The Modular Control Mapping and FMEA methods developed in this thesis have leveraged (in part) processes from a BIM benchmark industry. The potential for further techniques and methods from the BIM benchmark industry (electronics) is discussed and some proposals put forward for future research in this area. (Chapter 8).

Conclusions on both the performance assessment and upgrade option appraisal method, and the modular control mapping and FMEA method are summarised in the final chapter (Chapter 9). The extent to which the research of this thesis has delivered useful outcomes to support a) performance assessment and option appraisal and b) translation of intent into performance in practice is reviewed. Opportunities for further research and development to build on the outcomes of this thesis are then proposed.

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# PART A:

# Performance assessment and option appraisal

# Chapter 3: Performance assessment and option appraisal: Overall method, logic and underpinning calculations

*The aim is to test the hypothesis that a low cost, real time, simulation based performance assessment and option appraisal method can be developed to support a range of users in the context of the EPBD.*

*The focus in this chapter is on the overall technical approach and a definition of the underpinning logic and calculation framework. The approach is demonstrated through an example deployment to the Scottish domestic building stock.*

*Subsequent chapters address processes for user application of the method; give the findings from test applications of the method; and review the outcomes against the original hypothesis.*

*For clarity, a statement on the relationship of this work to prior work in ESRU is provided in appendix A.*

## 3.1 Aim and general approach

The aim is to answer the research question: *"Can a low cost method based on dynamic simulation be developed for real-time use by non-simulation experts that supports performance assessment and low carbon building upgrade option appraisal in the context of the EU EPBD?"*

As stated earlier the underlying assertion is that dynamic simulation has the potential to model building performance much more accurately and provide detailed insights such as: indoor environmental conditions, overheating, thermal comfort, occupant behaviour, moisture, lighting, systems performance, control, and interactions which are not possible with non-dynamic methods.

The hypothesis was advanced that a low cost, real time, simulation based performance assessment and option appraisal method can be developed to support a range of users in the context of the EPBD.

The hypothesis was then tested through: the development of a method including its underpinning logic and calculations (this chapter); pilot applications of the method (following chapters 4 and 5); evaluation and critical appraisal of the method (chapter 5). The outcomes were then discussed and proposals put forward for potential future research, developments and refinements (chapter 5 and chapter 9).

The Scottish housing sector was chosen for the pilot as there was a critical need in this sector due to a plethora of new technical options, expansion in number of potential decision makers, and a lack of access to simulation and building services expertise.

Engagement with a Scottish Government focus group on EPBD implementation gave access to potential users including policymakers, local authority and social landlords, building warrant officers, developers and other building professionals, and tenants and homeowners. The research into the simulation based method was of interest to the user group as a potential future improvement on the simple methods used historically for performance assessment, upgrade option appraisal and to inform policy.

The methods developed and demonstrated here for the Scottish domestic building stock are intended to be generally applicable to other building stocks and situations. The deployment for the Scottish domestic building stock is put forward as an example to be followed in future applications, and to provide insights to inform future research and development.

In this chapter the high level method is elaborated. The development of the method for application to the Scottish domestic building stock is then described.

## 3.2 Initial definition of high level requirements

### 3.2.1 Technical requirements

The technical requirements were in part derived from the EPBD itself which defines the: "'energy performance of a building': the amount of energy actually consumed or estimated to meet the different needs associated with a standardised use of the building, which may include, *inter alia*, heating, hot water heating, cooling, ventilation and lighting. This amount shall be reflected in one or more numeric indicators which have been calculated, taking into account insulation, technical and installation characteristics, design and positioning in relation to climatic aspects, solar exposure and influence of neighbouring structures, own-energy generation and other factors, including indoor climate, that influence the energy demand" (EU 2002, 2009). The EU CEN standard 13790 states that in determining space heating energy demands dynamic simulation calculations must consider: transmission heat transfer characteristics (CEN 2007); ventilation heat transfer characteristics; internal heat sources; solar heat sources; dynamic parameters; and internal conditions. The EPBD further specifies "The energy performance certificate shall be accompanied by recommendations for the cost-effective improvement of the energy performance". The EPBD calculation methodology adopted across the UK was the Government's simple monthly Standard Assessment Procedure (SAP) for new dwellings, and a reduced data input version of SAP (RDSAP) for existing dwellings (BRE 2013). One implied technical requirement for the proposed simulation based method was to support at least a similar range of technical upgrade options to those available in these existing simple methods.

While the EPBD defines the technical requirements in some detail there is scope for different specifics of how these requirements are complied with. One important consideration is the availability, accessibility, and reliability, of data. The implementation of the method should consider these factors.

### 3.2.2 User and process requirements

Application of formal methods for gathering user requirements and user feedback (such as the Delphi method (Hsu and Sandford 2007)) were considered. Selected principles of the Delphi method were followed, i.e. involving experts in an iterative discussion and refinement process, initial dialogue based on open questions etc. The user group (in this case the focus group on EPBD implementation) was engaged through facilitated discussions, execution of pilot trials, and quantitative and qualitative feedbacks at several stages.

The initial user requirements were gathered through meetings of the EPBD focus group. Questions asked were:

1. “What would be the potential uses of a performance assessment and option appraisal method?
2. Who would be the potential users of a performance assessment and option appraisal method?” and
3. “What are the requirements of these users (considering both inputs and outputs)?”

The participants were asked to discuss each question in turn for 15 minutes in sub-groups of 3 or 4 people and then each group presented their requirements, then the whole group discussed points of similarity or divergence. The outputs from the first and second questions were that the group confirmed that an option appraisal method would potentially be useful for:

- Performance rating and option appraisal requirements for Energy Performance Certificates (EPCs) by accredited individuals (e.g. building control officers, energy or maintenance managers)
- Local Authority and Social Landlord housing stock assessment and upgrade planning by energy, development or maintenance officers
- Policy analysis by Government officials
- Building design or upgrade strategy option appraisals by architects or developers
- Education of current and potential future building professionals through CPD and University / College teaching.

It was clear that the method could potentially be useful to a range of users with different requirements and technical skill levels.

Some of the wide ranging requirements expressed in the facilitated sessions were:

- The method should support a range of users with different technical expertise and different levels of access to technical data.
- The method should support the use of pre-existing databases where available.
- The method should be able to produce results based on inputs gathered from a simple questionnaire filled in by homeowners or landlords (similar to a tax form).
- The method should provide immediate results that are displayed and also able to be output as data tables for further analysis and reporting.
- The method should provide energy, $CO_2$ and financial outputs.
- The method should incorporate all domestic energy uses (EPBD does not include energy for appliances and IT equipment).
- The method should contain default values (e.g. boiler efficiencies, fuel costs) but allow the user to update these if required.
- The method should provide similar outputs to the simple regulatory method when the regulatory standard climates and patterns of use are applied (occupancy, heating, lighting, hot water and appliance use).
- The method should allow different patterns of building use to be assessed.
- The method should allow different (local) climates to be represented.
- The method should capture a wide range of potential upgrade options.
- The results must be realistic.
- Ideally the outputs displayed should include an EPC type graphic and a display of the key input and output parameters for both the baseline and the option being assessed.
- Ideally the method should be able to support analysis of building stocks as well as individual buildings.

Additional more global requirements were also imposed on the method for this thesis to ensure its broader applicability:

- The method should be general and able to be redeployed to other stocks.

These initial EPBD and user group requirements were used to inform the concept and initial development of the method. Further feedback was sought and received from the user group (and sub-groups) at later stages of the development process.

### 3.3. Proposed high level technical design for the method

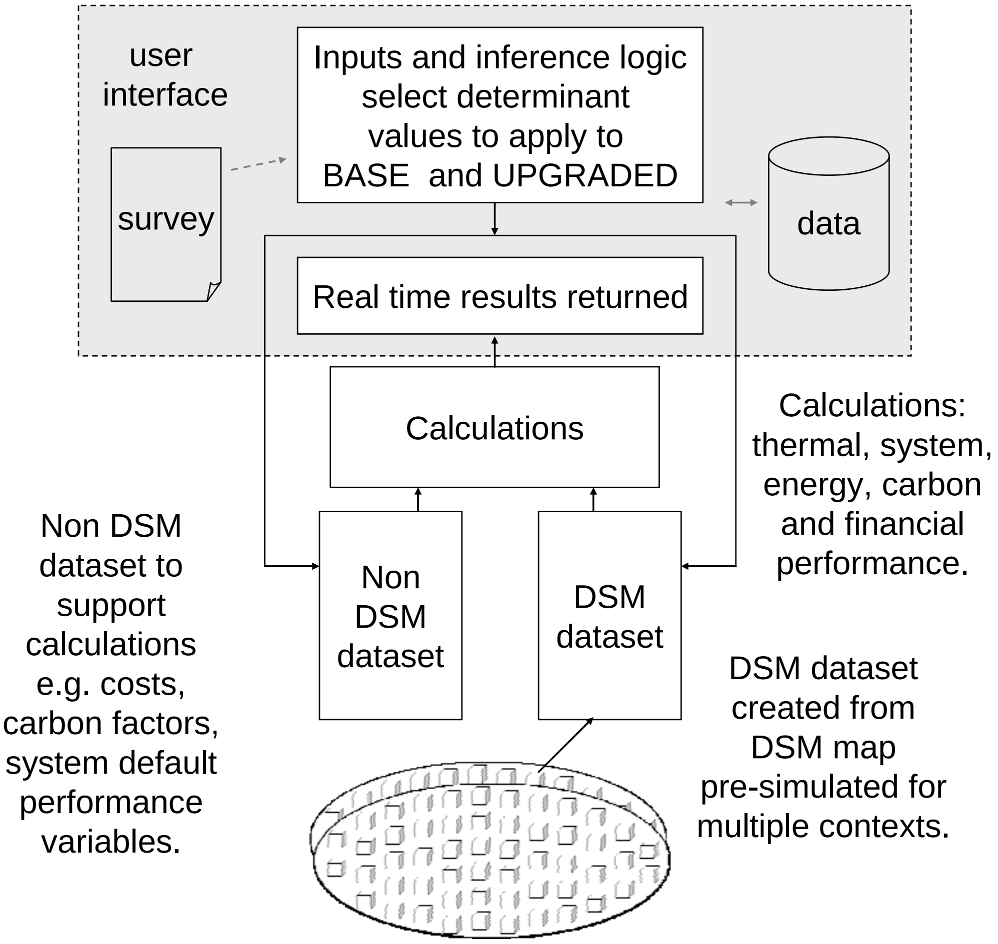
Based on the literature review and the high level technical and user requirements a technical design concept for the method was proposed (figure 3.2). The key elements are:

- User interface(s) that support a range of data input and output modes depending on user e.g. expertise and data availability.
- The ability to accept high level inputs (e.g. householder survey) and use inference logic to select appropriate values for performance determinant parameters to drive the performance calculations.
- The ability to accept inputs from and provide outputs to existing databases (e.g. Local Authority stock condition or maintenance databases etc) or support creation of a new database.
- The ability to determine the performance of the current building (base) and the performance with upgrades applied.
- The ability to generate output files and reports at various levels of detail giving performance assessments and upgrade option appraisals (Capital costs, Running costs, $CO_2$, Energy or Fuels by end use, plus performance determinant parameter values etc).
- The ability to return results 'real time' through the use of calculations based on performance determinant parameter values to select calculation inputs from a both a non-simulation dataset and from a set of pre-simulated dynamic simulation results.
- The dynamic simulation dataset would be pre-generated to include a range of different contexts i.e. to represent variations in climate, occupant behaviour, pattern of use etc.
- The non simulation dataset will include parameters representing financial, carbon intensities and calculation inputs associated with performance determinant values where these are not directly included in the simulation dataset. (e.g. system efficiencies).

Within this general high level concept there is the possibility of using DSM to varying extents depending on the objectives of the application. A range of dynamic modelling ‘domains’ could be applied as appropriate to the application including thermal, airflow, plant, moisture, lighting, visualisation, and behavioural domains. Where parameters are to be included in the dynamic simulation domain these could be either as determinant parameters with varying values, as fixed parameters (e.g. set at some conservative value), or as post simulation scaling factors.

While in the proposed method dynamic simulation expertise is required to establish and simulate the underlying array of models representing the current and future performance map of the building stock, once this DSM dataset is established analysis can then be done without any specialist simulation knowledge.

***Figure 3.2. High level design of the option appraisal method (note ' DSM' is used here as an abbreviation for 'dynamic simulation modelling').***



### 3.4 Key challenges

At high level the challenges in developing this concept to meet the requirements here are: to incorporate the factors required to be assessed under the EPBD; to establish the appropriate performance determinant parameters, values, and associated thermodynamic classes to represent the full range of current and future thermal performance; to establish the non dynamic calculations; to encapsulate the method in software to meet the needs of non simulation experts; to evaluate, demonstrate, deploy and assess the method for a range of applications.

Breaking down these high level challenges gave the following technical tasks required for implementation of the method:

(i) To establish the determinant parameters, dynamic simulation models and DSM dataset:

- Define the approach to cover all parameters to be addressed in context of EPBD.
- Incorporate the required detailed geometry factors.
- Define the performance map to include existing and up to the most advanced performance standards (e.g. Passive House).
- Create the ability to analyse individual or combined elemental upgrades with detailed inputs (rather than pre-defined ‘packages’ of upgrades with pre-set levels).
- Align results with the survey data supporting simplified EPBD regulatory methods when a regulatory context selected (climate, pattern of use).
- Align results with available survey and monitored data.
- Identify model determinant parameters and levels required to describe current and future stock to appropriate detail.
- Establish full set of simulation models that address points above.
- Simulate the set of models for the required contexts (climates and pattern of use) to create the DSM dataset.

(ii) To establish the non-DSM dataset and calculations, and inference logic

- Establish a comprehensive set of building systems calculation models in synergy with the DSM dataset and associated performance determinant parameters to cover the required range of fuels, systems and controls for domestic heating, hot water, ventilation and renewable generation, with performance up to Passive House or other advanced standard.
- Define energy, carbon and financial calculations.
- Define calculation models for combining DSM and non-DSM performance to give required outputs.
- Define relationships to allow determinant parameter values to be inferred from available datasets and high level inputs.

(iii) To establish the software framework

- Provide the capability for display and tabular data inputs and outputs.
- Provide the capability for pre-existing databases to be used as input.
- Provide for underlying performance parameters and datasets to be adjusted by expert users (e.g. fuel costs, carbon emission factors, default system efficiencies etc).
- Support direct use by persons with a range of expertise and data availability, through inferred default values to be set from high level inputs or through more detailed inputs where these are available.
- Provide specifications and guidance documentation including data inputs and outputs and data gathering questionnaire templates.

An underlying challenge is associated with the availability of the information required to inform the method. The information available to the users is a consideration which influences the choices made. Users with access to different levels of data need to be considered. The information available to inform the underpinning logic, calculations and dynamic simulation models has an influence on configuration of these elements.

There is some tension between the level of detail required to inform the method, data quality, and effort required to obtain and validate the data. The approach taken here has been to formulate the method to fit with readily available data for the stock in question and avoid the requirement for detailed building geometric survey data. This approach is in line with the ‘low cost’ aspiration expressed in the research question. This formulation places then some restrictions on the scope, these restrictions and alternate formulations are discussed in more detail later (chapter 5).

### 3.5 Method development and example formulation for application to the Scottish domestic building stock.

The hypothesis was tested by first developing (this chapter) then applying (chapter 4 and 5) the proposed method to the Scottish housing stock, then carrying out an evaluation and critical review (chapter 5).

The pilot application necessarily involved making initial decisions on the approach to be taken; some of these decisions were difficult to make up front and could be viewed as being place-holders; the impact of these initial choices and how these choices may be best approached for future applications is discussed in chapter 5.

The steps taken to develop the concept for the pilot application were: to identify the technical requirements of the EPBD; to define performance determinant parameters and categorise them appropriately (fabric, geometry, system and context categories were established); to decide which determinant parameters are to be represented in dynamic simulation and how e.g. as a model array determinant, fixed in the models, or post simulation scaling factor; to establish the simulation model array and simulate for the required range of contexts (climates, user behaviours and patterns of use) to provide the DSM dataset; to define the non simulation calculations determinant parameters and levels; to develop the user interface and required user functionality including inference relationships appropriate to a range of user groups.

For this pilot application it was decided to use the thermal dynamic modelling domain. The potential use of other domains is discussed later.

### 3.5.1 Performance determinant parameters.

The main technical determinants of performance are reasonably well established e.g. in the EU CEN 13790 standard (CEN 2007) and the UK's EPBD compliant methods SAP and NCM (BRE 2012, 2012a), these are briefly summarised here:

Transmission heat transfer determinant characteristics include: area and heat loss properties of each surface, lengths and heat loss properties for each junction between surfaces, and heat loss properties of any point bridges within surfaces. These are represented in simple calculation methods by surface heat loss parameters (U-values, $W/m^2.K$) and areas ($m^2$) , linear heat loss parameters (Psi values, W/m.K) and lengths (m) and point heat loss parameters (Chi values, W/K). These are addressed in simulation models by assigning construction materials and junctions with appropriate physical properties and geometries.

Ventilation heat transfer determinant characteristics represent the heat loads associated with both unintended infiltration through the building fabric and the intended ventilation either through window opening behaviour or mechanical means. These are represented as a resultant ventilation rate or effective air change rate in relation to volume in simple methods and can be addressed in the same way in thermal simulation or by using more detailed ventilation and airflow modelling.

Internal heat gains from occupants, lighting, cooking, heating and hot water systems make a contribution to the space heating requirement; these are represented by monthly average values in the simple methods but can be represented by more detailed sub-hourly schedules in simulation. Similarly solar heat sources which contribute to heating requirements can be represented in more detail in simulation. The utilisation of these internal and solar heat gains is modelled in the simple methods using a utilisation factor dependent on thermal mass and gains to loss ratio, but is more explicitly modelled in dynamic simulation through interactions between solar radiation, physical properties of constructions, system and control responses.

The performance of the systems that supply the heating, hot water, ventilation and lighting, and the renewable generation systems, need to be represented. The overall performance is to be expressed in financial, energy and carbon terms.

The first column of table 3.1 summarises the properties to be addressed by the method in the context of the EPBD.

The second column groups and relates these properties to higher level performance determinant parameters e.g. surface, point and linear heat losses are all related to the ‘insulation’ determinant parameter level, infiltration and ventilation are related to the ‘air-change’ determinant parameter etc.

To allow the determinant parameters to be organised logically (for ease of discussion and also ease of selection) they are grouped into four categories labelled: Fabric, Geometry, Systems and Context (column 3).

- The Fabric category includes the parameters that describe the thermal performance of the building fabric and construction such as insulation, infiltration and thermal mass.
- The Geometry parameters describe the building physical shape and size.
- The Systems parameters describe the systems and controls performance.
- The Context parameters describe the climate, and behavioural parameters such as occupancy and appliance, heating system and hot water use.

There are some areas where more than one category of determinant is required to set a property value e.g. total air change depends on infiltration (Fabric), ventilation system performance (Systems) and occupant window opening behaviour (Context).

Table 3.1 properties, determinant parameters and categories

| Properties to be addressed by the method (EPBD) | Determinant Parameter(s) | Determinant Parameter Category |
|---|---|---|
| Surface heat loss | Insulation | Fabric |
| Junction heat loss | Insulation | Fabric |
| Point heat loss | Insulation | Fabric |
| Surface area | Geometry | Geometry |
| Junction length | Geometry | Geometry |
| Infiltration air change | Air change | Fabric |
| Ventilation air change | Air change | Fabric, Systems |
| Total air change | Air change | Fabric, Systems, Behaviour |
| Climate | Climate | Context |
| Volume | Geometry | Geometry |
| Consequential internal gains | Behaviour, Systems | Context, System |
| Solar internal gains | Geometry, Climate, Glazing, Shading, Behaviour | Geometry, Fabric, Context |
| Gain utilisation | Thermal mass, Gain to loss ratio, Systems (response), Behaviour. | Fabric, System, Context |
| Appliance and equipment use | Behaviour | Context |
| Heating set-points and schedules | Behaviour, Thermal mass | Context, Fabric |
| Heating system performance | Systems, Controls | Systems |
| Hot water use | Behaviour, Systems | Context, Systems |
| Hot water system performance | Systems, Controls | Systems |
| Control system performance | Systems, Controls | Systems |
| Ventilation system performance | Systems, Fabric | Systems |
| Lighting system performance | Systems, Behaviour | Systems |
| Renewable generation system performance | Systems | Systems |
| Carbon and financial performance | Carbon factors, costs | Context |

Decisions had to be made on how determinant factors were to be represented in dynamic simulation i.e. either as a model array determinant, fixed in the models, or as a post simulation scaling factor. Each of the parameters to be considered was reviewed and decisions made based on an assessment of parameter impact and data availability (data to inform the method; or data available to users to inform their inputs).

Available data sources to inform the development of the method for the pilot application to the Scottish housing stock include house condition surveys (Scottish Homes 2002), historical building regulations, and other Government and agency publications (BRE 2012, Utley and Shorrock 2008, Shorrock et al 2005, Scottish Building Standards 2007, 2010, EST 2012). In addition to these macro surveys, local authority and social landlords' databases, constructed for stock maintenance and legislative compliance, were also considered.

The data sources considered to be available to users ranged from inputs likely to be reliably gathered from homeowners or landlords through a simple questionnaire (similar to a tax return), to those available through the local authority or social landlord databases. The simple questionnaire was proposed by the user group as a means of addressing gaps in available data particularly in the private sector which has historically been less well documented. The questionnaire method of data gathering is discussed more later (chapter 4).

### 3.5.2 Fabric determinant parameters.

From initial scoping (table 3.1) the fabric determinant parameters were identified as Insulation, Air Change, Solar Gains, and Gains Utilisation (Thermal Mass).
The Passive House standard was selected as the highest probable future building fabric performance level (labelled as 'super' performance level as the Passive House is not the only standard which specifies these performance levels).

As stated earlier the initial treatments of determinant parameters for this pilot implementation should be viewed as placeholders. Decisions taken for the pilot are reviewed later in the evaluation and critical review section.

#### 3.5.2.1 Insulation

It was proposed that the as-built insulation could be readily categorised into 5 levels (labelled: poor, standard, medium, good, super) based on major breakpoints in the building regulations plus a look ahead to Passive House standards, with associated U-values as specified in table 3.2. Corresponding values for thermal bridging could be applied based on those set as defaults in UK regulatory calculations except for the ‘super’ case where ‘thermal bridge free’ junctions were assumed consistent with the Passive House standard. This approach meant that the building age would be an input which could be used to infer the as-built insulation levels. The build date was an available parameter in social landlord databases and deemed to be available to private owners (or accessible through local authority records).

In the dynamic models constructions were then adjusted by varying insulation thicknesses appropriately (the dynamic models are described in detail later – see section 3.5.4 and figure 3.9). Insulation parameter levels were set to the following levels with associated descriptions:

| | |
|---|---|
| ▪ poor (pre-83) | Insulation levels representing a typical Scottish dwelling built prior to the 1981 Scottish building regulations. |
| ▪ standard (83-02) | Insulation levels applied representing building standards defined by the 1981 Scottish building regulations. |
| ▪ medium (03-07) | Insulation levels applied representing building standards defined by the 2002 Scottish building regulations. |
| ▪ good (post07) | Insulation levels applied representing building standards defined by the 2007 Scottish building regulations. |

| | | |
|---|---|---|
| ▪ | super (PH) | Insulation levels applied representing building standards defined by the ‘Passivhaus’ guidelines. |

**Table 3.2 Insulation determinant parameter values**

| **U-values ($W/m^2.K$)** | poor (pre-83) | standard (83-02) | medium (03-07) | good (post07) | super (PH) |
|---|---|---|---|---|---|
| **Glazing** | **5** | **5** | **2** | **1.8** | **0.8** |
| **Roof** | **0.96** | **0.45** | **0.16** | **0.13** | **0.13** |
| **Walls** | **1.7** | **0.6** | **0.3** | **0.22** | **0.13** |
| **Floor** | **0.7** | **0.7** | **0.35** | **0.25** | **0.13** |

Following Clarke et al. the insulation levels for the dynamic models were initially set in ‘packages’ aligned with the regulations breakpoints (but extended to include the more advanced standards). This approach however restricts the possible analysis to consideration only of upgrades from one discrete ‘package’ to another. While at a high level these 5 levels of insulation may provide useful information (e.g. impact of upgrading an unimproved 1960s dwelling to post 2002 or to PH standards could be assessed), the impact of some pre-existing or applied singular or combinations of upgrades such as glazing or loft insulation, or cavity wall insulation plus glazing could not be assessed.

To address this issue two possible approaches were considered: either create more determinants and a more detailed dynamic performance map (i.e. separate determinants for each performance level for each individual building element) or use interpolation to scale between the existing points in the DSM performance map. The creation of more performance determinants to represent each of the building elements while improving resolution would still leave the issue of discretisation. In this pilot application interpolation was selected in order to explore the use of this technique. The potential use of interpolation compared to the alternative strategy of increased detail in the dynamic performance map is discussed in the later critical review section (chapter 5).

Interpolation for insulation elements was based on the available elemental heat losses (available for each simulation model) and allows any value for wall, floor, roof or glazing U-value (within the range of the performance map) to be input. The interpolation logic is configured to select the two best candidates within the map and a factor calculated based on the elemental heat losses applied to give the required result. This method allows existing or proposed future upgrade options to be input explicitly irrespective of pre-defined levels in the simulation model set. The inclusion of interpolation here allowed any combination of insulation parameter values to be represented.

To set insulation performance then requires the ‘as-built’ insulation level in combination with the performance level associated with any subsequent improvement measure(s). Data to set the performance level of subsequent improvements could potentially be determined from social landlord databases or inferred from the date of installation (e.g. double glazing) or insulation thickness applied (e.g. loft insulation).

While this method could deal with the application of any thermal upgrade some additional information on the applicable types and associated financial costs of upgrade required to be captured to allow differentiation e.g. between cavity wall insulation and non-cavity wall insulation and between suspended floor and solid floor insulation etc. This is covered later in the non dynamic calculations section (3.5.5).

#### 3.5.2.2 Air change

The air change rate, which can be expressed either as a volume rate of air change or relative to building volume, is a function of both infiltration and ventilation and determines the heating energy demand due to air movement from the outside.

The air-tightness of construction has been covered directly in building regulations through the input of blower door test results into calculations only since 2005; prior to

2005 the construction air-tightness calculations were based on construction type, number of storeys, percentage of windows and doors that were draught stripped, and the amount of sheltering from surrounding buildings. Systems factors that influence infiltration rate are the numbers of open chimneys, open flues, trickle vents, fans and other service openings.

The ventilation rate in dwellings without mechanical ventilation systems represents the use of windows and doors by occupants; it is presumed the motivation is to achieve desired internal conditions (air quality, moisture etc). Where there is mechanical ventilation then it may also be controlled to provide these desired conditions.

Three levels of air change rate were set to represent the range of infiltration and ventilation seen in buildings where ventilation control is by window opening behaviour. The ‘poor’ level was set at 1.5ac/h consistent with Clarke et al (2004). This level is consistent with Government regulatory calculations for un-improved buildings with masonry construction, suspended timber floors, single glazing, no draught lobby and several service openings (i.e. chimneys, flues) open to outside air (SAP, BRE 2012); it is also consistent with the standard heat loss calculations used for designing heating systems for old unimproved dwellings (TEHVA 2006). The ‘standard’ level was set to represent a dwelling with draught proofed windows and doors and fewer service openings to outside air. This level was associated with 2002 building regulations where double glazing of a good standard was specified. The ‘tight’ level was set to represent a building with construction air-tightness of $10m^3/m^2/h$ at 50Pa (relative to $m^2$ external envelope area), and only intermittent kitchen and bathroom fan service openings and window trickle vents to outside air, giving an infiltration rate of 0.5ac/h. The 0.6 ac/h air change value set for the ‘tight’ level represents occupant use of trickle vents to augment infiltration and achieve this overall air change rate, 0.1 ac/h higher than through infiltration alone, consistent with the behaviour assumed in UK 2007 building regulation calculations.

Air-change determinant levels were set to three levels with descriptions:

| | |
|---|---|
| poor | This represents the value of air-changes that would be expected in a property with single glazing without draught proofing and where no other draught sealing measures have been carried out. If ‘poor’ selected then an average air change rate of 1.5ac/h is used. |
| standard | This represents the value of air-changes that would be expected in a property with good double or draught proofed single glazing and doors. If ‘standard’ then 0.84ac/h is used. |
| tight | This represents the value of air-changes that would be expected in a property built to 2007 details or where extensive draught proofing has been carried out (glazing, doors, loft, floor, service openings etc). If ‘tight’ then 0.6ac/h is used. |

These three levels (unimproved pre 2002; post 2002 or double glazed / draught proofed windows and doors; post 2007 or comprehensive draught proofing of all elements) were chosen to cover the range in the stock and be easy to set based on existing databases or simple questions on building age and glazing type.

Similar to the insulation case, interpolation between these levels was also established based on responses to explicit questions on each of the contributory elements to overall air change rate (i.e. draught proofing applied to each of: glazing, doors, loft, floor, service openings). This allowed appropriate credit to be given for individual improvement measures rather than just the combined ‘packages’ represented by the three simulation model determinant levels.

The Passive House standard references CEN standard 13779 on indoor air quality and is based on construction blower door air-tightness of < 0.6 ac/h at 50Pa (approximately 0.04 ac/h at average conditions) and a mechanical ventilation rate of 0.3 ac/h (PHI 2012) giving an overall air change rate (without window and door opening behaviour) of 0.34 ac/h. Given that the Passive House standard specifies mechanical ventilation with heat recovery (MVHR) of greater than 75% efficiencies the ‘energetic effective’ air change rate for a Passive House with MVHR is < 0.115 ac/h. The impact of mechanical ventilation systems is accounted for by both the fan power used by the ventilation system, and the ‘energetic effective’ air change rate adjusted by post simulation scaling based on the system type selected. This is covered in the later section on systems (3.5.5).

#### 3.5.2.3 Thermal mass

The thermal mass determinant of Clarke et al. had nine possible combinations of thermal mass capacity level and capacity position based on the building construction type. The EPBD CEN 13790 requirements are that the thermal mass available to interact with the indoor air (i.e. on the inside of the insulation layer) should be taken into account by simple methods. The Passive House PHPP and the UK SAP had until more recently (2007 for PHPP, 2009 for SAP) not required thermal mass to be included in the heating demand calculation for new dwellings; the latest versions of PHPP and SAP for new dwellings do include an assessment of the available thermal mass for each construction element. The difference in heating demand between the most lightweight and the highest exposed thermal mass standard construction for a Passive House modelled in PHPP is of the order of 0.5kWh/m$^2$.a (5%) in favour of the higher thermal mass (i.e. lower heating demand for higher thermal mass). The UK regulatory simplified method for rating existing dwellings uses a fixed medium level for the thermal mass parameter.

Thermal mass can have competing effects on building performance: higher thermal mass and more stable temperatures allow increased capture of solar gains before occupants feel uncomfortable and compensate by releasing energy through increased ventilation; higher thermal mass decreases the responsiveness of the building to changes in demand temperatures potentially leading to longer periods at higher temperatures with associated higher heat loss. A simulation study was carried out to investigate the impact of thermal mass in combination with variations in UK local climates, patterns of use and ventilation rates on summer and winter performance (Tuohy et al. 2005). This study indicated that for two extremes of construction the differences in heating demand for insulation levels better than 2002

UK regulations ('medium') were less than 2 kWh/m$^2$.a in favour of high mass, but in less well insulated dwellings could be 5 kWh/m$^2$ worse for high mass (10%). Overall, thermal mass was found to have lower impact than insulation level or local climate (figure 3.3).

Two construction options were established for the dynamic simulation model set for the pilot, with either high or low thermal mass elements (figure 3.4). As thermal mass parameters were not readily available in the pre-existing databases and deemed to be difficult to accurately obtain through the simple questionnaire it was decided that for this pilot application, unimproved dwellings prior to 1983 would be represented by the higher thermal mass wall constructions with lightweight floor and roof while dwellings after 1983 would be represented by lower thermal mass wall constructions.

***Figure 3.3 Heating demand: Impact of insulation level (standard, medium, super) and local climate (N = North UK (cold), S = South UK (warm)), darker bars (dark blue and orange) represent higher thermal mass for each case.***

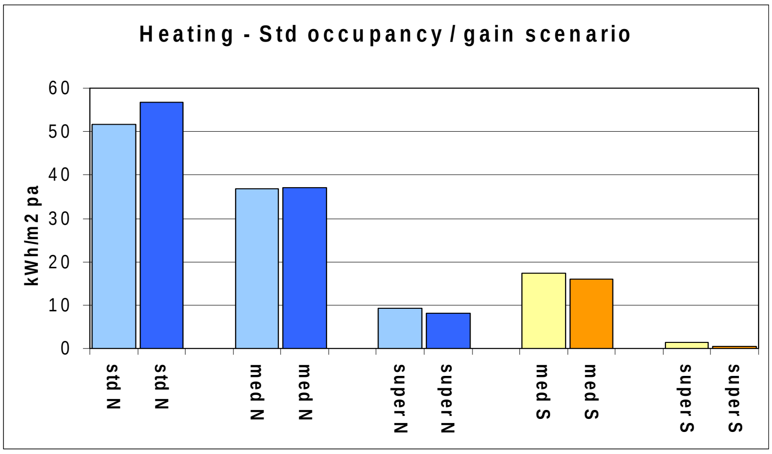
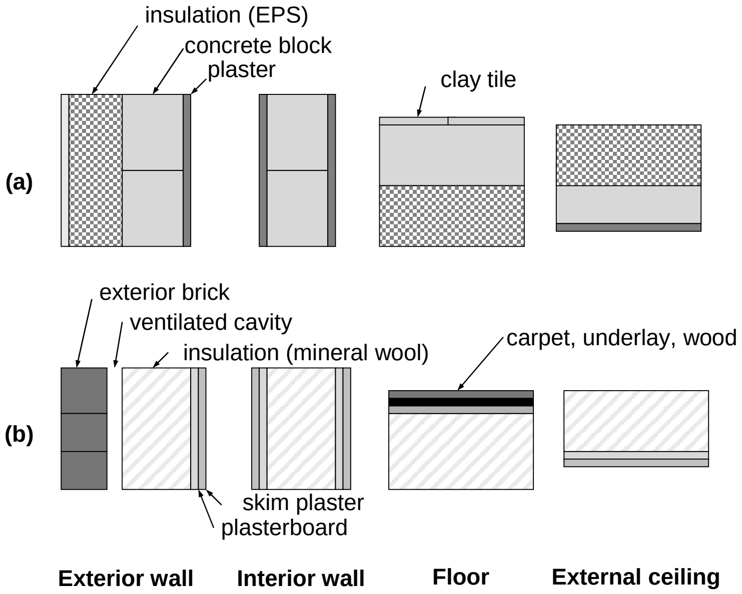


*Figure 3.4 Construction, (a) high thermal mass, (b) low thermal mass.*



### 3.5.3 Geometry determinant parameters

The approach of Clarke et al. (2004) was to describe the thermal performance for space heating of the entire stock through a range of thermo-physical performance determinant parameters applied to a single seed model with fixed geometry, with surface areas modified by the window area determinant only. The method returned a normalised heating energy demand and scaled this by the actual floor area to get the absolute heating demand for the dwelling in question. While this approach was deemed sufficient in their study, the single seed geometry approach has significant limitations when reviewed against the requirements of the EPBD where many geometry dependent factors are required to be comprehended.

To illustrate the principles involved figure 3.5 shows 9 possible configurations ((i) to (ix)) for an 100m$^2$ internal floor area dwelling. All have a single storey except (ii) and (iv) which are 2 storey. The layouts are detached except (iii), (iv) and (vi) which are in a mid-terrace situation with party walls to neighbouring properties on each side (party walls indicated by dotted lines).

A simple geometrical analysis is given in tables 3.3 and 3.4. It is immediately apparent that these geometrical factors have a large influence on the relative heat loss areas and junction lengths. Some observations:

Comparing single storey (i) against 2 storey (ii):

- The 2 storey has 20% less heat loss surface per $m^2$ of internal floor area.
- The area of the roof or ground floor is 1.25 larger than the external wall surface area for the single storey but 2.5x smaller than the external wall surface area for the 2 storey.

Comparing detached (i),(ii), against mid-terrace (iii),(iv):

- The mid terrace has 17% (1 storey) and 30% (2 storey) less heat loss surface.
- The mid-terrace ratio of roof or ground floor area relative to the external wall area is much larger than for the detached.

Table 3.4 investigates the impact of other geometric parameters: ceiling height, floor plan (square, rectangular or irregular), and size. It can be observed that:

- Increasing the ceiling height from 2.5 to 3.5m increases the heat loss surface by 13% and the volume by 40% (very significant where ventilation rates are applied through specifying air-changes relative to volume).
- The change from a square floor plan (i) to a slightly rectangular floor plan (ix) has only a small effect but changing to a narrow rectangular floor plan (v) and (vi) changes the overall heat loss surface by the order of 10%.
- The change from a square floor plan (i) to an irregular or very irregular floor plan (vii), (viii), can increase the heat loss surface by 10% or 20% respectively, and greatly increase the heat loss junction lengths.
- Reducing the floor area from $100m^2$ (i) to $64m^2$ and then $49m^2$ shows a 10% and 15% increase respectively in heat loss area to floor area ratio.

*Figure 3.5 Geometrical variations for a 100m$^2$ floor area dwelling*

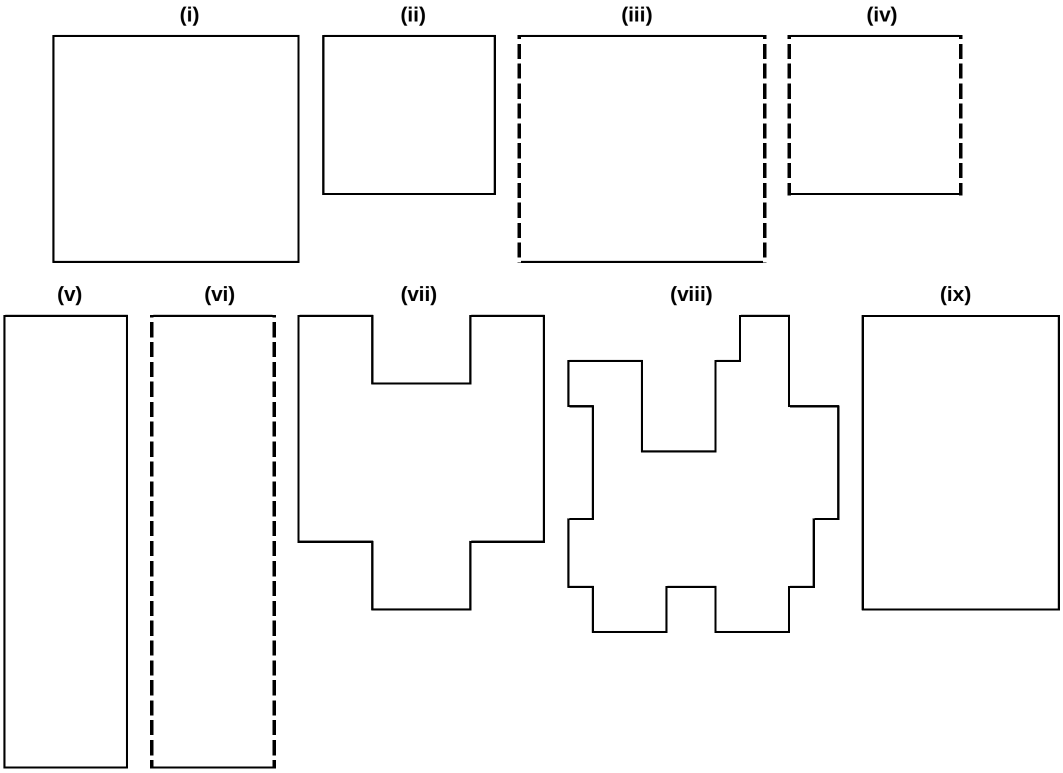


**Table 3.3 Geometrical analysis for variations of a 100m$^2$ floor area dwelling**

| scenario:<br>internal dimensions (m, m$^2$, m$^3$) | (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) |
|---|---|---|---|---|---|---|---|---|---|
| internal floor area | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| storeys | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 |
| mid terrace? (default is detached) | no | no | yes | yes | no | yes | no | no | no |
| internal length | 10 | 7 | 10 | 7 | 20 | 20 | na | na | 13 |
| internal width | 10 | 7 | 10 | 7 | 5 | 5 | na | na | 8 |
| ceiling height | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| internal volume | 250 | 252 | 250 | 252 | 250 | 250 | 300 | 300 | 250 |
| external floor or roof area | 100 | 50 | 100 | 50 | 100 | 100 | 100 | 100 | 100 |
| ext perimeter length | 40 | 28 | 20 | 14 | 50 | 10 | 52 | 64 | 41 |
| gross ext wall area | 100 | 142 | 50 | 71 | 125 | 25 | 130 | 160 | 103 |
| net ext wall area (excl windows) | 80 | 122 | 30 | 51 | 105 | 5 | 110 | 140 | 83 |
| vertical junctions | 4 | 4 | 4 | 4 | 4 | 4 | 12 | 26 | 4 |
| junction length | 90 | 77 | 50 | 48 | 110 | 30 | 134 | 193 | 92 |
| total heat loss surface (excl windows) | 280 | 223 | 230 | 152 | 305 | 205 | 310 | 340 | 283 |
| total heat loss surface | 300 | 243 | 250 | 172 | 325 | 225 | 330 | 360 | 303 |
| opaque heat loss area compared to (i) | 1.0 | 0.8 | 0.8 | 0.5 | 1.1 | 0.7 | 1.1 | 1.2 | 1.0 |
| roof to heat loss walls (excl windows) area ratio | 1.25 | 0.4 | 3.3 | 1.0 | 1.0 | 20.0 | 0.9 | 0.7 | 1.2 |
| ext heat loss surface to floor area ratio | 3.0 | 2.4 | 2.5 | 1.7 | 3.3 | 2.3 | 3.3 | 3.6 | 3.0 |

### Table 3.4 Geometrical variations from a 100m$^2$ floor area dwelling (2)

| scenario:<br>internal dimensions (m, m$^2$, m$^3$) | (i) | (i) hi ceiling | (i) larger | (i) small | (i) smaller | (i) smallest |
|---|---|---|---|---|---|---|
| internal floor area | 100 | 100 | 144 | 64 | 49 | 36 |
| storeys | 1 | 1 | 1 | 1 | 1 | 1 |
| mid terrace? (default is detached) | no | no | no | no | no | no |
| internal length | 10 | 10 | 12 | 8 | 7 | 6 |
| internal width | 10 | 10 | 12 | 8 | 7 | 6 |
| ceiling height | 2.5 | 3.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| internal volume | 250 | 350 | 360 | 160 | 122.5 | 90 |
| external floor or roof area | 100 | 100 | 144 | 64 | 49 | 36 |
| ext perimeter length | 40 | 40 | 48 | 32 | 28 | 24 |
| gross ext wall area | 100 | 140 | 120 | 80 | 70 | 60 |
| net ext wall area (excl windows) | 80 | 120 | 91.2 | 67.2 | 60.2 | 52.8 |
| vertical junctions | 4 | 4 | 4 | 4 | 4 | 4 |
| junction length | 90 | 94 | 106 | 74 | 66 | 58 |
| total heat loss surface (excl windows) | 280 | 320 | 379 | 195 | 158 | 125 |
| total heat loss surface | 300 | 340 | 408 | 208 | 168 | 132 |
| opaque heat loss area compared to (i) | 1.0 | 1.1 | 1.4 | 0.7 | 0.6 | 0.4 |
| roof to heat loss walls (excl windows) area ratio | 1.25 | 0.8 | 1.6 | 1.0 | 0.8 | 0.7 |
| ext heat loss surface to floor area ratio | 3.0 | 3.4 | 2.8 | 3.3 | 3.4 | 3.7 |

This simple analysis highlights the influence of geometrical factors: exposure (level of attachment), storeys, ceiling height, floor plan and floor area all have significant impact on the heat loss surface to floor area ratio.

There are other geometry factors with an impact on solar gains such as window sizes, window placement and orientation, window frame factors, shading from overhangs, reveals, and external objects.

Further geometrical factors could also be considered such as the presence of conservatories, extensions, attic rooms, basements etc.

The approach taken for this pilot was to focus on geometry factors required for correct identification of appropriate upgrades to modifiable building elements (mainly insulation and air change). Less emphasis was placed on parameters which could not be modified as part of an upgrade e.g. floor area, window placement, and over-shading. The approach taken and alternatives is discussed in the following sections and discussed further in the review section (chapter 5).

### 3.5.3.1 Exposure / level of attachment

From geometric analysis the basic level of exposure / attachment of walls floors and roofs was determined to be a significant factor. It was also determined to be easy to ascertain from databases and questionnaire. Levels set for this parameter for the simulation models were:

| | |
|---|---|
| detached | Represents a detached dwelling where all 4 sides plus roof and floor are exposed to the external environment. |
| semi-det | Represents a semi-detached or end terrace dwelling where 3 sides plus roof and floor are exposed to the external environment. |
| mid-terr | Represents a mid terrace dwelling where 2 sides plus roof and floor are exposed to the external environment. |
| flat(g) | Represents a ground floor flat where 3 sides plus floor are exposed to the external environment but the roof is not exposed. |
| flat(t) | Represents top floor flat where 3 sides plus roof are exposed to the external environment but the floor is not exposed. |
| flat(m) | Represents a mid floor flat where 3 sides are exposed to the external environment but the roof and floor are not exposed. |

These levels are easily implemented in the simulation model array by setting the non-exposed surfaces to be adjacent to similar internal spaces as appropriate.

The wall exposure parameter was considered as a candidate for additional parameter levels (e.g. ‘mid terrace flat’ or ‘end of block flat’ etc) and possible use of interpolation to allow absolute data entry (i.e. further differentiation in terms of numbers of exposed sides or the actual length of exposed wall). However after some exploration of the availability and ease of collection of data it was decided not to pursue this for the pilot.

### 3.5.3.2 Shape / Number of storeys

It was clear from the analysis that the number of storeys was a significant determinant and easy to obtain from database or simple questionnaire. Two levels were set for the shape parameter for the pilot application (easily extended to 3 or more in future but 2 storeys was deemed sufficient to cover the majority of the stock and for this pilot):

- 1-storey Represents a single storey dwelling
- 2-storey Represents a two storey dwelling.

To implement the shape determinant in the simulation array requires the creation of a duplicate set of models within the array (1 and 2 storey shapes in this case).

### 3.5.3.3 Ceiling height

Ceiling height data was shown to be an important parameter. It was however not consistently available in landlord databases and considered to be difficult to ascertain accurately through questionnaire (without perceived risk to individuals). For the pilot implementation this variable was treated as a 2 level post simulation scaling parameter (‘standard’ (2.4m) and ‘high’ ceilings (3.5m)) with ventilation and wall heat losses scaled appropriately based on geometric factors and selected insulation and air change determinant parameter levels. The possibility of including ceiling height as a simulation model determinant parameter and applying interpolation within the array was also considered and will be discussed in the review (chapter 5).

### 3.5.3.4 Floor plan

The shape of the floor plan can have a significant effect on performance but it was deemed to be too difficult to obtain reliable data (some attempts at formulating questionnaire questions on floorplan are covered in chapter 4). If the length of the exposed wall (discussed in 3.5.3.1) was to become available then this could be used as a proxy. Floor plans of a slightly rectangular dwelling (e.g. 12.5 by 8 as in (ix) of table 3.3) gave similar results to the square dwelling. For the pilot the floor plan used in the model array was fixed as a square to represent something close to an 'average' although no data was available that characterised the actual distribution of property floor plans.

#### 3.5.3.5 Floor area

Smaller dwellings have higher external heat loss surface ratio to floor area than larger dwellings and, based on this factor alone, would be expected to have higher heating demand per unit floor area. Other factors however have effects based on floor area: occupant density tends to be higher in smaller dwellings with associated higher internal heat gains which may act to partly offset the increase in heat loss surface area; the fraction of the dwelling heated to comfortable living temperatures may tend to be higher in a smaller dwelling adding to the heating energy demands.

The current UK regulatory calculations for dwellings (SAP) tend to give poorer calculated thermal performance overall for smaller dwellings but then this poorer performance is offset through the use of a factor which renders the performance largely independent of floor area for the environmental (EI) and cost indicators (SAP) used in performance ratings. The stated aim of this UK regulatory approach is to avoid encouraging larger dwellings which use greater absolute energy.

Figure 3.6 illustrates the UK regulatory approach, showing three different SAP outputs for a range of dwellings with the same thermal properties (insulation levels, air-changes) and systems (heating, hot water, lights and ventilation) but where the floor area is scaled between 50 and 150m$^2$. As expected (overall larger volume to be heated in larger dwellings) increasing the dwelling floor area gives an increase in the overall energy use and calculated carbon footprint from around 4,500 kgCO$_2$ per annum to around 10,000 kgCO$_2$ per annum. Also as could be expected (from the reduced external heat loss surface relative to the floor area for larger dwellings) the heating energy intensity per unit floor area decreases with increasing floor area resulting in a lower Carbon Emissions Rating (CER) $kgCO_2/m^2$ (in this case from 75 $kgCO_2/m^2$ pa to 50 $kgCO_2/m^2$ pa). However the outputs which are used in SAP for ratings and compliance (SAP rating and Environmental Impact (EI) ratings) are adjusted to be largely independent of floor area, in this case the EI rating is constant at 50 $kgCO_2/m^2$* (* adjusted).

For the pilot the floor area was treated as a scalar to be applied post simulation to the simulated heating demand per unit floor area of the models. The floor area of the models was set to represent the UK average and then the scaling factor applied based on user inputs (default scaling factors were initially based on $91m^2$ for houses and 74 $m^2$ for flats, to represent UK average values (EHCS 2012). The potential inclusion of floor areas as a determinant of the simulation model array and the use of interpolation will be discussed later in the review (chapter 5).

It was initially suggested by the client/user group that in some cases the floor area may be beyond the capability of respondents to a questionnaire survey and that floor area may have to be inferred. An approach was developed using data to be obtained from questions asking for a count of the number of bed-spaces (i.e. 2 for a double bedroom and 1 for a single) and the general size of the rooms: ‘small’, ‘medium’ or ‘large’. Some curve fitting was done to available benchmark data to enable this functionality but as can be seen from figure 3.7 the reliability of this method was somewhat questionable. (The benchmark data was extracted from a range of public sources e.g. published plans for commercial housebuilders etc.)

***Figure 3.6 Effect of floor area in UK regulatory calculation method (SAP): (Carbon footprint, kgCO$_2$ p.a., carbon emissions rate (CER, kgCO$_2$/m$^2$ and environmental index (EI, kgCO$_2$/m$^2$* *adjusted).***

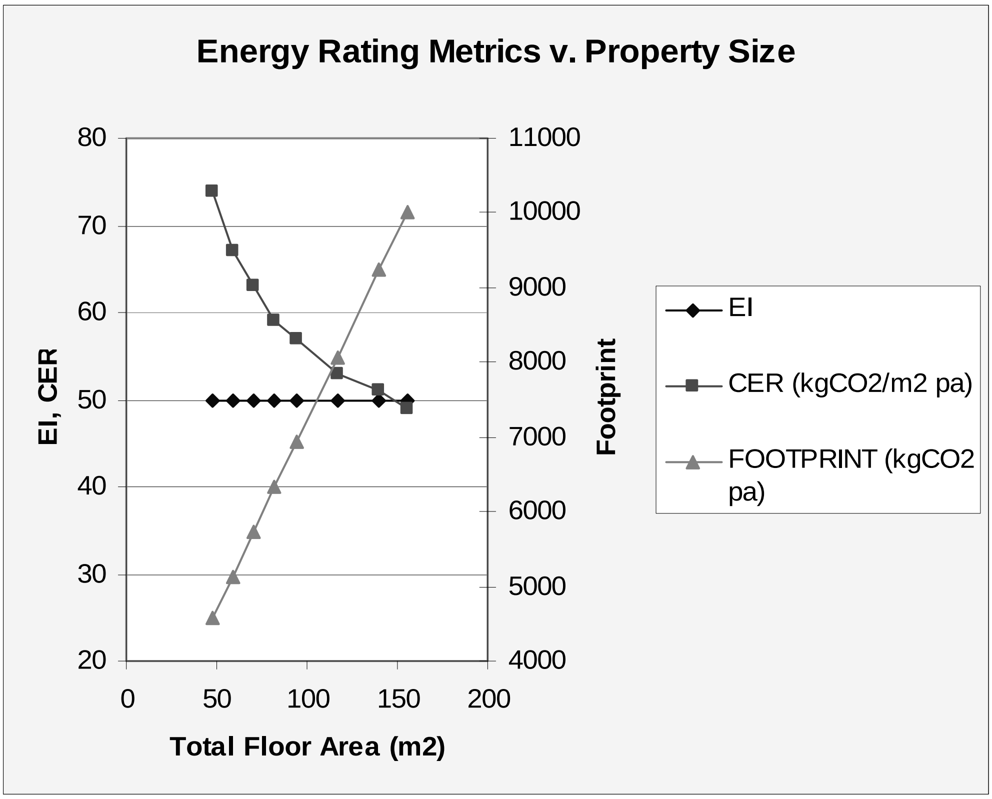
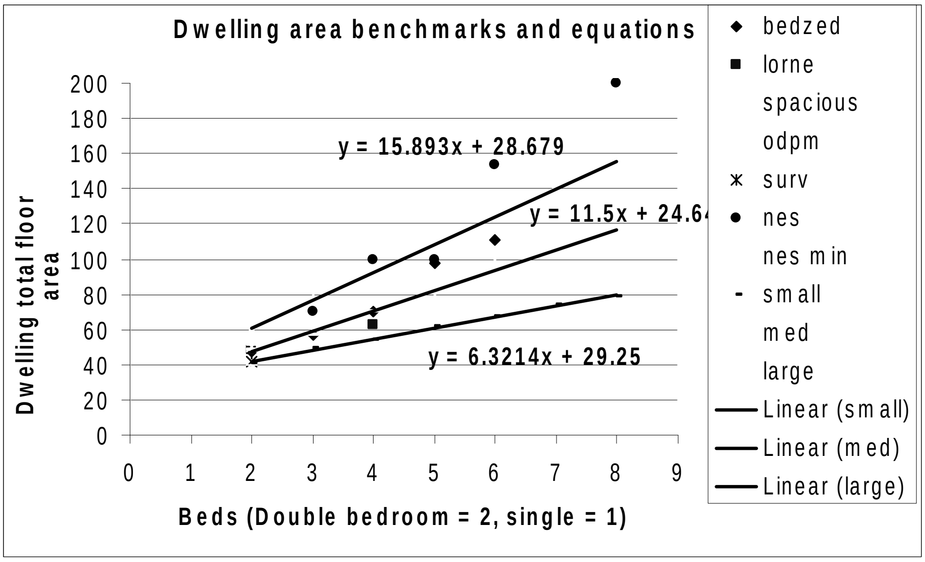


***Figure 3.7 Floor area estimated using number of bed-spaces and general dimensions of dwelling (small, medium or large).***



#### 3.5.3.6 Solar gains

The gathering of data on individual window sizes, orientations, frame fractions, overhangs/reveal depths, external shading etc was determined to be beyond the scope of available data or that which could be easily gathered from questionnaire from owners or landlords (some trials targeted the gathering of window areas, also a hypothesis that certain construction types and building age bands had larger or smaller windows did not stand up to investigation e.g. Victorian tenement flats although having individual windows that were large did not have a large overall window area w.r.t. floor area due to narrow floor plans and high levels of attachment). For the pilot application the window areas were set at the average values from historical surveys (BRE 2012) and windows were spread equally between north and south facing facades. The south façade was then shaded by an extended 3 storey building 15m to the south of the south façade. This represented a fixed worst case assumption where solar gains in the heating season were largely restricted to those from diffuse radiation only.

#### 3.5.3.7 Other geometry parameters

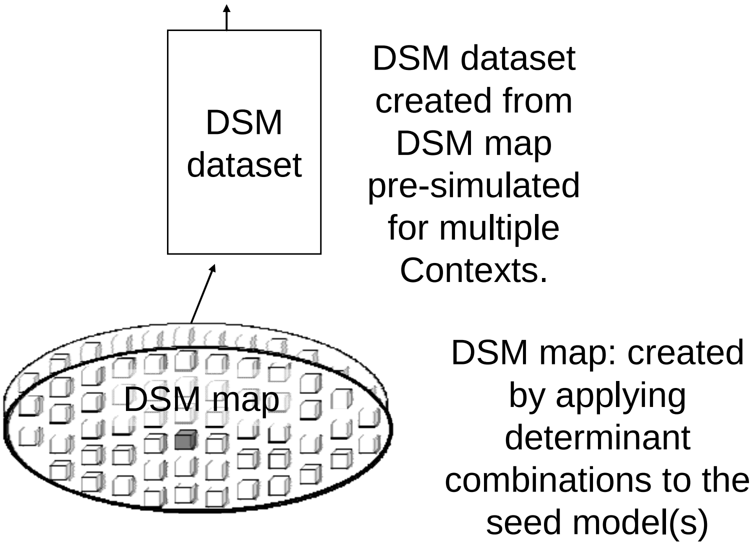
The impact of the selection made of the fabric geometry determinant parameters and the discrete levels that define the array of simulation models will be discussed further in the critical analysis (chapter 5).

### 3.5.4 Dynamic simulation models and contexts

Having defined the fabric and geometry determinant parameters and levels, the steps required to define the DSM dataset to be used in the method were: to define representative seed models; to create the DSM performance map by applying combinations of determinant parameter levels to the seed models to represent existing and possible future performance; to define the required contexts (i.e. weather conditions, patterns of use) to be applied; to simulate the DSM map for the required contexts; and to construct the dataset of results (figure 3.8).

Two important requirements were that the method must give realistic results and that the method must give similar results to the Government regulatory methods when the regulatory context (UK standard climate and occupancy assumptions) is selected.

***Figure 3.8 The DSM based elements of the method***



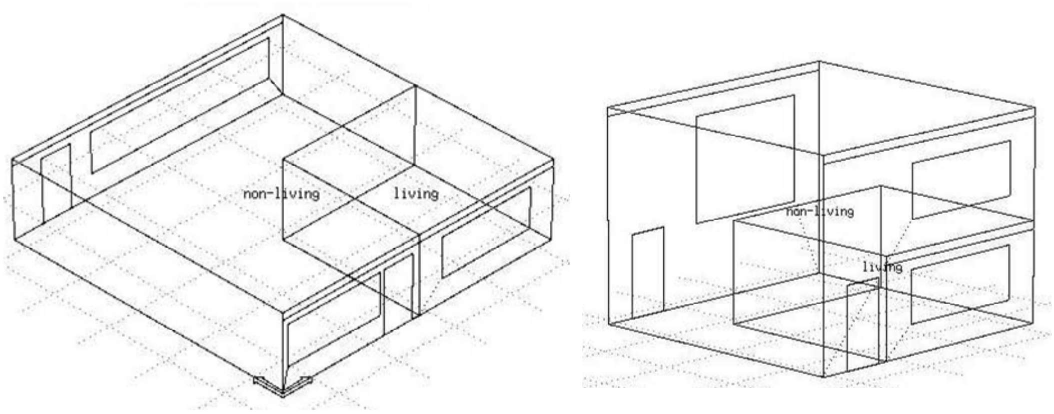
To give realistic results it was proposed that where possible the representative dynamic models should be aligned with monitored data. For the UK and EU domestic stock two significant sources of monitoring data exist that have been used to underpin the UK Governments SAP and the EU Passive House calculation method PHPP. These are the 1980s and 1990s UK studies that informed the UK BREDEM and SAP methods (Uglow 1982, Dickson et al. 1996, Henderson and Shorrock, 1986), and the 1998 to 2001 CEPHEUS studies which included ‘typical’, ‘low energy’ and ‘passive house’ dwellings and informed the PHPP method (CEPHEUS 2012). It was proposed then that for a UK regulatory context (i.e. UK average climate and behaviours) the results should be in alignment with these datasets and therefore in alignment with SAP and PHPP results for existing and advanced dwellings respectively. The approach taken was to establish the base set of models first in alignment with this UK regulatory context, and then simply by applying different dynamic simulation contexts (i.e. different climates or behaviour patterns) to the base set of models, generate results for these alternative context scenarios.

#### 3.5.4.1 The seed models - geometry

A set of seed models was developed with geometries selected to align with UK housing statistics e.g. the average UK dwelling internal floor area is 91m$^2$ (EHCS 2012) and the average UK dwelling ceiling height is 2.4m. The glazing and door areas were also set to represent the UK average (BRE 2012). The main orientation of the seed models was set as south facing and the glazing and door orientation set as being equally distributed between north and south facades. External shading was applied in the form of an extended obstruction to represent the effect of an extended multi storey building 15 metres from the south façade, significantly reducing winter solar gains (a worst case assumption). The exposure performance determinant parameter levels (level of attachment) could then be applied to the seed model by changing the properties of surfaces without affecting the geometry. The shape performance determinant parameter (number of storeys) required the creation of a separate seed model to capture the change in ratio of wall to floor/ceiling to allow more accurate assessment of the impact of individual upgrades. Extra surfaces were added to the walls to represent the thermal bridges; the areas of these bridges were adjusted as required.

The monitoring data behind SAP/BREDEM suggested that two distinct temperature zones ‘living’ and ‘non living’ were adequate to represent the indoor temperatures of buildings (Henderson and Shorrock 1986) but that where the overall heat losses are reduced, as would be the case in more advanced buildings with better insulation and infiltration/ventilation properties, that the difference in temperature between these two zones is greatly reduced. The PHPP based on the monitoring of highly insulated and airtight passive house dwellings with whole house mechanical ventilation systems assumes a constant temperature of 20$^{o}$C throughout. The approach taken here was to adopt a two zone thermal model in alignment with the SAP/BREDEM approach. The living zone percent of total floor area in SAP varies with the size of the dwelling, it was set to 25% of floor area in the seed models as this was the appropriate size in SAP for the seed model geometry. The geometry of the two seed models for single and two storey buildings is illustrated in the wire-frame diagrams of figure 3.9.

*Figure 3.9 Wire-frame representation of the 1 storey and 2 storey seed models*



### 3.5.4.2 The seed models and DSM map – alignment to regulatory contexts.

To establish simulation contexts that would give model alignment with UK regulatory methods required the setup of appropriate dynamic model inputs to represent: the standard UK regulatory climate (a representative dynamic climate file); UK average occupancy schedules including use of appliances and equipment (internal gains for the dynamic models); and UK average behaviour in the setting of heating set-points and schedules (control set-points for the dynamic thermal models).

The UK regulatory calculations have until 2009 used a standard annual climate based on the weather of the East Pennines region during the 1970s and 80s. From 2009 a new monthly climate has been introduced in the regulatory calculations reflecting a significantly milder UK climate based on more recent data (unfortunately this change occurred just before the exceptionally cold winters of 2010 and 2011, illustrating the unpredictability of weather). For this work available simulation climate databases were reviewed and a Representative Scottish Climate (RSC) selected (based on the available Dundee 1980 dynamic simulation file) to represent a worst case Scottish Climate (figure 3.10). This climate is compared using degree day to historical data for East Pennines and Scottish regions from the UK Government Carbon Trust database, now supplied through the ECI Oxford (ECI 2012).

The decision was made to use this available Scottish dynamic simulation weather file as the base for the pilot implementation. The subsequent release by CIBSE of a set of UK weather files for use in dynamic simulation for regulation compliance (CIBSE 2012) is a step forward and could be considered in future implementations of the method. The use of the colder Scottish dynamic climate file in this case was found to give good agreement in dynamic simulation with the regulatory simplified method (more details below). The inputs and calculation basis for the two methods are different and may be the source of this apparent anomaly. An investigation of this could be the subject of future work. An alternative narrative could be that this harsher climate but similar space heating demand reflects a more frugal lifestyle of Scottish occupants but there is no data presented here to justify this.

The internal gains and other building use factors such as hours of occupation and heating set-points were then established for the 'UK average' context. There is potential for large variation in heat gains due to: occupants themselves; their use of equipment and appliances; cooking; lighting; hot water use and systems associated with hot water production; and the systems (e.g. pumps) that support supply of space heating. Figure 3.11 gives a comparison between the assumptions of the Passive House PHPP, the assumptions for a typical dwelling modelled in SAP, and the range of assumptions used in previous work to represent a range in occupant behaviour from very low gains through to high gains scenarios (Tuohy 2005). It should be noted that the Passive House standard gains assumption does not include gains from hot water systems, assumes high efficiency appliances, and takes account of the evaporation of moisture from wet surfaces and towels etc as a reduction in the available internal gains.

Internal gains in SAP vary between 5 and 11 W/m$^2$ depending on the various factors described above. A graph of the internal gains against floor area and hot water system type is shown in fig 3.12.

For the regulatory context the gains in the DSM models were set at an average of 6.85 W/m$^2$ based on the 91m$^2$ of the simulation model and a modern water and space heating system, and distributed between living and non living zones as shown in table 3.5. The gains schedules can be changed as required to reflect other contexts.

***Figure 3.10 Comparison of Pennine and Scottish climates including a representative Scottish climate (RSC) selected for 'regulatory compliance' context for the pilot.***

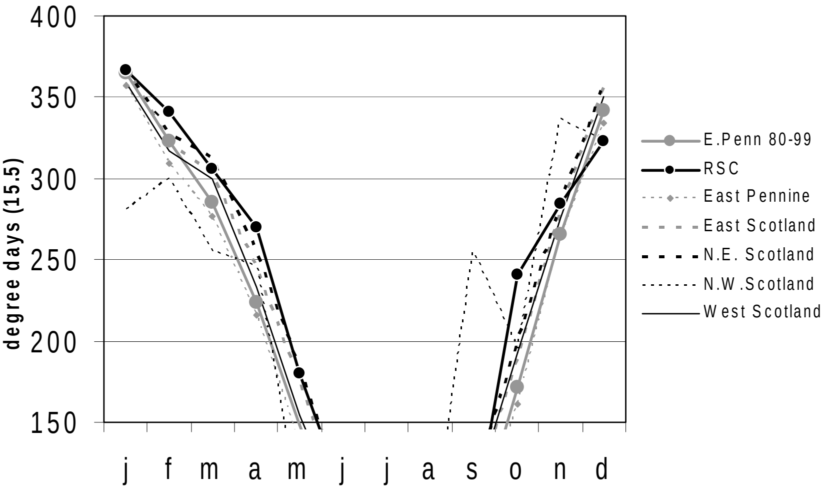


***Figure 3.11 Internal gains***

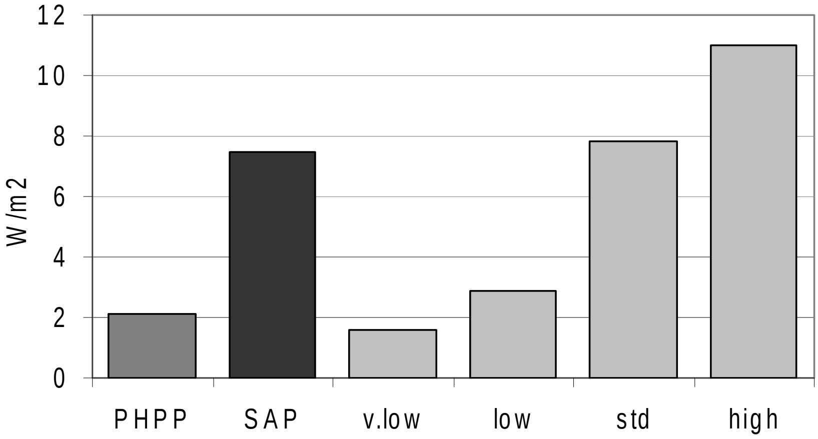


***Figure 3.12 Internal gains variation with floor area and system type in SAP***

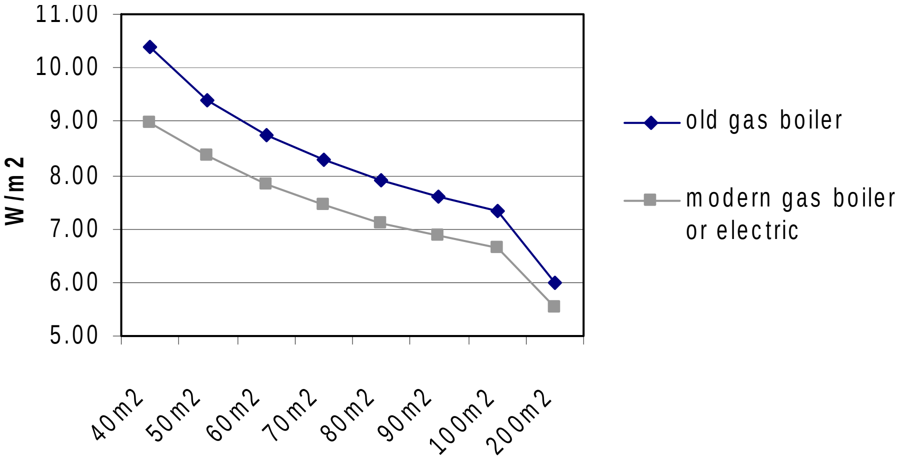


*__Table 3.5 Gains profile used for the UK regulatory context__*

| | period: | 23-7.30 | 7.30-9.30 | 9.30-18 | 18-23 |
|---|---|---|---|---|---|
| | hrs: | 8.5 | 2 | 8.5 | 5 |
| Living | occ: | 0 | 139 | 0 | 222 |
| | lights: | 0 | 99 | 0 | 99 |
| | app: | 74 | 260 | 74 | 319 |
| Non-living | occ: | 185 | 139 | 0 | 56 |
| | lights: | 0 | 99 | 0 | 99 |
| | app: | 148 | 499 | 148 | 599 |
| Total | | 407 | 1235 | 222 | 1394 |
| | | AVE | 616 | W | |
| | | AVE/m2 | 6.85 | W/m2 | |

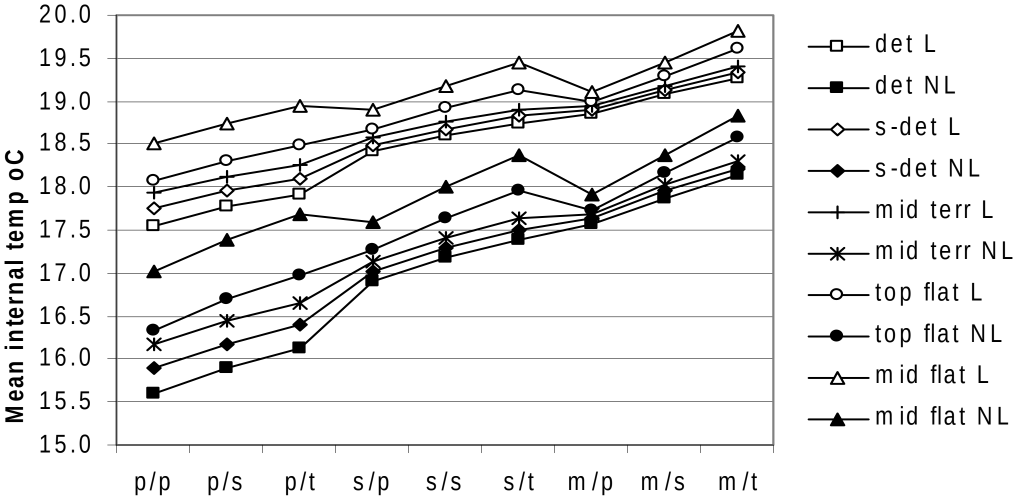
The seed models were then replicated with the determinant parameters applied giving 5 insulation x 3 air-changes x 2 mass x 6 exposures x 2 shapes = 360 replicates making up the DSM performance map.

The operating schedule for the heating system was then adjusted (by an iterative process) to give similar average temperatures for the living and non living zones as those predicted by SAP (figure 3.13). This was achieved by applying a 21 $^{o}$C resultant temperature set-point between 6am and 11am and 3pm till midnight each day of the week in the heating season with a set-back temperature of 15 degrees. The same heating set-point applied to each of the zones gave the best agreement with the average temperatures of SAP, the non-living zone average temperatures being lower than the living due to the higher heat loss areas and lower gains relative to respective floor areas. This applied schedule should be viewed as an averaging of a wide range of different heating patterns rather than representing a ‘typical’ heating pattern (e.g. an average of: single working person, elderly couple, young working family, young non working family etc). These different patterns can be modelled later as different context scenarios.

One critical point highlighted during this iterative process was the representation and scheduling of internal gains and heating system in the thermal dynamic model. The results were very sensitive to the advance of the heating relative to the onset of increased internal gains from occupant activity and setting of this parameter was key. This parameter setting could be viewed as representing occupant behaviour (i.e.

heating on in advance so that the building is warm on wake-up or arrival) and also physical processes not explicit in this thermal model i.e. the thermal response time (lag) of the heating system, the physical and temporal separation of the gains and the location that the heat is required by occupants, the thermal lag between gains generation and the associated energy input affecting the thermal environment of the occupant e.g. a kettle boiled or oven used in the kitchen may in reality take a significant time to affect the temperature in the living room etc.

***Figure 3.13 Living (L) and non-Living (NL) seasonal mean temp for a range of insulation and construction airtightness ('p/s' indicates 'poor' insulation in combination with 'standard' air-change etc. the range in insulation covered is poor, standard and medium, the range of air-changes is poor, standard and tight as described in earlier sections)***



Simulating the DSM map with these contexts gave good agreement in space heating energy demand with SAP calculations for similar geometry dwellings and construction elements. Figure 3.14, shows a comparison for dwellings with poor to medium levels of insulation and poor to tight air-changes (solid shapes represent SAP, open shapes the dynamic models). Figure 3.15 shows results for passive house construction (super insulation and tight air-changes), for a range of dwelling exposures, and a range of ventilation strategies including the incorporation of a passive house ventilation system ('MVHR super', open shapes). The passive house construction and ventilation system in combination meet the passive house criteria of < 15kWh/m$^2$ p.a. The Passive House results and the incorporation of mechanical ventilation are discussed again in the section on systems (3.5.5).

In this pilot application the effects of system responsiveness and controls were factored into system efficiencies rather than the average internal temperatures and internal gains as in SAP. It would be possible if desired in future applications to include the different systems and their impact on internal temperature profiles more explicitly through the use of plant and control dynamic modelling domains.

***Figure 3.14 Space heating demand comparison between DSM model array simulated with the UK regulatory context (climate, gains, heating set-points) and SAP calculations for similar geometries and a range of existing construction standards. (the x-axis indicates the insulation determinant parameter value and the attachment i.e. 'P flat(m)' indicates 'poor' insulation values for a mid floor flat etc. the key indicates the air-change value and whether the results are from the simulation models or the SAP calculations i.e. 'P sim' indicates 'poor' air-change and results of simulation etc.)***

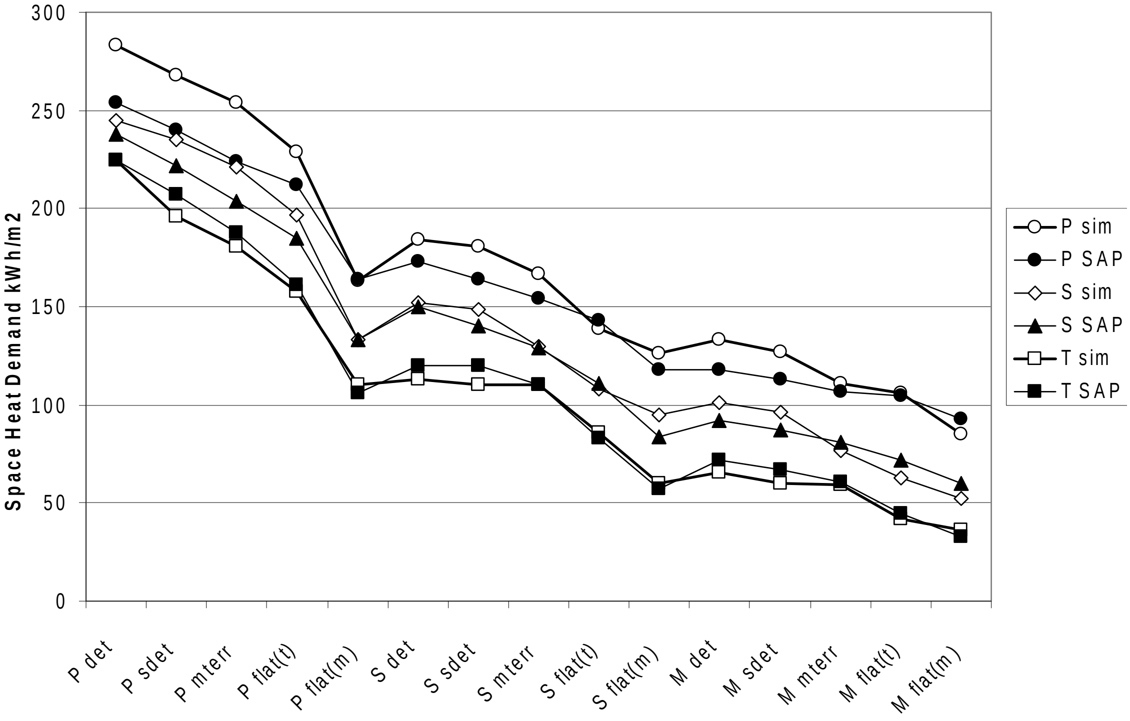
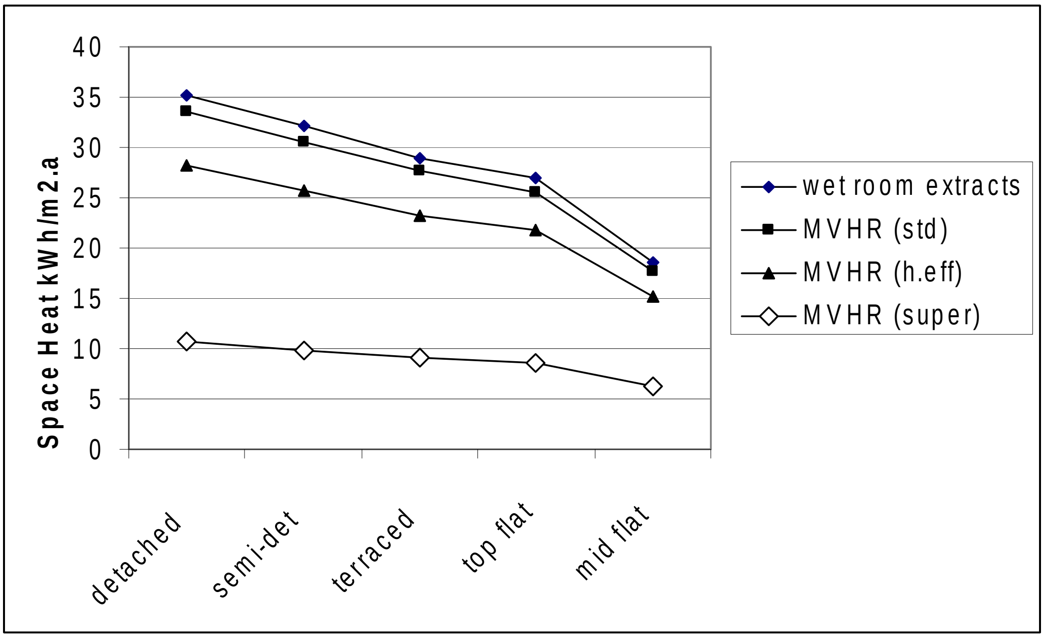


***Figure 3.15 Space heating demand for DSM model array simulated with the UK regulatory context (climate, gains, heating set-points) for a dwellings with Passive House construction and a range of ventilation systems. The 'MVHR super' represents Passive House air-tightness and MVHR specifications.***



Having established the DSM map and regulatory context (climate, pattern of use) to give results aligned with SAP for historical performance levels, and Passive House for dwellings likely to be built in future, it is a simple task to change the contexts and re-simulate to create results that allow these alternative contexts to be represented in the DSM dataset and selected as required (an example of this is described in a later section).

The preceding sections have described the formulation of the dynamic simulation modelling (DSM) component for deployment to the Scottish domestic building stock. The model array has been defined in alignment with the EPBD requirements, the range of performance in the existing and potential future stock, and the available data. The next step then is to formulate the non DSM components of the method for this deployment of the method.

### 3.5.5 Non dynamic simulation modelling (non-DSM) calculations

Figure 3.2 gave the high level architecture of the method and illustrates the relationship between components. The previous sections have described the formulation of the dynamic simulation modelling (DSM) component for the example application. In this section the complementary non-DSM components are briefly described.

The non-DSM calculations are given in detail in the technical manual (Appendix B). A summary to illustrate the approach is given here.

The calculations flow and relationship to the DSM performance map is illustrated by figure 3.2. A more detailed flow of the calculation process is given below (from the manual, Appendix B). Steps 3 to 11 are the required non dynamic calculations:

1. Establish Geometry (floor area, ceiling heights etc.)
2. Establish Heating Energy Demand (from DSM performance map plus geometry inputs).
3. Establish Heating Energy Use and Carbon Emissions.
4. Establish Lighting Energy Use and Carbon Emissions.
5. Establish Appliance Energy Use and Carbon Emissions.
6. Establish Ventilation and Cooling Energy Use and Carbon Emissions.
7. Establish Occupancy and Hot Water Demand.
8. Establish Energy from Solar Hot Water System.
9. Establish Hot Water Energy Use and Carbon Emissions.
10. Establish Energy and Carbon Emissions Impact from Local Generation.
11. Establish Totals, Costs, Carbon, Energy, Ratings.

The non dynamic calculations used are largely based on CEN 13790, UK regulatory calculations, and CIBSE guidance but default values have been set in alignment with monitored data where available e.g. DTI and EST Field Studies of Domestic Renewables.

The non DSM input data to the calculations depend on the values set for the non DSM determinant parameters based on user inputs. In the same way as for the geometry and fabric determinant parameters, the levels were set based on available information. Pre-defined parameter levels are stored in the non DSM dataset to be selected based on high level inputs, or levels are set by direct entry of parameter values where detailed information is available.

The non DSM dataset includes tables capturing systems, carbon emission factors, running costs and capital costs. The non-DSM dataset is pre-established but any of the default values can be made modifiable by the user to reflect user specific circumstances e.g. system efficiencies, upgrade costs, fuel costs or tariffs etc.

For example: Heating and hot water systems are selected by fuel type, system type and controls. These inputs are used to identify the appropriate system efficiencies, emission factors and fuel costs to be used in the calculations. Two approaches were followed for the setting of system efficiencies. Initially levels were set based on the system installation date e.g. for gas boilers 4 boiler types (non-condensing, non-condensing combi, condensing, condensing combi) each with three levels of efficiency associated with pre-1998 installations, 1998 – 2004 installations and post 2004 installations were set based on boiler data from the UK Government (table 3.6). Later, categorisation directly by boiler efficiency was implemented and direct entry of boiler efficiency data if known enabled. The appropriate emissions factors and cost factors are selected for use in calculations based on the system fuel type and context inputs (grid intensity, tariffs).

**Table 3.6 Example of a system look up table**

| performance determinants | | | outputs to calculations | | |
|---|---|---|---|---|---|
| fuel | Boiler type | age | eff% | $CO_2$fuel | £fuel |
| gas | Non condensing boiler | pre 98 | 65 | emm_g | rcost_g |
| | | 98-04 | 77 | | |
| | | post 04 | 85 | | |
| gas | Non condensing combi boiler | pre 98 | 65 | emm_g | rcost_g |
| | | 98-04 | 77 | | |
| | | post 04 | 85 | | |
| gas | Condensing boiler | pre 98 | 75 | emm_g | rcost_g |
| | | 98-04 | 85 | | |
| | | post 04 | 90 | | |
| gas | Condensing combi boiler | pre 98 | 75 | emm_g | rcost_g |
| | | 98-04 | 85 | | |
| | | post 04 | 90 | | |

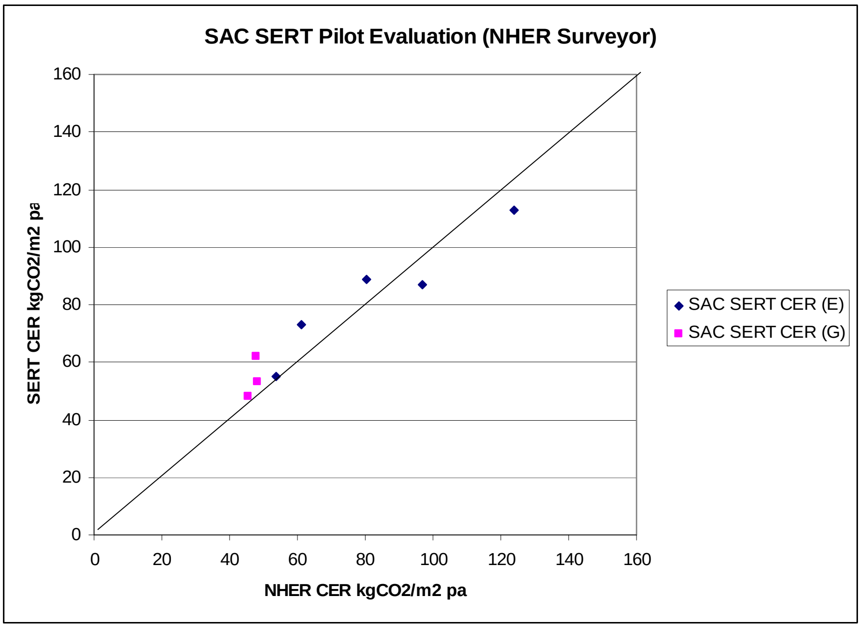
In some cases there are linkages between the systems determinants and the resulting final heating energy demand. One example is where there is mechanical ventilation with heat recovery, another is where lighting energy use is varied. The impact of mechanical ventilation on final space heating energy demand is illustrated in figure 3.15 for a range of dwellings all with ‘super’ insulation and ‘tight’ air-changes selected. The heat recovery impact on space heating demand is represented using a post simulation scaling factor formed using the ratio of the total heat losses with MVHR to the heat losses without MVHR. The fan energy use of the MVHR is captured in the electricity use. The heat recovery efficiencies and fan efficiencies are set to represent UK standard, UK best practice and Passive House with heat recovery efficiencies of 66%, 85% and 88%, and fan powers of 2, 1 and 0.5W/l/s respectively. The MVHR ‘super’ option is only to be selected where the dwelling achieves the Passive House air-tightness criterion of 0.6 air changes per hour at 50Pa and the ventilation unit achieves the specifications of the Passive House criteria (heat recovery %, fan power, noise levels). For the other MVHR options the ‘tight’ air-change rate corresponds with 2007 building regulations level of infiltration where accredited construction details have been used (i.e. an air permeability of 10 $m^3/m^2$ per hour at 50 Pa). In this method the electricity for intermittent extract fans is included (this electricity use is neglected in SAP). Scaling factors are applied for the impact on space heating energy demand of variation in lighting and appliance efficiencies. More details of the calculations are given in the technical manual (Appendix B). In future applications it would be an option to treat these factors explicitly in the model array as model determinants.

Tables within the non DSM dataset have been established with costs for upgrades, these costs have been based on available data from Local Authorities, the EST, and EAGA. The values are modifiable by the users. Values are set for upgrades of each building fabric element for the full range of possible upgrades (i.e. from each starting condition to each possible improved condition for each fabric element). The costs are differentiated by the construction type as for example cavity wall, suspended floor and loft insulation has a different cost to solid wall, solid floor and flat roof insulation. The fabric upgrade costs are represented as values per square metre and then total costs calculated based on the building geometry. System upgrade costs are also tabulated.

Much more detail is given on the basis for the non-DSM calculations in the user manual (Appendix B). The implementation of each of the non-DSM calculations was checked against the referenced data sources. The non-DSM calculations are combined with the DSM calculations and applied within appropriate software and user contexts in the following chapters (chapter 4 and chapter 5) then the hypothesis reviewed (chapter 5).

The method was deployed in a number of test applications. Given the number of inferred or default parameters used in the proposed method generally good agreement was found between the results from the proposed method and the Government approved software when deployed for a Scottish social housing stock (Figure 3.16). The details of these test deployments are given in the next chapters (chapter 4 and 5).

*Fig. 3.16 Carbon emissions rate (CER) comparison of the proposed low cost simulation based method (SERT) and UK Government legislative method (NHER surveyor) for both electric and gas fuelled dwellings in the South Ayrshire Council (SAC) stock (more details in the next chapter).*



## 3.6 Performance assessment and option appraisal method: Proposed method and underpinning calculations – Conclusions.

In this chapter the concept design for a method intended to test the hypothesis (i.e. that a low cost simulation based real time method can be developed to support decision making for a range of users in the contexts of the EPBD) has been proposed, and a set of underpinning technical calculations and logic developed.

The requirements used to shape the proposed method were defined based on: the technical specifications of the EPBD, and non-technical inputs from a client/user group in response to propositions from the author.

The formulation of technical calculations (DSM and non-DSM) and logic to underpin the method for example application to the Scottish housing stock was described in detail.

The user processes developed for a range of test applications of the method, and the performance of the method for these test applications, are described in the following chapters (4 and 5).

The choices of approach made in the formulation of the method for the example application to the Scottish stock were highlighted. Possible alternative approaches were also discussed and are reflected on again after the test applications (chapter 5).

The method and its performance in the test applications is reviewed against the original hypothesis and possible future work proposed in chapter 5.

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# Chapter 4. Performance assessment and option appraisal method: An application for EPC generation based on simple questionnaire.

*In the preceding chapter the performance assessment and option appraisal method is described at a high level. Then the underpinning logic and calculations for an example deployment for the Scottish domestic building stock are developed.*

*The underpinning logic, DSM and non-DSM calculations now need to be embedded within an application process and suitable software to facilitate the useful deployment and testing of the overall method.*

*This chapter investigates the deployment of the method for the generation of Energy Performance Certificates (EPCs) from simple questionnaire inputs.*

*The development of the application process and the formulation of the overall method, including the software interface configuration for use within this application process, are described. Then the method is tested and the outcomes are reviewed.*

## 4.1 Introduction

Based on the breakdown of requirements of the different potential users, the test application of the performance assessment and upgrade appraisal method was approached in two parts:

1. The application of the method for generating EPCs based on simple questionnaires.
2. The more general application of the method in support of performance assessment and upgrade option appraisal for: social landlord stock management, developer or architect option appraisal, policy development, and in education.

The first of these applications is the focus of this chapter. The second more general application of the method will be the focus of chapter 5. Conclusions on the first application are given at the end of this chapter. Conclusions on the overall research into the performance assessment and upgrade option appraisal method are given at the end of chapter 5.

The first test application was intended to deliver energy ratings (including EPCs) for Scottish domestic buildings based on data gathered through a simple questionnaire. The motivation for the use of the simple questionnaire approach to capture data was to investigate lower cost alternatives to the traditional approach which requires a detailed survey of each individual property by a qualified energy assessor.

It was proposed that a simple questionnaire could potentially be obtained from householders similar to a tax return (i.e. either in paper form or on line). For the social rented stock building maintenance officers or people in similar positions were viewed as potential providers of the required questionnaire inputs.

The application for EPC generation was intended to give broadly similar results to the UK simplified regulatory methods and so was formulated with a fixed context (climate and pattern of use) hidden from the users and with determinant parameter values inferred from high level inputs only.

The high level input and inference approach taken for this test application was inevitably going to have some loss of fidelity compared to the full survey approach, particularly in assumptions made on geometrical factors as highlighted in the previous chapter. This research explores potential limitations, provides some useful insights for this test application and for future research and developments to build on.

The development of the application process and the formulation of the overall method for use within this application process are described in the following sections.

Then the method is tested for this application and the outcomes reviewed.

## 4.2 EPC generation based on questionnaire

Both the design of the proposed homeowner questionnaire and the software user interface for data entry are in the form of a survey and their development for the pilot followed well established principles for survey design (IHSN 2012):

- Clear survey objectives, scope and coverage.
- Engagement of a design team (in this case including policymakers, researchers, data collectors and homeowners).
- Questions organised in modules with logical sequencing.
- Questions should be short, simple and clear.
- Questions should be closed and pre-coded (for technical data gathering).
- Pre-testing and pilot testing should be carried out.
- Pilot testing should be of the entire process of data gathering and data entry and include guidance documentation, user manuals etc.

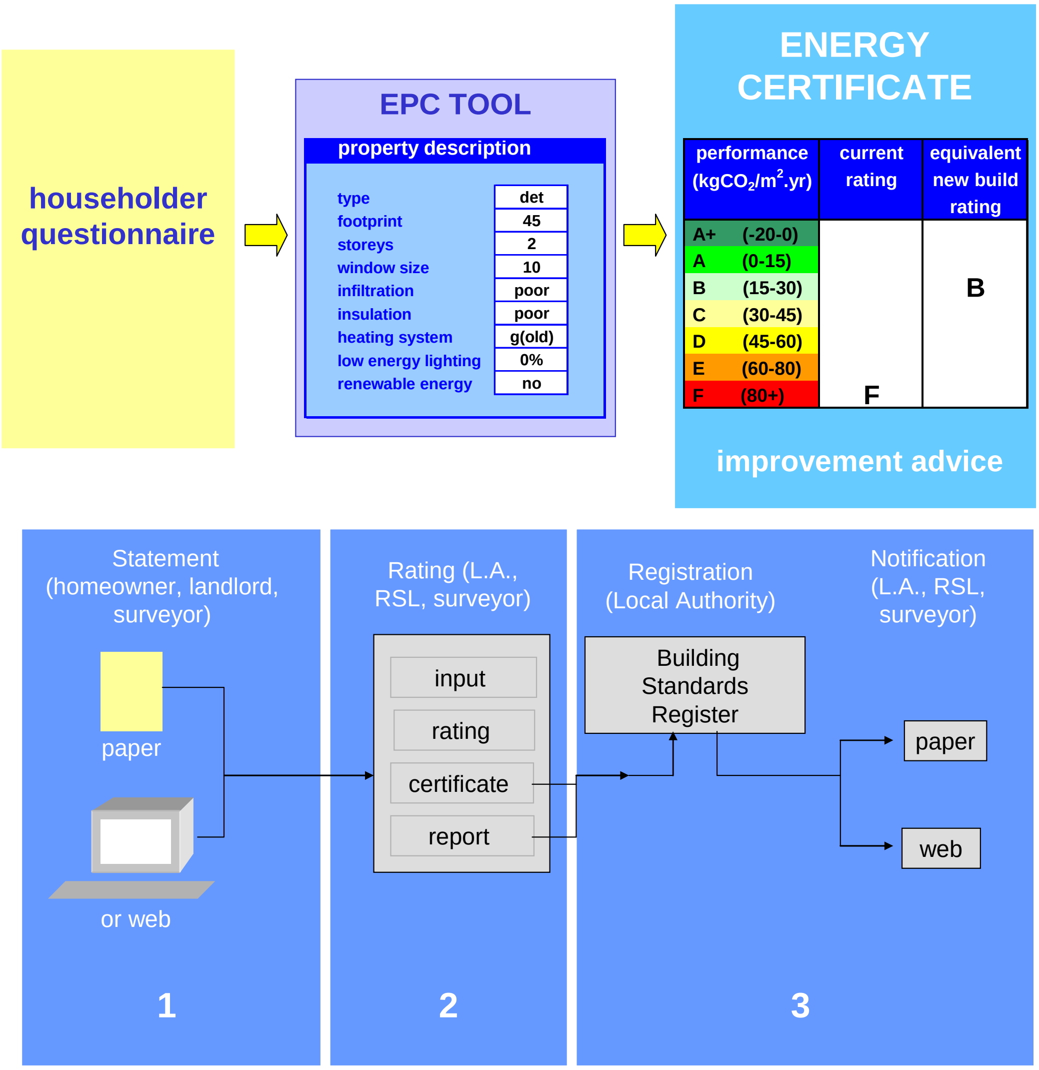
### 4.2.1 Initial application process, questionnaire and software development and testing

The concept illustrated in figure 4.1 was conceived as the method to be researched for potential as the low cost (minimal requirement for expert input) method to meet the requirements of the EPBD i.e. that existing dwellings should have an EPC capturing their energy and associated carbon performance and identifying potential improvements. The inputs were to be kept as simple as possible, ideally to allow individual homeowners to provide responses to enable ratings to be established. The returns would be received and checked by a building control officer or similarly qualified person and the calculation tool used to generate the required outputs.

Several iterations of questionnaire and software interface were developed by the author and tested either with the EPBD implementation team themselves (the team was made up representatives of building standards officers, building control officers, local authority energy managers, social landlords and housing developers) or with users that they provided access to (landlords and homeowners for the questionnaire;

building control officers and local authority energy or maintenance officers for the user interface and guidance documentation for data entry).

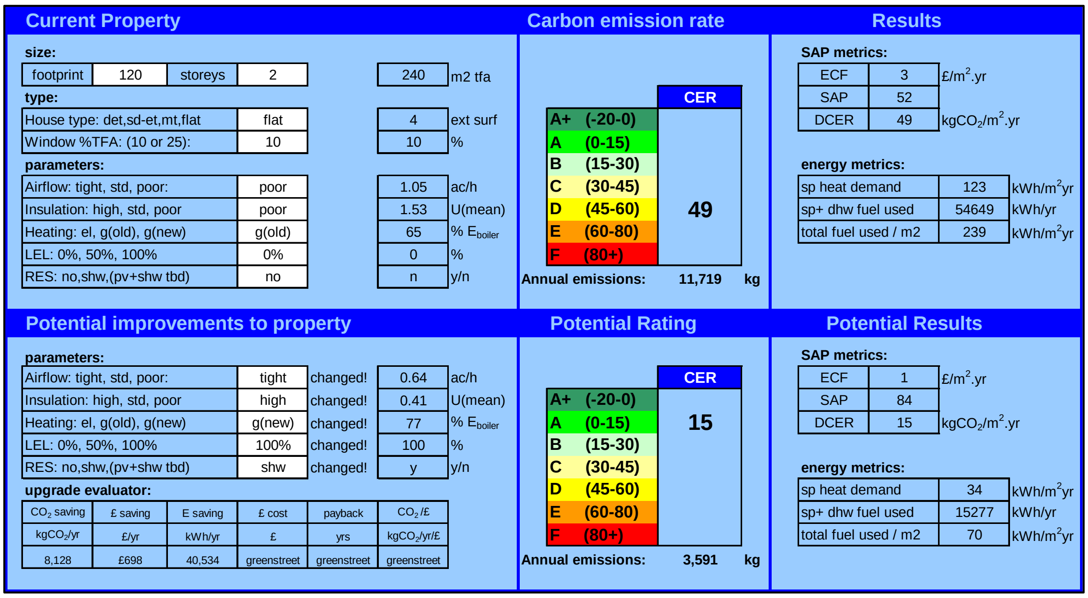
**Figure 4.1. *Concept for the generation of EPC ratings from a questionnaire.***



To facilitate initial discussions with the user group and get initial feedback mock-up versions of the survey sheet and calculation method were created and demonstrated. Feedback from these potential users was received and the tool revised. An example of an early mock-up version of the user interface is shown in figure 4.2.

Much discussion centred on the extent and provenance of the information that would be reliably obtained from a simple questionnaire return from a person who was not a buildings professional, this was then one of the points to be tested in the trials.

***Figure 4.2. An early working trial version of the calculation tool.***



**Current Property**

size:

| | | | | | |
|---|---|---|---|---|---|
| footprint | 120 | storeys | 2 | 240 | m2 tfa |

type:

| | | | |
|---|---|---|---|
| House type: det,sd-et,mt,flat | flat | 4 | ext surf |
| Window %TFA: (10 or 25): | 10 | 10 | % |

parameters:

| | | | |
|---|---|---|---|
| Airflow: tight, std, poor: | poor | 1.05 | ac/h |
| Insulation: high, std, poor | poor | 1.53 | U(mean) |
| Heating: el, g(old), g(new) | g(old) | 65 | % $E_{boiler}$ |
| LEL: 0%, 50%, 100% | 0% | 0 | % |
| RES: no,shw,(pv+shw tbd) | no | n | y/n |

**Carbon emission rate**

| | CER |
|---|---|
| A+ (-20-0) | 49 |
| A (0-15) | |
| B (15-30) | |
| C (30-45) | |
| D (45-60) | |
| E (60-80) | |
| F (80+) | |

Annual emissions: 11,719 kg

**Results**

SAP metrics:

| | | |
|---|---|---|
| ECF | 3 | £/m$^2$.yr |
| SAP | 52 | |
| DCER | 49 | kgCO$_2$/m$^2$.yr |

energy metrics:

| | | |
|---|---|---|
| sp heat demand | 123 | kWh/m$^2$yr |
| sp+ dhw fuel used | 54649 | kWh/yr |
| total fuel used / m2 | 239 | kWh/m$^2$yr |

**Potential improvements to property**

parameters:

| | | | | |
|---|---|---|---|---|
| Airflow: tight, std, poor: | tight | changed! | 0.64 | ac/h |
| Insulation: high, std, poor | high | changed! | 0.41 | U(mean) |
| Heating: el, g(old), g(new) | g(new) | changed! | 77 | % $E_{boiler}$ |
| LEL: 0%, 50%, 100% | 100% | changed! | 100 | % |
| RES: no,shw,(pv+shw tbd) | shw | changed! | y | y/n |

upgrade evaluator:

| CO$_2$ saving | £ saving | E saving | £ cost | payback | CO$_2$ /£ |
|---|---|---|---|---|---|
| kgCO$_2$/yr | £/yr | kWh/yr | £ | yrs | kgCO$_2$/yr/£ |
| 8,128 | £698 | 40,534 | greenstreet | greenstreet | greenstreet |

**Potential Rating**

| | CER |
|---|---|
| A+ (-20-0) | |
| A (0-15) | 15 |
| B (15-30) | |
| C (30-45) | |
| D (45-60) | |
| E (60-80) | |
| F (80+) | |

Annual emissions: 3,591 kg

**Potential Results**

SAP metrics:

| | | |
|---|---|---|
| ECF | 1 | £/m$^2$.yr |
| SAP | 84 | |
| DCER | 15 | kgCO$_2$/m$^2$.yr |

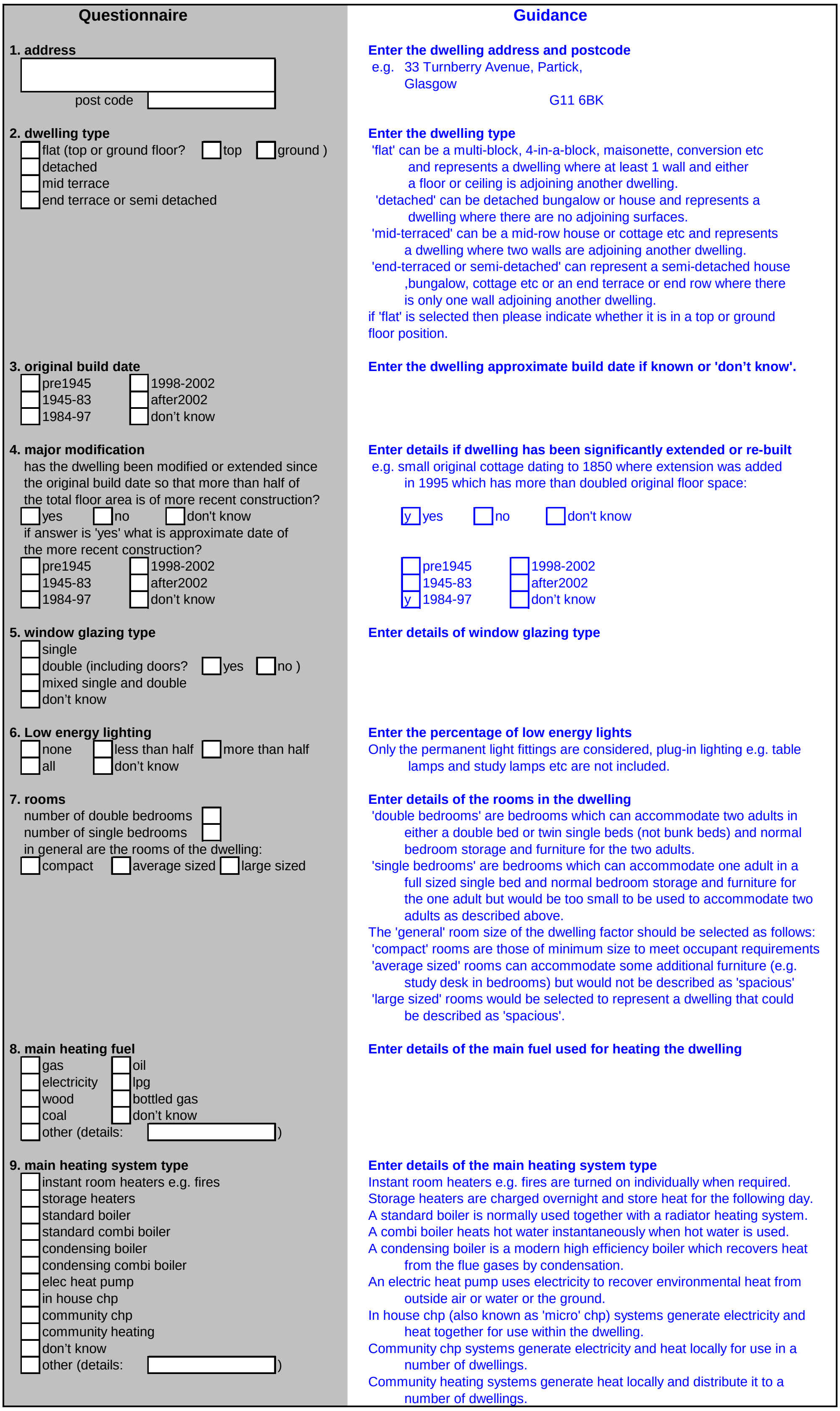
energy metrics:

| | | |
|---|---|---|
| sp heat demand | 34 | kWh/m$^2$yr |
| sp+ dhw fuel used | 15277 | kWh/yr |
| total fuel used / m2 | 70 | kWh/m$^2$yr |

Once this discussion process had been iterated several times and sufficient agreement reached to allow the method to be taken forward, the method was frozen and the interface, data tables and calculations encoded into Java for use in the pilot studies. This first 'encapsulation' of the method was labelled the 'Scottish Energy Rating Tool' (SERT) (Scot Gov 2006). Figure 4.3 shows an example questionnaire with guidance notes to facilitate gathering of data inputs. These inputs are then to be used to generate the required results using: inference logic to determine appropriate determinant parameter levels; the corresponding values selected values from the DSM and non DSM datasets; and the embedded logic and calculations, as described in chapter 3. Further iterations of the questionnaire are discussed at the end of this chapter.

The first pre-testing was carried out with two local authorities (South Ayrshire Council, Inverclyde Building Control) and a private housing association (North Ayrshire HA). Participants initially installed the software, familiarised themselves with it and provided feedback on the user interface and any other areas of interest. A second version was then provided which had incorporated suggested improvements in the user interface (figure 4.4). The three participants each used this version to rate 6 properties in their local area and return results along with comments. The range of properties for which data was gathered was biased towards more recent buildings; a benefit of this was the availability of SAP ratings for comparison. Some further improvements to the guidance documentation were suggested and incorporated. This pre-testing phase was then deemed to have been successful and the tool was judged to be ready to use in a wider study. This version was then used for a larger pilot application to a range of Local Authority and private sector properties in the west of Scotland.

## *Figure 4.3 An example of an early version of the homeowner questionnaire*



| Questionnaire | Guidance |
|---|---|
| **1. address**<br>post code | **Enter the dwelling address and postcode**<br>e.g. 33 Turnberry Avenue, Partick,<br>Glasgow<br>G11 6BK |
| **2. dwelling type**<br>☐ flat (top or ground floor? ☐ top ☐ ground )<br>☐ detached<br>☐ mid terrace<br>☐ end terrace or semi detached | **Enter the dwelling type**<br>'flat' can be a multi-block, 4-in-a-block, maisonette, conversion etc and represents a dwelling where at least 1 wall and either a floor or ceiling is adjoining another dwelling.<br>'detached' can be detached bungalow or house and represents a dwelling where there are no adjoining surfaces.<br>'mid-terraced' can be a mid-row house or cottage etc and represents a dwelling where two walls are adjoining another dwelling.<br>'end-terraced or semi-detached' can represent a semi-detached house ,bungalow, cottage etc or an end terrace or end row where there is only one wall adjoining another dwelling.<br>if 'flat' is selected then please indicate whether it is in a top or ground floor position. |
| **3. original build date**<br>☐ pre1945 ☐ 1998-2002<br>☐ 1945-83 ☐ after2002<br>☐ 1984-97 ☐ don't know | **Enter the dwelling approximate build date if known or 'don't know'.** |
| **4. major modification**<br>has the dwelling been modified or extended since the original build date so that more than half of the total floor area is of more recent construction?<br>☐ yes ☐ no ☐ don't know<br>if answer is 'yes' what is approximate date of the more recent construction?<br>☐ pre1945 ☐ 1998-2002<br>☐ 1945-83 ☐ after2002<br>☐ 1984-97 ☐ don't know | **Enter details if dwelling has been significantly extended or re-built**<br>e.g. small original cottage dating to 1850 where extension was added in 1995 which has more than doubled original floor space:<br>y yes ☐ no ☐ don't know<br>☐ pre1945 ☐ 1998-2002<br>☐ 1945-83 ☐ after2002<br>y 1984-97 ☐ don't know |
| **5. window glazing type**<br>☐ single<br>☐ double (including doors? ☐ yes ☐ no )<br>☐ mixed single and double<br>☐ don't know | **Enter details of window glazing type** |
| **6. Low energy lighting**<br>☐ none ☐ less than half ☐ more than half<br>☐ all ☐ don't know | **Enter the percentage of low energy lights**<br>Only the permanent light fittings are considered, plug-in lighting e.g. table lamps and study lamps etc are not included. |
| **7. rooms**<br>number of double bedrooms ☐<br>number of single bedrooms ☐<br>in general are the rooms of the dwelling:<br>☐ compact ☐ average sized ☐ large sized | **Enter details of the rooms in the dwelling**<br>'double bedrooms' are bedrooms which can accommodate two adults in either a double bed or twin single beds (not bunk beds) and normal bedroom storage and furniture for the two adults.<br>'single bedrooms' are bedrooms which can accommodate one adult in a full sized single bed and normal bedroom storage and furniture for the one adult but would be too small to be used to accommodate two adults as described above.<br>The 'general' room size of the dwelling factor should be selected as follows:<br>'compact' rooms are those of minimum size to meet occupant requirements<br>'average sized' rooms can accommodate some additional furniture (e.g. study desk in bedrooms) but would not be described as 'spacious'<br>'large sized' rooms would be selected to represent a dwelling that could be described as 'spacious'. |
| **8. main heating fuel**<br>☐ gas ☐ oil<br>☐ electricity ☐ lpg<br>☐ wood ☐ bottled gas<br>☐ coal ☐ don't know<br>☐ other (details: ) | **Enter details of the main fuel used for heating the dwelling** |
| **9. main heating system type**<br>☐ instant room heaters e.g. fires<br>☐ storage heaters<br>☐ standard boiler<br>☐ standard combi boiler<br>☐ condensing boiler<br>☐ condensing combi boiler<br>☐ elec heat pump<br>☐ in house chp<br>☐ community chp<br>☐ community heating<br>☐ don't know<br>☐ other (details: ) | **Enter details of the main heating system type**<br>Instant room heaters e.g. fires are turned on individually when required.<br>Storage heaters are charged overnight and store heat for the following day.<br>A standard boiler is normally used together with a radiator heating system.<br>A combi boiler heats hot water instantaneously when hot water is used.<br>A condensing boiler is a modern high efficiency boiler which recovers heat from the flue gases by condensation.<br>An electric heat pump uses electricity to recover environmental heat from outside air or water or the ground.<br>In house chp (also known as 'micro' chp) systems generate electricity and heat together for use within the dwelling.<br>Community chp systems generate electricity and heat locally for use in a number of dwellings.<br>Community heating systems generate heat locally and distribute it to a number of dwellings. |

**10. main heating install date**

☐ pre- 1998 ☐ post 2004
☐ 1998-2004 ☐ don't know

if new boiler installed since full system install date give new boiler date

☐ pre- 1998 ☐ post 2004
☐ 1998-2004 ☐ don't know

**Enter details of main heating system age**

Where a replacement boiler has been installed please give the approximate installation date

**11. water heating system type**

- ☐ water heated by main heating system
- ☐ electric immerser
- ☐ electric instant heater
- ☐ gas instant heater
- ☐ don't know
- ☐ other (details: )

**Enter details of the water heating system type**

**12. water heating install date**

☐ pre- 1998 ☐ post 2004
☐ 1998-2004 ☐ don't know

if new hot water tank (cylinder) installed since full system install date give new cylinder date

☐ pre- 1998 ☐ post 2004
☐ 1998-2004 ☐ don't know

**Enter details of water heating system age**

Where a new hot water tank has been installed please give approximate installation date

**13. ventilation**

- ☐ window openings only
- ☐ kitchen extract fan
- ☐ bathroom extract fan
- ☐ whole house passive ventilation system
- ☐ whole house mechanical ventilation system
- ☐ don't know

**Enter details of ventilation type**

'window openings only' includes trickle ventilators in windows

**14. renewable energy**

☐ solar water heater approx area ☐ $m^2$
☐ photovoltaic approx area ☐ $m^2$
☐ wind turbine approx diameter ☐ m
number ☐

- ☐ none
- ☐ don't know
- ☐ other (details: )

**Enter details of renewable energy integrated into the dwelling**

Solar water heaters and solar photovoltaic panels generate hot water and electricity from sunshine, please enter approximate area if these systems are in place

Wind turbines for dwellings can generate electricity, please enter the approximate diameter and number of turbines in place.

**15. upgrades**

indicate below any known upgrades

- ☐ loft insulation 150mm
- ☐ loft insulation 300mm

- ☐ cavity wall insulation
- ☐ non cavity wall insulation

- ☐ ground floor insulation

- ☐ draught strip windows
- ☐ draught strip doors
- ☐ draught strip loft access
- ☐ draught proof ground floor

- ☐ hot water tank/pipe insulation

- ☐ porch or internal space outside external doors
- ☐ thermostatic radiator valves
- ☐ other (details: )

approx date if a major refurbishment done covering several of the items above

☐ pre1984 ☐ after2002
☐ 1984-97 ☐ don't know
☐ 1998-2002 ☐ not applicable

**Enter details of upgrades that have been carried out on the dwelling**

150mm (6inches) of glasswool typically fills the space between rafters.

300mm (12inches) of glasswool provides 1 layer between rafters plus a second layer over the rafters.

'cavity wall insulation' is typically injected into the cavity.

'non cavity wall insulation' is insulation applied as either an internal or external layer to the solid walls of the dwelling

'ground floor insulation' can be installed below suspended floors or under concrete floors (during re-laying).

Draught strip is brush, nylon or foam material which seals the cracks around windows, doors or hatches etc. when shut.

Draught proofing ground floor is the sealing of cracks between boards and around the floor edges to avoid draughts.

If the water tank insulation has been increased by addition of extra jacket and the hot water pipes insulated, please check this box.

Please enter whether external doors open into a sheltered space.

Please enter whether thermostatic radiator valves are installed.

**16. advanced building standards**

- ☐ insulation 15% better than regulations

- ☐ insulation to UK Advanced standards
- ☐ mvhr with low power dc fans

**Enter details of advanced building standards used in dwelling**

Ecohomes Ene2 encourages 15% improvement in insulation over regulations, check this box if this standard has been achieved.

The UK Advanced standard encourages super-insulation standards.

Low energy (low energy DC fans) mechanical ventilation with heat recovery.

**17. conservatory**

☐ yes ☐ no ☐ don't know

is it heated by the main dwelling heating system?

☐ yes ☐ no ☐ don't know

is it separated from the main dwelling by external quality walls, doors, windows?

☐ yes ☐ no ☐ don't know

**Enter details of a conservatory if dwelling has one**

A conservatory is a construction of mainly frame and glass built external to the dwelling. A conservatory has poorer insulation properties than an extension.

If the main dwelling heating system is used to heat the conservatory indicate 'yes' e.g. radiator in conservatory.

If the walls, doors and windows between the dwelling and the conservatory are of similar properties to the rest of the external walls, windows and doors then indicate 'yes' if of internal type indicate 'no'.

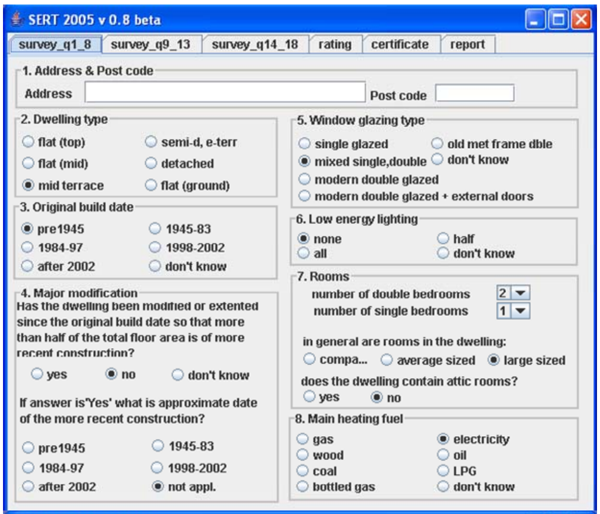
**18. Air conditioning**

is air conditioning installed

☐ yes ☐ no ☐ don't know

**Indicate whether air conditioning is installed**

*Figure 4.4 Data input and output interface for the EPC rating application*



1. Address & Post code

Address

Post code

2. Dwelling type

○ flat (top) ○ semi-d, e-terr
○ flat (mid) ○ detached
● mid terrace ○ flat (ground)

3. Original build date

● pre1945 ○ 1945-83
○ 1984-97 ○ 1998-2002
○ after 2002 ○ don't know

4. Major modification

Has the dwelling been modified or extented since the original build date so that more than half of the total floor area is of more recent construction?

○ yes ● no ○ don't know

If answer is'Yes' what is approximate date of the more recent construction?

○ pre1945 ○ 1945-83
○ 1984-97 ○ 1998-2002
○ after 2002 ● not appl.

5. Window glazing type

○ single glazed ○ old met frame dble
● mixed single,double ○ don't know
○ modern double glazed
○ modern double glazed + external doors

6. Low energy lighting

● none ○ half
○ all ○ don't know

7. Rooms

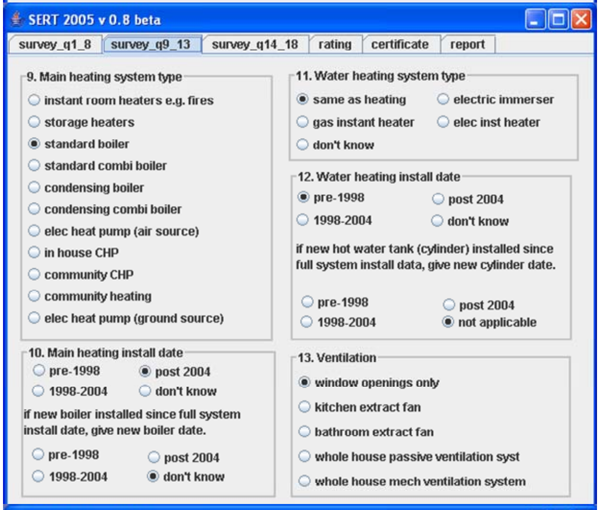
number of double bedrooms 2
number of single bedrooms 1

in general are rooms in the dwelling:
○ compa... ○ average sized ● large sized

does the dwelling contain attic rooms?
○ yes ● no

8. Main heating fuel

○ gas ● electricity
○ wood ○ oil
○ coal ○ LPG
○ bottled gas ○ don't know



9. Main heating system type

○ instant room heaters e.g. fires
○ storage heaters
● standard boiler
○ standard combi boiler
○ condensing boiler
○ condensing combi boiler
○ elec heat pump (air source)
○ in house CHP
○ community CHP
○ community heating
○ elec heat pump (ground source)

10. Main heating install date

○ pre-1998 ● post 2004
○ 1998-2004 ○ don't know

if new boiler installed since full system install date, give new boiler date.

○ pre-1998 ○ post 2004
○ 1998-2004 ● don't know

11. Water heating system type

● same as heating ○ electric immerser
○ gas instant heater ○ elec inst heater
○ don't know

12. Water heating install date

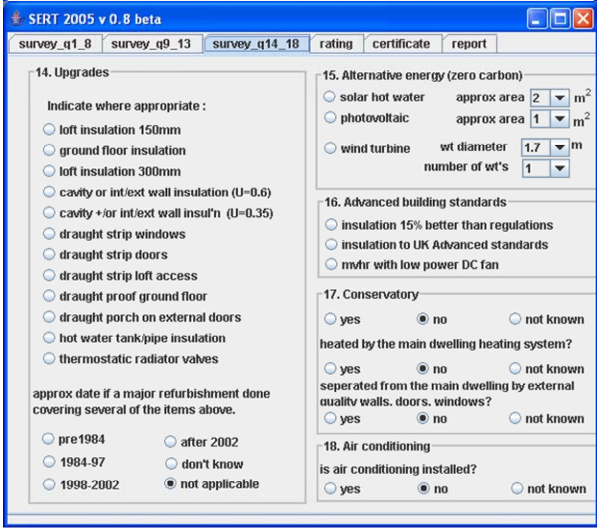
● pre-1998 ○ post 2004
○ 1998-2004 ○ don't know

if new hot water tank (cylinder) installed since full system install data, give new cylinder date.

○ pre-1998 ○ post 2004
○ 1998-2004 ● not applicable

13. Ventilation

● window openings only
○ kitchen extract fan
○ bathroom extract fan
○ whole house passive ventilation syst
○ whole house mech ventilation system



14. Upgrades

Indicate where appropriate :

○ loft insulation 150mm
○ ground floor insulation
○ loft insulation 300mm
○ cavity or int/ext wall insulation (U=0.6)
○ cavity +/or int/ext wall insul'n (U=0.35)
○ draught strip windows
○ draught strip doors
○ draught strip loft access
○ draught proof ground floor
○ draught porch on external doors
○ hot water tank/pipe insulation
○ thermostatic radiator valves

approx date if a major refurbishment done covering several of the items above.

○ pre1984 ○ after 2002
○ 1984-97 ○ don't know
○ 1998-2002 ● not applicable

15. Alternative energy (zero carbon)

○ solar hot water approx area 2 $m^2$
○ photovoltaic approx area 1 $m^2$
○ wind turbine wt diameter 1.7 m
number of wt's 1

16. Advanced building standards

○ insulation 15% better than regulations
○ insulation to UK Advanced standards
○ mvhr with low power DC fan

17. Conservatory

○ yes ● no ○ not known

heated by the main dwelling heating system?

○ yes ● no ○ not known

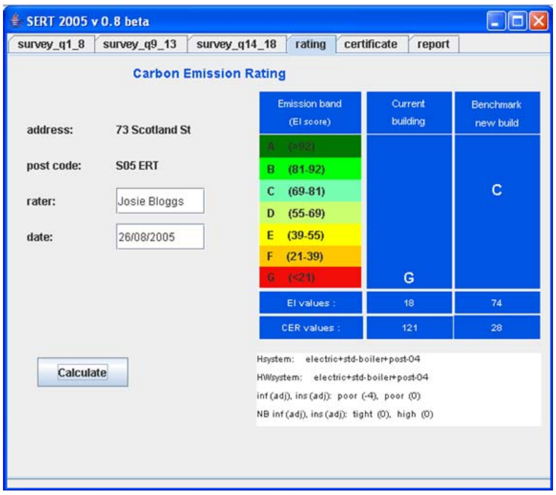
seperated from the main dwelling by external quality walls. doors. windows?

○ yes ● no ○ not known

18. Air conditioning

is air conditioning installed?

○ yes ● no ○ not known

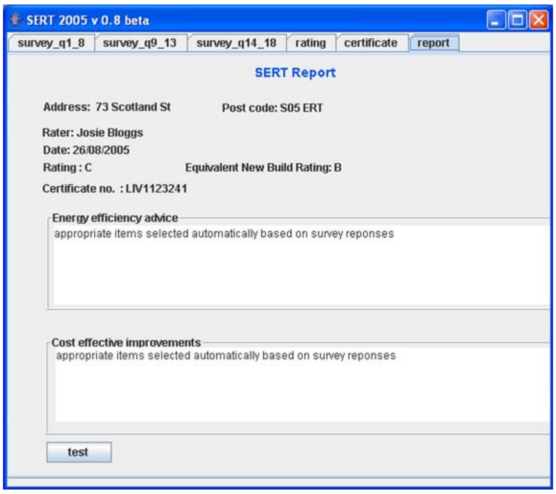


Carbon Emission Rating

address: 73 Scotland St
post code: S05 ERT
rater: Josie Bloggs
date: 26/08/2005

| Emission band (EI score) | Current building | Benchmark new build |
|---|---|---|
| A (>92) | | |
| B (81-92) | | |
| C (69-81) | | C |
| D (55-69) | | |
| E (39-55) | | |
| F (21-39) | | |
| G (<21) | G | |
| EI values : | 18 | 74 |
| CER values : | 121 | 28 |

Hsystem: electric+std-boiler+post-04
HWsystem: electric+std-boiler+post-04
inf (adj), ins (adj): poor (-4), poor (0)
NB inf (adj), ins (adj): tight (0), high (0)

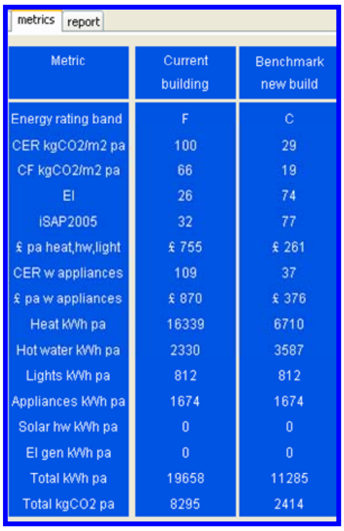


SERT Report

Address: 73 Scotland St Post code: S05 ERT
Rater: Josie Bloggs
Date: 26/08/2005
Rating : C Equivalent New Build Rating: B
Certificate no. : LIV1123241

Energy efficiency advice
appropriate items selected automatically based on survey reponses

Cost effective improvements
appropriate items selected automatically based on survey reponses



| Metric | Current building | Benchmark new build |
|---|---|---|
| Energy rating band | F | C |
| CER kgCO2/m2 pa | 100 | 29 |
| CF kgCO2/m2 pa | 66 | 19 |
| EI | 26 | 74 |
| iSAP2005 | 32 | 77 |
| £ pa heat,hw,light | £ 755 | £ 261 |
| CER w appliances | 109 | 37 |
| £ pa w appliances | £ 870 | £ 376 |
| Heat kWh pa | 16339 | 6710 |
| Hot water kWh pa | 2330 | 3587 |
| Lights kWh pa | 812 | 812 |
| Appliances kWh pa | 1674 | 1674 |
| Solar hw kWh pa | 0 | 0 |
| El gen kWh pa | 0 | 0 |
| Total kWh pa | 19658 | 11285 |
| Total kgCO2 pa | 8295 | 2414 |

### 4.2.2 Field trials of the performance assessment method for EPC generation.

After pre-testing a multi-stage pilot was used to evaluate the method which for this application was known as the Scottish Energy Rating Tool (SERT).

1) SERT was applied to local authority housing and the results compared to an available Local Authority National Home Energy Rating (NHER) database, compiled by energy consultants (NHER is a BREDEM based annual method, similar to SAP and historically used for legislation compliance by social landlords (BRE 2004);

2) SERT and the UK Government regulatory method for existing dwellings (RDSAP 2005 (BRE 2012)) were then applied in parallel to a range of local authority and privately owned dwellings to allow direct comparison of results. It should be noted that the RDSAP 2005 method was a pilot version also targeting EPBD implementation but based on site survey by accredited professionals;

3) SERT was directly compared to the UK Government detailed regulatory calculation procedure for new dwellings (SAP 2005 (BRE 2012)) for 4 privately owned dwellings.

The first stage of the pilot, application to social landlord housing stock, was in co-operation with South Ayrshire Council. A range of 8 rural and urban dwellings with varying performance were rated using the SERT method by a Council employee who visited the properties and filled out the questionnaire while there. Typical properties are shown in figure 4.5. Three of these properties were heated with gas and five with electricity. Subsequently as part of an on-going condition survey the same properties were rated by outside consultants using the BREDEM based NHER Surveyor commercial software. The comparison of results for this pilot study is shown in figure 4.6. In general there was good agreement between the two methods given the assumptions made in the underlying method as described in chapter 3 (e.g. geometry).

This first evaluation was extended by inputting data from the local authority database to generate SERT ratings in a desktop survey mode. A further 7 properties were rated in this way, 3 electrically heated and 4 heated with gas. Again reasonable agreement between SERT results generated from the local authority database and the NHER results generated by the energy consultants was observed (figure 4.7).

***Fig. 4.5 Examples of three typical South Ayrshire Council dwellings***

A second evaluation was carried out with the same South Ayrshire social landlord dwellings as in the earlier evaluation plus a number of private dwellings (mainly Victorian sandstone tenement or flat conversions) in the west end of Glasgow. This second evaluation compared the use of SERT to the use of RDSAP 2005 which was under development at that time.

The RDSAP results were generated by independent energy assessors. Their assessment included physical measurements and inspections and required approximately a 30 minute visit to each dwelling.

The SERT evaluation in the case of the Glasgow privately owned properties was based on homeowners completing the questionnaires and these inputs being entered into the SERT calculation software by the author.

There were large differences between methods in this study (figure 4.8). It was observed that in general the SERT results gave higher energy use and associated emissions than RDSAP except for dwellings with the poorest thermal performance.

In order to investigate further the root causes for the differences a third evaluation was carried out that compared SERT to the governments detailed regulatory calculation method for new dwellings (SAP 2005). Access to four of the Glasgow dwellings was arranged. The SAP results were generated by the author from an approximately 60 minute detailed survey of the dwelling and entry of data into SAP software. The SERT results, generated in this case from the same detailed inspection of the properties. The results, including the previous RDSAP results, for are given in Table 4.1.

*Fig. 4.6 Carbon emissions comparison of the SERT method (with inputs based on site survey and landlord questionnaire) v. NHER.*

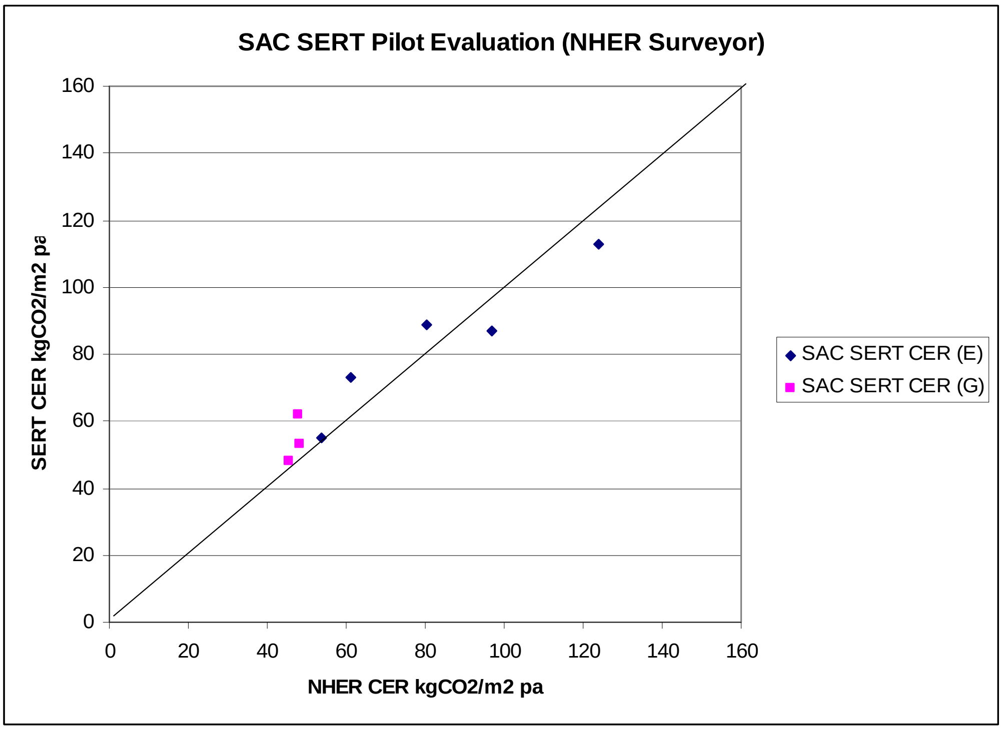


*Fig. 4.7 Carbon emissions comparison of the SERT method (with additional inputs based on Landlords database (SERTrules)) v. NHER*

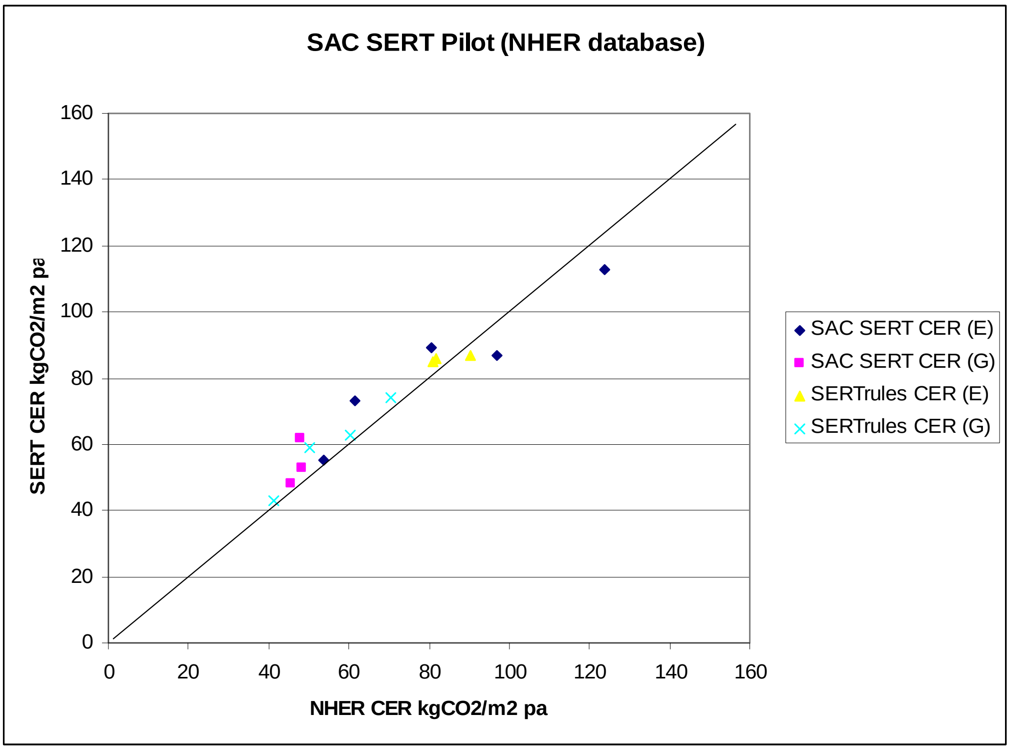


*Fig. 4.8 Carbon emissions comparison of SERT v. RDSAP.*

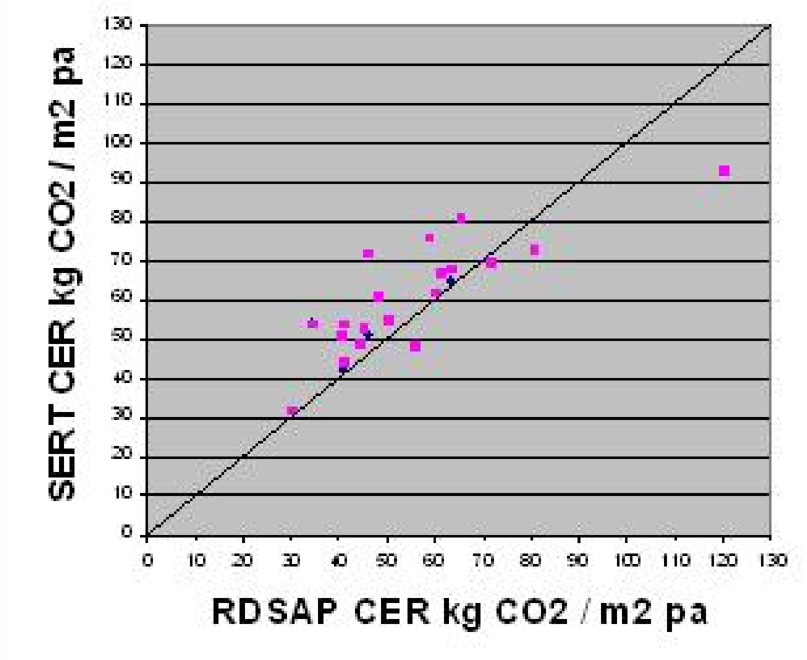


**Table 4.1 SERT v SAP and RDSAP**

| $kgCO_2/m^2$ | SAP2005 | RDSAP2005 | SERT |
|---|---|---|---|
| Property A | 51 | 46 | 72 |
| Property K | 42 | 41 | 44 |
| Property B | 42 | 35 | 54 |
| Property D | 65 | 60 | 68 |

### 4.3 Observations based on calculation outputs.

The second and third evaluations highlighted a number of points of difference between the results from the different methods (figure 4.8, table 4.1), particularly for the Glasgow privately owned Victorian properties (results for these in table 4.1).

In general the SERT results were more conservative than those of RDSAP possibly due to the worst case setting of default parameters that are not directly measured. There are some exceptions to this particularly in the case of the dwellings with the poorest rating in RDSAP and NHER (figures 4.6, 4.7 and 4.8). An explanation is that in RDSAP there can be un-insulated walls with a range of U-values up to 2.1 W/m$^2$.K depending on wall construction, which is higher than the single value for un-insulated walls in SERT of 1.7 W/m$^2$.K which is more representative of Scottish sandstone construction. More construction type information could potentially be added in to the SERT method. This will be discussed later.

In the detailed examination of the four Glasgow properties using SERT, RDSAP and SAP methods large differences are apparent (table 4.1) of up to 20% particularly for properties A and B.

One significant difference (particularly apparent in the case of property A in table 4.1) was that the worst case default heating system determinant value based on boiler age assumed in SERT (65% in this case) was much worse than the actual boiler efficiency (84%) from the boiler specific SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) database used in RDSAP and SAP; this discrepancy could potentially be addressed by allowing the user to enter the boiler make and model into SERT and embedding the Governments SEDBUK database (as is done in SAP and RDSAP). A related issue was secondary heating, included in SAP and RDSAP but not in SERT which can potentially be significant in cases where inefficient appliances are used.

A second point of difference was that the high ceiling heights in the Victorian properties (up to 4.2 m) were not accurately accounted for in this version of SERT; this could be addressed by adding this parameter as a more explicit input (discussed later).

A third difference was identified as being due to the level of detail in the geometrical representation of the dwellings, particularly the extent of attachment, and the treatment of attic rooms, this was evident especially in the Victorian flat conversions (social housing stocks tend to have simpler shapes closer to the simulation models used). RDSAP despite being very simplistic in other respects does input physical measurements of floor areas, ceiling heights and external perimeter lengths giving a more accurate representation of geometries than available in SERT informed by the intentionally simple homeowner questionnaires. This difference in approach could potentially be partly addressed by using the same more detailed geometry inputs to inform SERT selection of appropriate performance from the dynamic performance map through either additional determinant parameters or interpolation / extrapolation.

An underlying difference between the methods is in the calculation of solar gains; SERT assumes North / South glazing but a very high degree of shading while RDSAP assumes an average level of over-shading and East / West windows only, and SAP inputs the window sizes, frame factors, orientations and shading factors explicitly.

This section has provided mainly technical insights from the test application. The next section reviews the insights gained from the process of application. Then an overall discussion and conclusion from this test application is given in section 4.5.

### 4.4 Observations on the application process for the questionnaire method

Feedback on the questionnaire method for data capture was received from homeowners, local authority and social landlord officers, building control officers and buildings standards officers. The following points of feedback were received:

- One topic of feedback was on the form of the questionnaire and the guidance notes, concern was raised that several terms and descriptions on the questionnaire could be made clearer with more detailed description such as: ‘standard boiler’, ‘non cavity wall insulation’, ‘ground floor insulation’.
- Another was that several of the terms used in the questionnaire would be beyond the knowledge of homeowners i.e. ‘advanced building standards’, ‘heat pump’, ‘whole house mechanical ventilation system’, ‘chp’. Similarly information could be unavailable to homeowners e.g. ‘install date’. This could lead to wrong answers, or selection of a large number of ‘don’t know’ responses triggering a low rating due to the conservative defaults.
- It was found that some questions could lead to false positive assumptions about building or systems e.g. non cavity wall insulation could be selected where dry-lining or external render was applied rather than insulation layers.

- There were situations not covered by the questionnaire such as: where there were two forms of space heating, where water was heated by two means (electric shower plus water cylinder heated by gas boiler etc), where there were attic rooms.
- The questions and responses did not provide sufficient information to allow accurate performance assessment e.g. wall insulation of 20mm not differentiated from wall insulation of 200mm; there was no question on room thermostats for heating system control; the building geometry was not sufficiently comprehended i.e. flats could have 1, 2, 3 or 4 sides exposed; ceiling heights not comprehended; upgrades to part of the building fabric only not well comprehended.
- Where the questionnaires were filled from local authority databases there were instances where the data held in the database was wrong.
- Homeowners perceived the ratings generated based on the questionnaire method to have less value than those generated from a professional survey of the dwelling.
- Homeowners stated a preference for having a professional visit their property, and the opportunity for interaction available through this, rather than have a rating based on the simple questionnaire inputs without any dialogue.

The detailed inspection by the author in the SAP assessments of the four Glasgow properties allowed comparison between the homeowner’s questionnaire data entry and that gathered by physical survey by the author. This highlighted that there can be difficulty due to a lack of homeowner knowledge leading to poorer than actual defaults being selected or lack of care taken in the data inputs (e.g. insulation thickness wrong, wrong heating system type) leading to the wrong input being selected. Similarly errors were identified where the local authority database had missing or incorrect data (e.g. upgrades applied but database not updated).

These insights into the application process are discussed, together with the technical insights highlighted earlier, in the following section. These conclusions are then considered again, together with the outcomes from further test applications, at the end of chapter 5.

## 4.5 Conclusions on the test application of the method for EPC rating based on simple questionnaires.

The development and testing of the proposed method for application to Energy Performance Certificates based on questionnaire provided many lessons and insights. A number of the insights led to modification of the approach during the piloting process, others are taken forward into the generation of the more general application described in the next chapter, and others are reflected in the review and considered in the recommendations for future research.

Through the test application to EPC generation a range of data collection methods and data sources were explored: questionnaires filled out directly by local authority housing officers, private homeowners, or the author, with and without site visits; through the use of Local Authority and Social Landlord databases; and through detailed surveys carried out on the properties being assessed to varying levels of detail associated with the requirements of the SERT questionnaire, RDSAP and SAP surveys.

Three interrelated topics of interest arise:

- The quality of input data.
- The level of detail required in the input data.
- The cost of implementing the system for gathering and assuring quality of the required input data.

The quality of the data obtained from homeowners and from existing local authority databases was in some cases flawed. To address this, the deployment of the simple questionnaire based method would need to be accompanied with an education framework (web resources, information sheets etc) and a quality control system to ensure erroneous data was screened and to provide a feedback mechanism so that the results generated are valid. Such education and quality control framework would have the potential benefit of up-skilling more of the population in energy use in buildings and how to reduce it, but require development and infrastructure with associated cost implications.

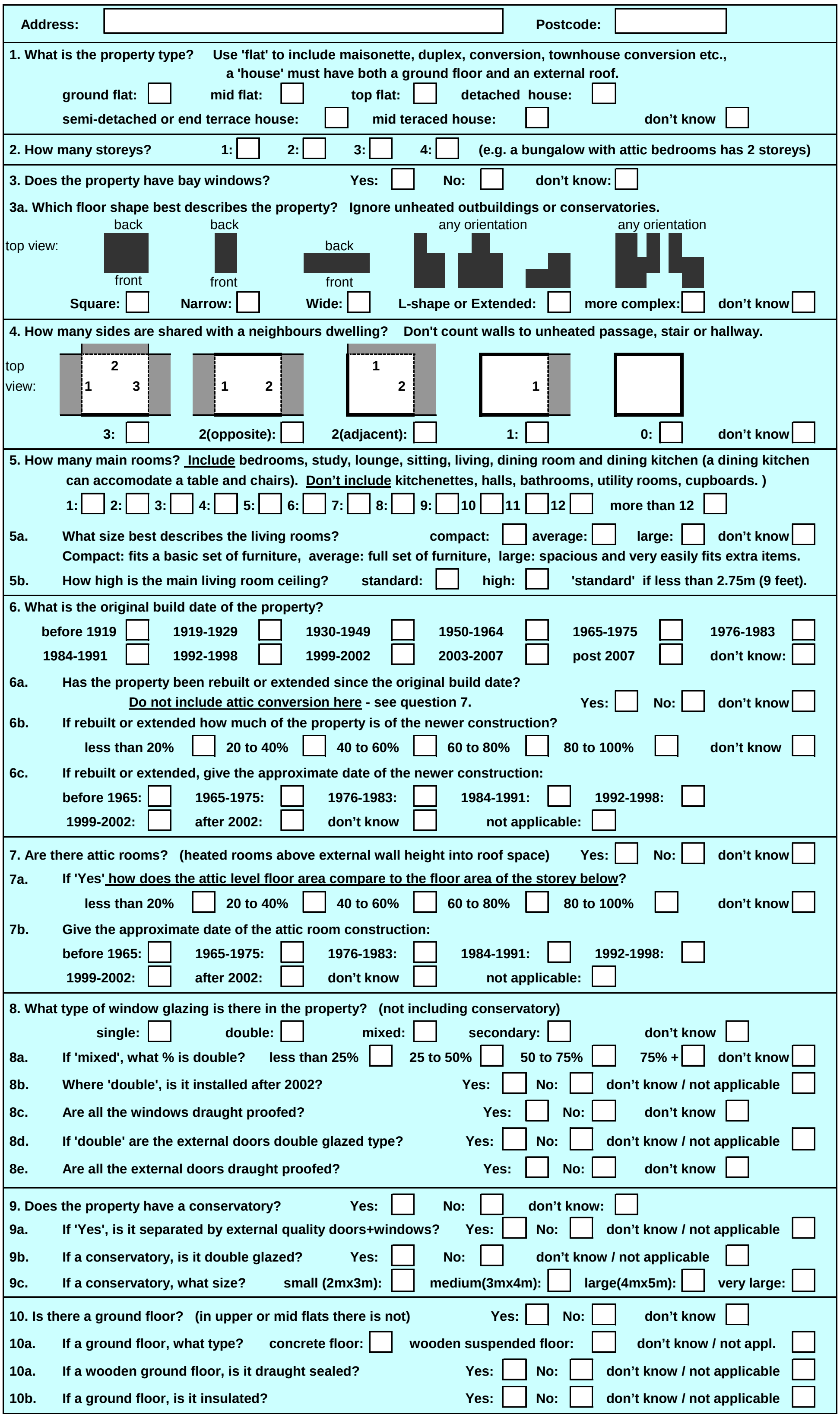
The level of detail required in input data to fulfil the purpose of this test application to assess energy use and identify appropriate upgrades emerged from the work as a discussion point. There are obvious costs (expert energy assessor time for data sourcing, site surveys etc.) associated with increasing the level of detail required to represent the building in question. Increasing the level of detail in a simple questionnaire e.g. to include boiler model details, to include accurate floor areas, heat loss wall areas etc. places a burden on the homeowner and the quality control person. While not having accurate boiler information could lead to an overestimate of potential savings from a boiler replacement, inaccurate geometrical information could lead to an overestimate of savings from a wall upgrade etc. Again an education process attached to the filling out of the questionnaire would potentially address this issue and have benefits but obviously the more details added then the greater the burden and the potential conflict with data quality.

Several iterations of the questionnaire were put forward to address the technical points, including the incorporation of further geometry and systems options; one of the later examples is shown in figure 4.9.

The development of the method and deployment in the test application for EPC generation provided useful insights that supported the Scottish Government in defining its approach to EPBD implementation (Scot Gov 2006).

The lessons learned through this research also informed the investigation of the method for a more general application. This more general test application is described in the following chapter (chapter 5). Then the outcomes from all of the test applications of the proposed method are reviewed against the hypothesis and conclusions drawn (end of chapter 5).

***Figure 4.9 Example of a more detailed questionnaire.***



**Address:** ☐ **Postcode:** ☐

**1. What is the property type?** Use 'flat' to include maisonette, duplex, conversion, townhouse conversion etc., a 'house' must have both a ground floor and an external roof.

ground flat: ☐ mid flat: ☐ top flat: ☐ detached house: ☐
semi-detached or end terrace house: ☐ mid teraced house: ☐ don't know ☐

**2. How many storeys?** 1: ☐ 2: ☐ 3: ☐ 4: ☐ (e.g. a bungalow with attic bedrooms has 2 storeys)

**3. Does the property have bay windows?** Yes: ☐ No: ☐ don't know: ☐

**3a. Which floor shape best describes the property?** Ignore unheated outbuildings or conservatories.

top view: back / front; back / front; back / front; any orientation; any orientation

Square: ☐ Narrow: ☐ Wide: ☐ L-shape or Extended: ☐ more complex: ☐ don't know ☐

**4. How many sides are shared with a neighbours dwelling?** Don't count walls to unheated passage, stair or hallway.

top view: 2 / 1 3; 1 2; 1 / 2; 1

3: ☐ 2(opposite): ☐ 2(adjacent): ☐ 1: ☐ 0: ☐ don't know ☐

**5. How many main rooms?** Include bedrooms, study, lounge, sitting, living, dining room and dining kitchen (a dining kitchen can accomodate a table and chairs). Don't include kitchenettes, halls, bathrooms, utility rooms, cupboards. )

1: ☐ 2: ☐ 3: ☐ 4: ☐ 5: ☐ 6: ☐ 7: ☐ 8: ☐ 9: ☐ 10 ☐ 11 ☐ 12 ☐ more than 12 ☐

5a. What size best describes the living rooms? compact: ☐ average: ☐ large: ☐ don't know ☐
Compact: fits a basic set of furniture, average: full set of furniture, large: spacious and very easily fits extra items.

5b. How high is the main living room ceiling? standard: ☐ high: ☐ 'standard' if less than 2.75m (9 feet).

**6. What is the original build date of the property?**

before 1919 ☐ 1919-1929 ☐ 1930-1949 ☐ 1950-1964 ☐ 1965-1975 ☐ 1976-1983 ☐
1984-1991 ☐ 1992-1998 ☐ 1999-2002 ☐ 2003-2007 ☐ post 2007 ☐ don't know: ☐

6a. Has the property been rebuilt or extended since the original build date?
Do not include attic conversion here - see question 7. Yes: ☐ No: ☐ don't know ☐

6b. If rebuilt or extended how much of the property is of the newer construction?
less than 20% ☐ 20 to 40% ☐ 40 to 60% ☐ 60 to 80% ☐ 80 to 100% ☐ don't know ☐

6c. If rebuilt or extended, give the approximate date of the newer construction:
before 1965: ☐ 1965-1975: ☐ 1976-1983: ☐ 1984-1991: ☐ 1992-1998: ☐
1999-2002: ☐ after 2002: ☐ don't know ☐ not applicable: ☐

**7. Are there attic rooms?** (heated rooms above external wall height into roof space) Yes: ☐ No: ☐ don't know ☐

7a. If 'Yes' how does the attic level floor area compare to the floor area of the storey below?
less than 20% ☐ 20 to 40% ☐ 40 to 60% ☐ 60 to 80% ☐ 80 to 100% ☐ don't know ☐

7b. Give the approximate date of the attic room construction:
before 1965: ☐ 1965-1975: ☐ 1976-1983: ☐ 1984-1991: ☐ 1992-1998: ☐
1999-2002: ☐ after 2002: ☐ don't know ☐ not applicable: ☐

**8. What type of window glazing is there in the property?** (not including conservatory)

single: ☐ double: ☐ mixed: ☐ secondary: ☐ don't know ☐

8a. If 'mixed', what % is double? less than 25% ☐ 25 to 50% ☐ 50 to 75% ☐ 75% + ☐ don't know ☐

8b. Where 'double', is it installed after 2002? Yes: ☐ No: ☐ don't know / not applicable ☐

8c. Are all the windows draught proofed? Yes: ☐ No: ☐ don't know ☐

8d. If 'double' are the external doors double glazed type? Yes: ☐ No: ☐ don't know / not applicable ☐

8e. Are all the external doors draught proofed? Yes: ☐ No: ☐ don't know ☐

**9. Does the property have a conservatory?** Yes: ☐ No: ☐ don't know: ☐

9a. If 'Yes', is it separated by external quality doors+windows? Yes: ☐ No: ☐ don't know / not applicable ☐

9b. If a conservatory, is it double glazed? Yes: ☐ No: ☐ don't know / not applicable ☐

9c. If a conservatory, what size? small (2mx3m): ☐ medium(3mx4m): ☐ large(4mx5m): ☐ very large: ☐

**10. Is there a ground floor?** (in upper or mid flats there is not) Yes: ☐ No: ☐ don't know ☐

10a. If a ground floor, what type? concrete floor: ☐ wooden suspended floor: ☐ don't know / not appl. ☐

10a. If a wooden ground floor, is it draught sealed? Yes: ☐ No: ☐ don't know / not applicable ☐

10b. If a ground floor, is it insulated? Yes: ☐ No: ☐ don't know / not applicable ☐

**11.** Does the property have a flat roof? Yes: ☐ No: ☐ don't know ☐

**11a.** Does the property have a loft? Yes: ☐ No: ☐ don't know ☐

**11b.** If a loft, what thickness best describes the loft insulation? See 11c. if there are attic rooms!
( where thicknesses vary enter the minimum thickness. note 50mm = 2 inches, 100mm = 4 inches )
0: ☐ 12mm: ☐ 25mm: ☐ 50mm: ☐ 75mm: ☐ 100mm: ☐ 150mm: ☐ 200mm: ☐
250mm: ☐ 300mm or more: ☐ don't know ☐ not applicable ☐

**11c.** If there are attic rooms, what thickness describes the minimum insulation around them?
In 11c. you should consider the insulation around the vertical and sloping walls of the attic rooms.
The minimum thickness over the horizontal surface areas around and above the attic rooms should be given in 11b
0: ☐ 12mm: ☐ 25mm: ☐ 50mm: ☐ 75mm: ☐ 100mm: ☐ 150mm: ☐ 200mm: ☐
250mm: ☐ 300mm or more: ☐ don't know ☐ not applicable ☐

**11d.** Are loft access doors and hatches draught proof? Yes: ☐ No: ☐ not applicable: ☐ don't know: ☐

**12.** What is the wall construction type? solid: ☐ cavity: ☐ timber frame: ☐ don't know: ☐

**12a.** Has cavity wall insulation been applied? Yes: ☐ No: ☐ don't know / not applicable ☐

**12b.** Has internal or external wall insulation been applied? Yes: ☐ No: ☐ don't know ☐

**13.** How many fully open chimneys are there (don't count if blocked)? 0: ☐ 1: ☐ 2: ☐ 3: ☐ 4: ☐

**13a.** Is an open fireplace used for the main heating system? Yes: ☐ No: ☐ don't know ☐

**14.** What is the main heating fuel?
mains Gas: ☐ electricity: ☐ coal / solid: ☐ oil: ☐ wood / bio: ☐ lpg / bottled gas: ☐

**14a.** What is the main heating system? If none of these options apply make a note at end of this form.
standard boiler ☐ roomheaters / fires (including back boilers) ☐
combi boiler ☐ electric storage heaters ☐ micro CHP (single dwelling) ☐
condensing boiler ☐ air source heat pump ☐ community CHP ☐
condensing combi boiler ☐ ground source heat pump ☐ community heating ☐

**14b.** What is the age of the main heating system?
pre- 1984 ☐ 1984 - 1998 ☐ 1999-2004 ☐ 2005-2007 ☐ don't know ☐

**14c.** Is temperature controlled using a wall thermostat? Yes: ☐ No: ☐ don't know ☐

**14d.** Does the main heating system use radiators? Yes: ☐ No: ☐ don't know ☐

**14e.** Are thermostatic radiator valves used to control temperature? Yes: ☐ No: ☐ don't know / not appl. ☐

**14f.** Is there a second source of heating? (not the main in 14a.) Yes: ☐ No: ☐ don't know ☐

**14g.** Fuel for secondary heating? same as main: ☐ electric: ☐ coal/solid: ☐ wood/bio: ☐ other/ not appl: ☐

**14h.** Is secondary heating an open fire? Yes: ☐ No: ☐ don't know / not applicable ☐

**14i.** If an open fire is it sealed to the chimney opening? Yes: ☐ No: ☐ don't know / not applicable ☐

**15.** Is hot water heated by the main heating system? Yes: ☐ No: ☐ don't know ☐

**15a.** If 'No' how is the water heated? electric immersion heater ☐ gas instant heater ☐
electric instant heater ☐ other / don't know ☐

**15b.** Is there a hot water store (cylinder)? No hot water store: ☐ Yes: ☐ don't know ☐

**15c.** If a hot water store what is its age? pre-1984 ☐ 84-98: ☐ 99-04: ☐ post 04: ☐ don't know / not appl: ☐

**15d.** If a hot water store, is it insulated by a factory applied foam coating or a loose jacket?
Foam coating: ☐ Loose jacket: ☐ don't know / not appl: ☐

**15e.** If there is a hot water store, how thick is the insulation? (50mm = 2 inches)
0: ☐ 12mm: ☐ 25mm: ☐ 35mm: ☐ 50mm: ☐ 80mm: ☐ 120mm: ☐ don't know / not appl: ☐

**15f.** If a store, are the pipes between boiler and store insulated? Yes: ☐ No: ☐ don't know / not appl: ☐

**15g.** Can hot water and heating be set for different times? Yes: ☐ No: ☐ don't know ☐

**15h.** Is there an electric shower? Yes: ☐ No: ☐ don't know ☐

**16.** How many of the permanent room lights are fitted with Low Energy Light bulbs?
none: ☐ some: ☐ half: ☐ most: ☐ all: ☐ don't know: ☐

**17.** Does the property have solar hot water heating? Yes: ☐ No: ☐ panel area: ☐ m2

**17a.** Does the property have a PV panel for electrical generation? Yes: ☐ No: ☐ panel area: ☐ m2

**17b.** Does the property have a domestic wind turbine? Yes: ☐ No: ☐ diameter: ☐ m

**18.** Any additional details? ☐

## 4.6 References

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## Chapter 5. Performance assessment and option appraisal: Application for policy, strategy, stock management and education, discussion and overall conclusions.

*In this chapter a more general application of the proposed method is explored.*

*The method developed in chapter 3 is re-cast to support a range of users and applications. A range of applications of the method are given as examples. Conclusions are drawn from the insights provided in these applications.*

*Overall conclusions are then drawn on the proposed method based on the general applications described in this chapter and the EPC application of chapter 4. The potential to build on this work is identified.*

### 5.1 Introduction

The objective of the work presented in this chapter is first to investigate the use of the method for policy, strategy, stock management, concept design and in education. Then at the end of this chapter the overall conclusions on the method are drawn (covering chapters 3, 4 and 5) and future work proposed.

To support the potential for more flexible use required a more flexible implementation. While the requirement of the EPC rating application was to have many of the calculation inputs hidden from the user, this more general application would support a wide range of users, allow high level or more detailed inputs, allow a wide range of contexts, support more detailed financial calculations, support customisation of calculation defaults, and support the creation of datasets or the use of existing datasets.

The same underpinning logic, DSM and non-DSM calculations described in chapter 3 and used in the EPC generation method of chapter 4 were used in the more general application described here. Points raised during the test application for EPC generation of chapter 4 were addressed by enabling more explicit data entry. These include: the direct input of floor area, the direct specification of system efficiencies, the direct specification of elemental insulation levels, and the incorporation and specification of secondary heating. The logic, DSM and non-DSM calculation results correspondence with the regulatory and other methods demonstrated in chapters 3 and 4, and the inferred correspondence of those methods with the historical survey data informing those methods, was deemed to be sufficient validation of the underpinning calculations.

An iterative process was used to define and refine the application process, software interface and user documentation (appendix B) for the more general method. Pre-testing was carried out through application of the method by the author to a number of projects (e.g. Tuohy et al. 2006). The method was used over several years in post-graduate student tutorials and assignments. Professional training was delivered to Architects, Local Authorities, Social Landlords and Housing Developers and several consultancy and research project activities were supported.

A subsequent custom version, derived from the general implementation was then created for a Local Authority, refined to meet their specific needs. This custom version is also described here to illustrate some useful features. The custom version incorporated the Local Authority housing database pre-loaded enabling dwellings to be selectable by postcode and address with local climates and tariffs set to be appropriate for the local postcode region. An assessment of the disposable income required for a particular dwelling for avoidance of fuel poverty also a feature of this custom deployment.

In this chapter, first the development of the more general deployment of the method is described, then a range of test applications explored and the outcomes reviewed.

Conclusions are drawn based on the test applications of this and the previous chapter. Then conclusions are drawn for the method overall suggestions put forward for potential further work.

These applications of the general method allowed the hypothesis to be tested for a range of situations.

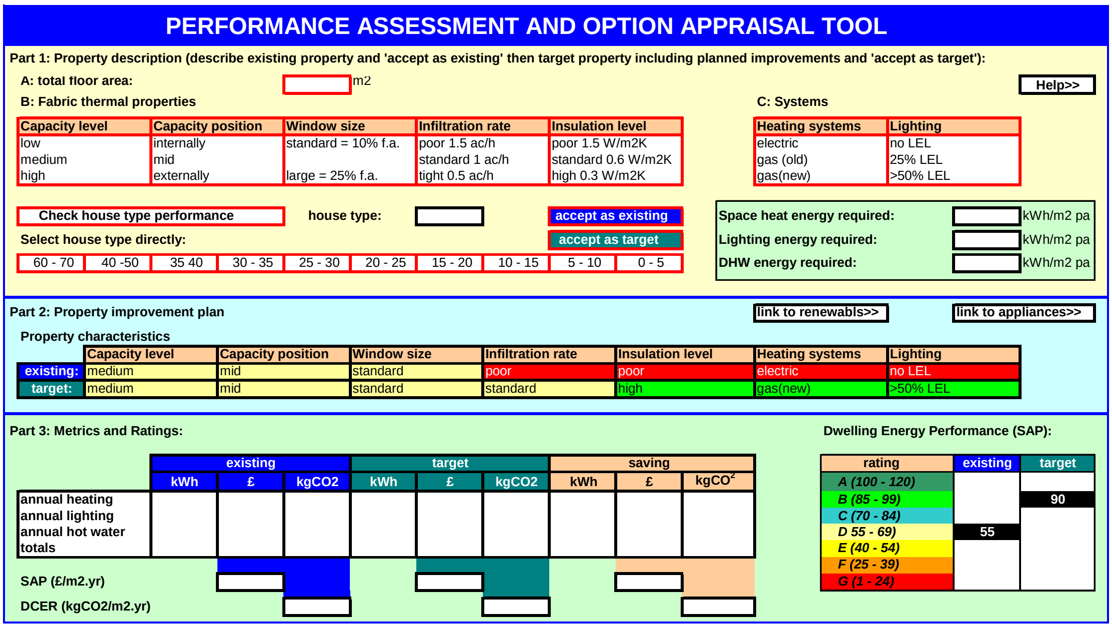
## 5.2 The general implementation of the method

This general implementation is designed for use by a range of users who have some understanding of the buildings industry and related products and specifications e.g. Local Authority or Social Landlord housing, energy or maintenance officers, Architects, housing developers, Engineering researchers and engineering students etc.

The same iterative process of refinement was used for the EPC generation application. Initially mock-up versions were created in Excel and piloted with users (figure 5.1) and feedback received. After some iterations the format for the more general implementation of the method was fixed.

The interface for this general implementation is shown in figure 5.2 and its operation described in the user manual (Tuohy 2012, Appendix B).

***Figure 5.1. An example early mock-up of the general implementation***



**PERFORMANCE ASSESSMENT AND OPTION APPRAISAL TOOL**

**Part 1: Property description (describe existing property and 'accept as existing' then target property including planned improvements and 'accept as target'):**

**A: total floor area:** ☐ m2

**Help>>**

**B: Fabric thermal properties**

| Capacity level | Capacity position | Window size | Infiltration rate | Insulation level |
|---|---|---|---|---|
| low | internally | standard = 10% f.a. | poor 1.5 ac/h | poor 1.5 W/m2K |
| medium | mid | | standard 1 ac/h | standard 0.6 W/m2K |
| high | externally | large = 25% f.a. | tight 0.5 ac/h | high 0.3 W/m2K |

**C: Systems**

| Heating systems | Lighting |
|---|---|
| electric | no LEL |
| gas (old) | 25% LEL |
| gas(new) | >50% LEL |

**Check house type performance**

**house type:** ☐

**accept as existing**

**accept as target**

**Select house type directly:**

| 60 - 70 | 40 -50 | 35 40 | 30 - 35 | 25 - 30 | 20 - 25 | 15 - 20 | 10 - 15 | 5 - 10 | 0 - 5 |
|---|---|---|---|---|---|---|---|---|---|

**Space heat energy required:** ☐ kWh/m2 pa

**Lighting energy required:** ☐ kWh/m2 pa

**DHW energy required:** ☐ kWh/m2 pa

**Part 2: Property improvement plan**

**link to renewabls>>**

**link to appliances>>**

**Property characteristics**

| | Capacity level | Capacity position | Window size | Infiltration rate | Insulation level | Heating systems | Lighting |
|---|---|---|---|---|---|---|---|
| **existing:** | medium | mid | standard | poor | poor | electric | no LEL |
| **target:** | medium | mid | standard | standard | high | gas(new) | >50% LEL |

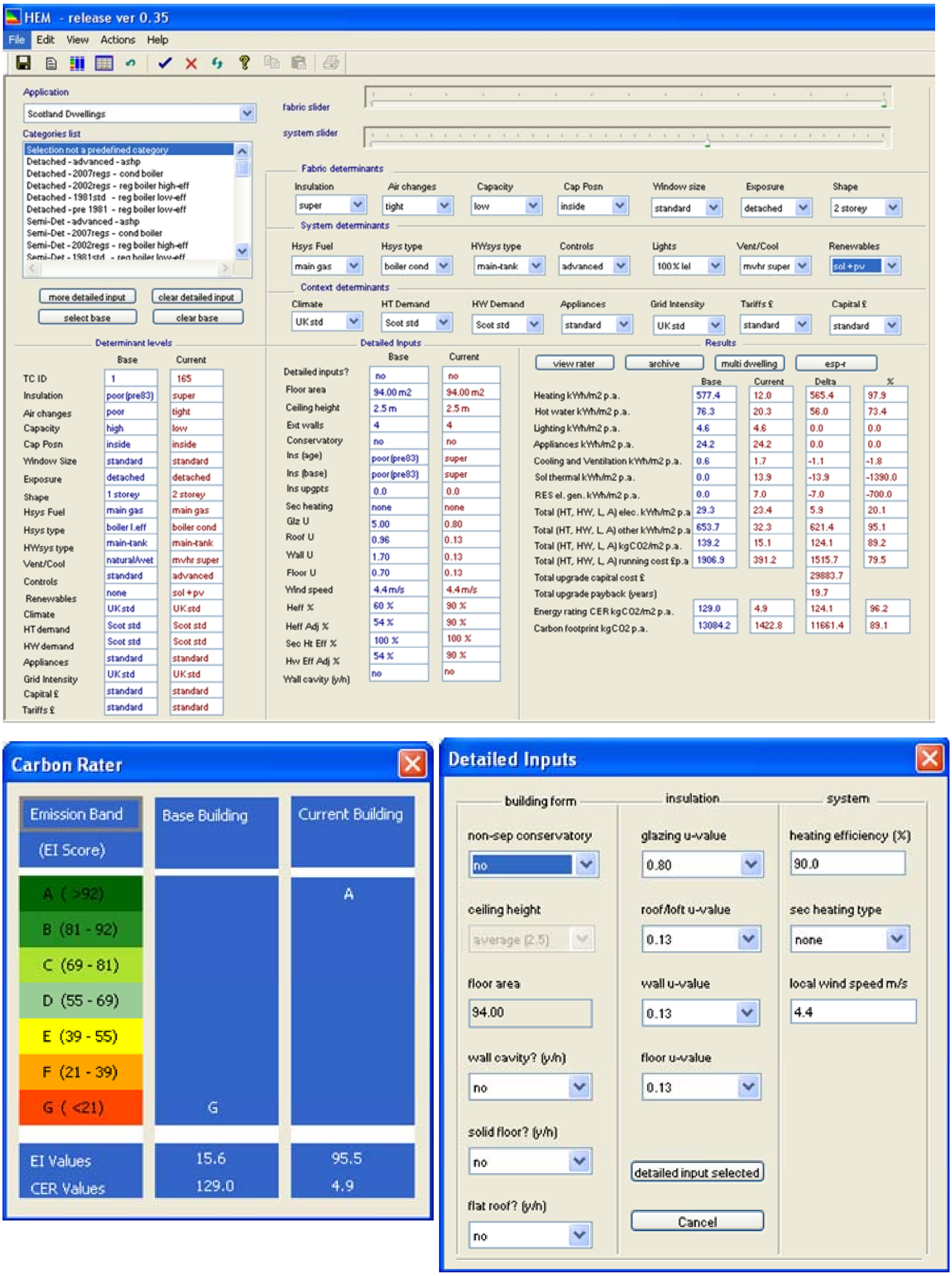
**Part 3: Metrics and Ratings:**

| | existing | | | target | | | saving | | |
|---|---|---|---|---|---|---|---|---|---|
| | kWh | £ | kgCO2 | kWh | £ | kgCO2 | kWh | £ | kgCO$^2$ |
| annual heating<br>annual lighting<br>annual hot water<br>totals | | | | | | | | | |
| SAP (£/m2.yr) | | | | | | | | | |
| DCER (kgCO2/m2.yr) | | | | | | | | | |

**Dwelling Energy Performance (SAP):**

| rating | existing | target |
|---|---|---|
| *A (100 - 120)* | | |
| *B (85 - 99)* | | 90 |
| *C (70 - 84)* | | |
| *D 55 - 69)* | 55 | |
| *E (40 - 54)* | | |
| *F (25 - 39)* | | |
| *G (1 - 24)* | | |

*Fig. 5.2 The software interface of the general implementation*



Application: Scotland Dwellings

Categories list:

- Selection not a predefined category
- Detached - advanced - ashp
- Detached - 2007regs - cond boiler
- Detached - 2002regs - reg boiler high-eff
- Detached - 1981std - reg boiler low-eff
- Detached - pre 1981 - reg boiler low-eff
- Semi-Det - advanced - ashp
- Semi-Det - 2007regs - cond boiler
- Semi-Det - 2002regs - reg boiler high-eff
- Semi-Det - 1981std - reg boiler low-eff

Fabric determinants

Insulation: super
Air changes: tight
Capacity: low
Cap Posn: inside
Window size: standard
Exposure: detached
Shape: 2 storey

System determinants

Hsys Fuel: main gas
Hsys type: boiler cond
HWsys type: main-tank
Controls: advanced
Lights: 100% lel
Vent/Cool: mvhr super
Renewables: sol + pv

Context determinants

Climate: UK std
HT Demand: Scot std
HW Demand: Scot std
Appliances: standard
Grid Intensity: UK std
Tariffs £: standard
Capital £: standard

Determinant levels

| | Base | Current |
|---|---|---|
| TC ID | 1 | 165 |
| Insulation | poor (pre83) | super |
| Air changes | poor | tight |
| Capacity | high | low |
| Cap Posn | inside | inside |
| Window Size | standard | standard |
| Exposure | detached | detached |
| Shape | 1 storey | 2 storey |
| Hsys Fuel | main gas | main gas |
| Hsys type | boiler l.eff | boiler cond |
| HWsys type | main-tank | main-tank |
| Vent/Cool | natural/wet | mvhr super |
| Controls | standard | advanced |
| Renewables | none | sol + pv |
| Climate | UK std | UK std |
| HT demand | Scot std | Scot std |
| HW demand | Scot std | Scot std |
| Appliances | standard | standard |
| Grid Intensity | UK std | UK std |
| Capital £ | standard | standard |
| Tariffs £ | standard | standard |

Detailed Inputs

| | Base | Current |
|---|---|---|
| Detailed inputs? | no | no |
| Floor area | 94.00 m2 | 94.00 m2 |
| Ceiling height | 2.5 m | 2.5 m |
| Ext walls | 4 | 4 |
| Conservatory | no | no |
| Ins (age) | poor (pre83) | super |
| Ins (base) | poor (pre83) | super |
| Ins upgpts | 0.0 | 0.0 |
| Sec heating | none | none |
| Glz U | 5.00 | 0.80 |
| Roof U | 0.96 | 0.13 |
| Wall U | 1.70 | 0.13 |
| Floor U | 0.70 | 0.13 |
| Wind speed | 4.4 m/s | 4.4 m/s |
| Heff % | 60 % | 90 % |
| Heff Adj % | 54 % | 90 % |
| Sec Ht Eff % | 100 % | 100 % |
| Hw Eff Adj % | 54 % | 90 % |
| Wall cavity (y/n) | no | no |

Results

| | Base | Current | Delta | % |
|---|---|---|---|---|
| Heating kWh/m2 p.a. | 577.4 | 12.0 | 565.4 | 97.9 |
| Hot water kWh/m2 p.a. | 76.3 | 20.3 | 56.0 | 73.4 |
| Lighting kWh/m2 p.a. | 4.6 | 4.6 | 0.0 | 0.0 |
| Appliances kWh/m2 p.a. | 24.2 | 24.2 | 0.0 | 0.0 |
| Cooling and Ventilation kWh/m2 p.a. | 0.6 | 1.7 | -1.1 | -1.8 |
| Sol thermal kWh/m2 p.a. | 0.0 | 13.9 | -13.9 | -1390.0 |
| RES el. gen. kWh/m2 p.a. | 0.0 | 7.0 | -7.0 | -700.0 |
| Total (HT, HW, L, A) elec. kWh/m2 p.a | 29.3 | 23.4 | 5.9 | 20.1 |
| Total (HT, HW, L, A) other kWh/m2 p.a | 653.7 | 32.3 | 621.4 | 95.1 |
| Total (HT, HW, L, A) kgCO2/m2 p.a. | 139.2 | 15.1 | 124.1 | 89.2 |
| Total (HT, HW, L, A) running cost £p.a | 1906.9 | 391.2 | 1515.7 | 79.5 |
| Total upgrade capital cost £ | | | 29883.7 | |
| Total upgrade payback (years) | | | 19.7 | |
| Energy rating CER kgCO2/m2 p.a. | 129.0 | 4.9 | 124.1 | 96.2 |
| Carbon footprint kgCO2 p.a. | 13084.2 | 1422.8 | 11661.4 | 89.1 |

**Carbon Rater**

| Emission Band (EI Score) | Base Building | Current Building |
|---|---|---|
| A ( >92) | | A |
| B (81 - 92) | | |
| C (69 - 81) | | |
| D (55 - 69) | | |
| E (39 - 55) | | |
| F (21 - 39) | | |
| G ( <21) | G | |
| EI Values | 15.6 | 95.5 |
| CER Values | 129.0 | 4.9 |

**Detailed Inputs**

building form

non-sep conservatory: no
ceiling height: average (2.5)
floor area: 94.00
wall cavity? (y/n): no
solid floor? (y/n): no
flat roof? (y/n): no

insulation

glazing u-value: 0.80
roof/loft u-value: 0.13
wall u-value: 0.13
floor u-value: 0.13

system

heating efficiency (%): 90.0
sec heating type: none
local wind speed m/s: 4.4

The method in this form supports three levels of data entry for the setting of fabric, system and context determinant parameter levels to facilitate use by a range of users:

- Pre-defined categories of buildings are provided (and can be customised by the user) which automatically select the appropriate determinant parameter levels (‘categories’ list, upper left figure 5.2).
- The parameter levels can be set directly using drop down menus (upper right figure 5.2).
- Where more specific information is available, direct entry of specific parameter values is facilitated through the ‘detailed inputs’ page (bottom right panel, figure 5.2). These more detailed inputs are then used to support interpolation between pre-set discrete levels or to facilitate the correct selection of upgrade option costs etc.

The process to be followed in using this implementation of the method is first to select the input parameters describing the ‘base’ dwelling. Data is then stored for the ‘base’ dwelling and the input data modified for the ‘current’ dwelling to represent the application of upgrades.

The calculation results are displayed for both the ‘base’ and the ‘current’ (with selected upgrade options) together with a comparison. The calculation results (energy, carbon and financial) are displayed by energy use category and aggregated in the ‘results’ panel together with a visual EPC type display.

In addition to the results the selected determinant parameter levels and detailed calculation parameter values are displayed back to the user.

The method allows the user to export the results to a file or to import from a suitably formatted file (which can be easily created from most Local Authority or Social Landlord databases). The file can then be used for analysis or to make graphs.

A training package has been developed to go along with the user manual and to introduce the tool and its facilities to potential users.

## 5.3 An example customised version of the general implementation

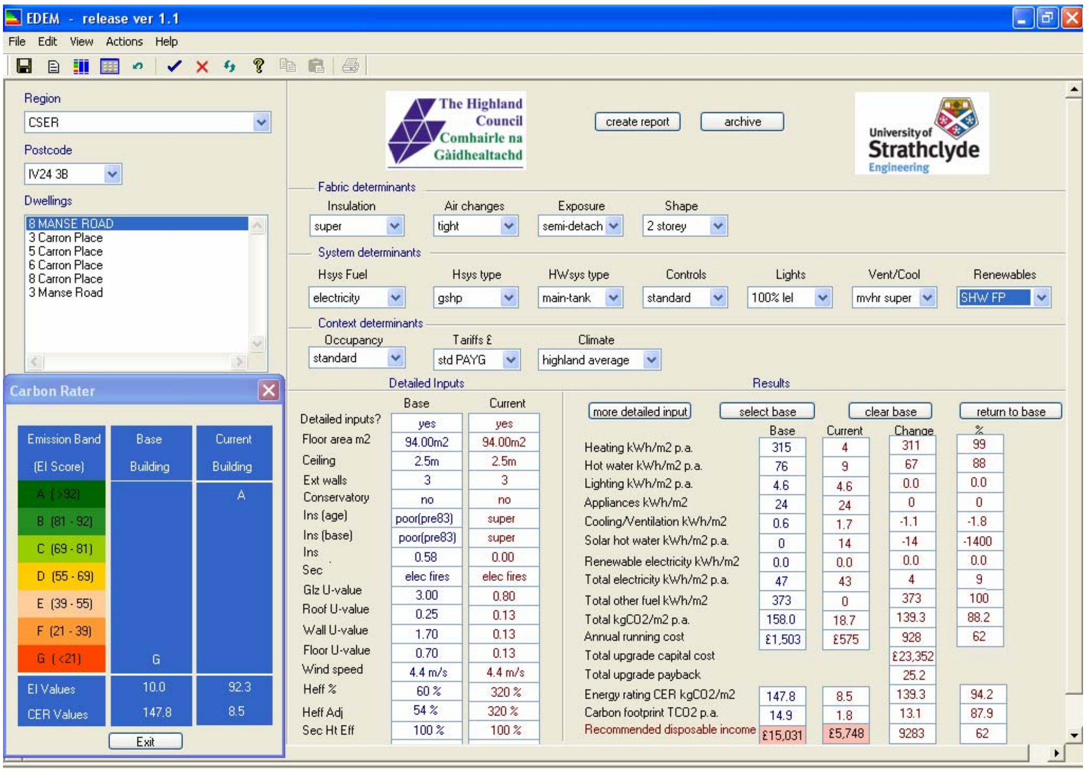
The Local Authority piloted the use of the general version with support from the author and gave feedback on their requirements to inform their customised version.

The pre-defined categories of the general version have been substituted with categories that are aligned with postcode and address with associated determinant parameters set using the authority's pre-existing housing database.

The determinants have been tailored to meet the needs of the council with thermal mass and window size determinants hidden from the user, the contexts (fuel tariffs, occupancy patterns and climates) have also been customised to match the local authority's particular situation. The anticipated running costs are used to give an indication of the disposable income required if fuel poverty is to be avoided.

A screenshot of a version customised for Highland Council is shown in figure 5.3.

*Fig. 5.3 A custom interface for a Local Authority social landlord*



Region: CSER

Postcode: IV24 3B

Dwellings:
- 8 MANSE ROAD
- 3 Carron Place
- 5 Carron Place
- 6 Carron Place
- 8 Carron Place
- 3 Manse Road

Fabric determinants

Insulation: super
Air changes: tight
Exposure: semi-detach
Shape: 2 storey

System determinants

Hsys Fuel: electricity
Hsys type: gshp
HWsys type: main-tank
Controls: standard
Lights: 100% lel
Vent/Cool: mvhr super
Renewables: SHW FP

Context determinants

Occupancy: standard
Tariffs £: std PAYG
Climate: highland average

| Emission Band (EI Score) | Base Building | Current Building |
|---|---|---|
| A (>92) | | A |
| B (81 - 92) | | |
| C (69 - 81) | | |
| D (55 - 69) | | |
| E (39 - 55) | | |
| F (21 - 39) | | |
| G (<21) | G | |
| EI Values | 10.0 | 92.3 |
| CER Values | 147.8 | 8.5 |

Detailed Inputs

| | Base | Current |
|---|---|---|
| Detailed inputs? | yes | yes |
| Floor area m2 | 94.00m2 | 94.00m2 |
| Ceiling | 2.5m | 2.5m |
| Ext walls | 3 | 3 |
| Conservatory | no | no |
| Ins (age) | poor(pre83) | super |
| Ins (base) | poor(pre83) | super |
| Ins | 0.58 | 0.00 |
| Sec | elec fires | elec fires |
| Glz U-value | 3.00 | 0.80 |
| Roof U-value | 0.25 | 0.13 |
| Wall U-value | 1.70 | 0.13 |
| Floor U-value | 0.70 | 0.13 |
| Wind speed | 4.4 m/s | 4.4 m/s |
| Heff % | 60 % | 320 % |
| Heff Adj | 54 % | 320 % |
| Sec Ht Eff | 100 % | 100 % |

Results

| | Base | Current | Change | % |
|---|---|---|---|---|
| Heating kWh/m2 p.a. | 315 | 4 | 311 | 99 |
| Hot water kWh/m2 p.a. | 76 | 9 | 67 | 88 |
| Lighting kWh/m2 p.a. | 4.6 | 4.6 | 0.0 | 0.0 |
| Appliances kWh/m2 | 24 | 24 | 0 | 0 |
| Cooling/Ventilation kWh/m2 | 0.6 | 1.7 | -1.1 | -1.8 |
| Solar hot water kWh/m2 p.a. | 0 | 14 | -14 | -1400 |
| Renewable electricity kWh/m2 | 0.0 | 0.0 | 0.0 | 0.0 |
| Total electricity kWh/m2 p.a. | 47 | 43 | 4 | 9 |
| Total other fuel kWh/m2 | 373 | 0 | 373 | 100 |
| Total kgCO2/m2 p.a. | 158.0 | 18.7 | 139.3 | 88.2 |
| Annual running cost | £1,503 | £575 | 928 | 62 |
| Total upgrade capital cost | | | £23,352 | |
| Total upgrade payback | | | 25.2 | |
| Energy rating CER kgCO2/m2 | 147.8 | 8.5 | 139.3 | 94.2 |
| Carbon footprint TCO2 p.a. | 14.9 | 1.8 | 13.1 | 87.9 |
| Recommended disposable income | £15,031 | £5,748 | 9283 | 62 |

### 5.4 Example test applications of the more general method

Some examples illustrating the range of analysis carried out by the author using the general method illustrated in figure 5.2 are given below. This non exhaustive selection covers application for concept design option appraisal, policy, strategy, and research.

These applications, while demonstrating some useful outputs from this work also are intended to test the hypothesis, inform the discussions, and shape proposals for future steps.

#### 5.4.1 Upgrade option analysis ($CO_2$, EPC rating)

At the request of a Social Landlord the method was tested for application to a range of properties to give insights into potential for reductions in carbon emissions. One example of the analysis is given here.

An electrically heated 1980s top floor flat that had previously been upgraded with cavity wall insulation, double glazing and 200 mm of loft insulation was investigated. A number of improvements were explored starting with fabric (insulation and air-tightness) improvements to 2002 standards, followed by system replacement options: gas-fired condensing combi-boiler; ground source heat pump; community biomass heating; community gas-fired combined heat and power (CHP); and a combination of condensing combi-boiler, solar water heating and a PV panel. From Table 5.1 it can be seen that two upgrade options were able to raise the initial ‘D’ rating to ‘A’: upgraded fabric with either community biomass heating or community gas-fired CHP.

For this application the method tested was able to provide a very quick and easy real time assessment of an appropriate range of upgrade options.

Limitations highlighted in this application related to specific details of the properties that were not able to be differentiated. These included the geometrical representation of different wall types e.g. where front façade is sandstone and close and rear walls are other constructions then it would be interesting to understand the cost and effect of an upgrade to the close walls only etc.

**Table 5.1 $CO_2$ emissions (kg/yr), Environment Index (EI) and Rating Band.**

| Upgrade | Emissions | EI Score | Rating Band |
|---|---|---|---|
| 0. As is | 3391 | 57 | D |
| 1. 2002 fabric | 2778 | 66 | D |
| 2. 1 + gas condensing combi-boiler | 1679 | 81 | B |
| 3. 1 + ground source heat pump | 1515 | 83 | B |
| 4. 1 + community biomass heating | 817 | 93 | A |
| 5. 1 + community gas-fired CHP | 1000 | 98 | A |
| 6. 2 + PV + solar thermal | 1454 | 84 | B |

### 5.4.2 Financial appraisal of upgrade options

The ability to carry out an assessment of the capital costs and associated financial performance was a specific request of a Local Authority and was built into the proposed methods and tested in this case. The Local Authority reviewed the default cost table for upgrade measures in the data tables and a financial analysis of upgrade options was carried out for a range of properties.

Specific measures to be applied to individual dwellings were assessed. For example (Table 5.2) a 3 bedroom mid terraced house built in 1929 with electric storage heating was evaluated with: ground floor insulation, external wall insulation, loft insulation, timber framed double glazing, low energy lighting, efficient A-rated appliances, ground source heat pump, controls and a solar water heater. The calculated cost of this upgrade package was £13,492 and the calculated fuel cost saving was estimated as £1773 per year giving a simple payback of 7.6 years. This upgrade produced a calculated reduction in carbon footprint from 9.3 $TCO_2$ to 1.8 $TCO_2$ per year (a predicted saving of 80%).

**Table 5.2 Analysis of an upgrade package applied to an individual dwelling.**

| | Original | Upgraded | Delta |
|---|---|---|---|
| Heating kWh/m2 pa. | 204 | 25 | 179 |
| Hot water kWh/m2 pa. | 36 | 8 | 28 |
| Lights kWh/m2 pa. | 9 | 5 | 4.5 |
| Appliances kWh/m2 pa. | 25 | 15 | 10 |
| Total KWh/m2 pa. | 274 | 53 | 221 |
| Running cost £ pa. | £2,245 | £472 | £1,773 |
| Total T CO2 pa. | 9.26 | 1.78 | 7.48 |
| EPC Rating | F | B | |
| Capital cost £ | | | £13,492 |
| Simple payback Years. | | | 7.6 |

The method provided a real time feedback on a financial appraisal. The results were deemed to be generally acceptable for use as illustrative examples but the limitations of the assumed geometrical parameters were discussed particularly for flats where the assumption of 3 external walls could lead to a misrepresentation of the costs and benefits of a wall upgrade if the flat had a different configuration with greater or less external wall area or for the case where only some walls could be upgraded..

### 5.4.3 Policy: Impact of grid generation mix and associated grid carbon intensity on the carbon performance of heating technology options (gas fuelled boilers and Combined Heat and Power (CHP) systems, and heat pumps (HP)).

The previous two examples have been for the investigation of upgrade options for individual dwellings. The applications described in this and following two sections (5.4.4 and 5.4.5) are to investigate future scenarios to inform policy.

The first study was to inform the 2050 scenarios proposed by the UK Government Buildings Market Transformation (BMT) project (Carbon Trust, 2008, BMT 2012). The impact of future electricity grid generation mix scenarios and their associated grid carbon intensities on the carbon performance for a range of technologies was assessed. The system options including boilers, Combined Heat and Power (CHP) and Heat Pump (HP) systems were applied to dwellings with different thermal properties.

An assumption used in the scenarios was that while imported electricity from the grid has overall grid carbon emissions associated with it, the electricity generated locally (CHP or renewable generation) preferentially displaces the carbon fuelled portion of grid generation plant and therefore has higher associated emissions savings.

Multiple grid generation mixes were included in the study including a current UK grid (0.54 kgCO2/kWh overall, 0.73 kgCO2/kWh for carbon fuelled portion i.e. carbon fuelled excludes wind, hydro or nuclear), a projected 2020 grid (0.42 kgCO2/kWh overall, 0.57 kgCO2/kWh carbon fuelled portion) and a projected 2050 grid (0.3 kgCO2/kWh overall, 0.4 kgCO2/kWh carbon fuelled portion).

The scenarios included gas fired CHP systems (with various overall and electrical efficiencies) and electric heat pumps (with various efficiencies / co-efficients of performance (COP)).

The method was used to quantify the carbon performance of the various systems applied to dwellings with poor, average or 2002 standards of insulation/infiltration for each grid scenario. Figure 5.4 and 5.5 show results for the 2020 and 2050 grids.

These results show that while CHP options can look most attractive in the current and 2020 grid scenarios, de-carbonizing the grid as in the 2050 scenario reduces the calculated carbon benefits of CHP and other local generation technologies making heat pumps look most attractive.

The ability to generate such analysis very quickly, for multiple systems and grid scenarios in this case, was an apparent strength of the method for this application. The ability to adjust the system performance parameters and the carbon emissions factors in the underpinning data tables was highlighted as a positive feature allowing quick and customisable analysis for a range of future scenarios. The use of the method in this high level policy context did not experience the same issues with geometry highlighted by the earlier test applications.

***Figure 5.4 Annual emissions associated with dwellings of poor, UK average and 2002 regulation fabric and a range of heating systems including gas boilers, CHP (micro (u), community (com) and fuel cell (FC)) and heat pumps (air and ground source) for the 2020 grid. The systems are described by their type, overall efficiency or COP and electrical efficiency if electricity generation i.e. 'FCCHP 85% (45e)' indicates Fuel Cell CHP, 85% overall efficiency with 45% electrical efficiency etc.***

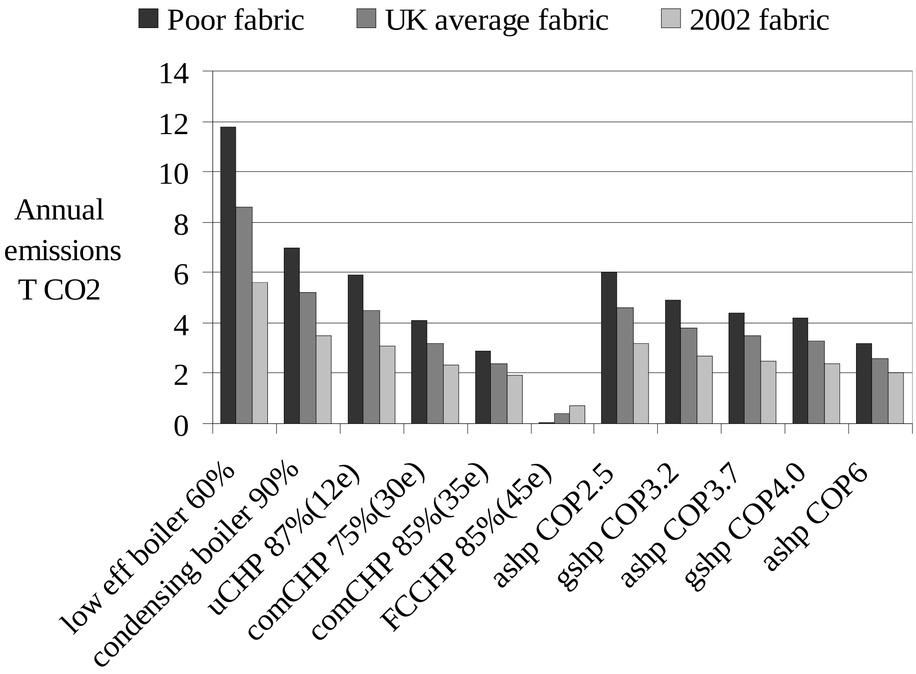
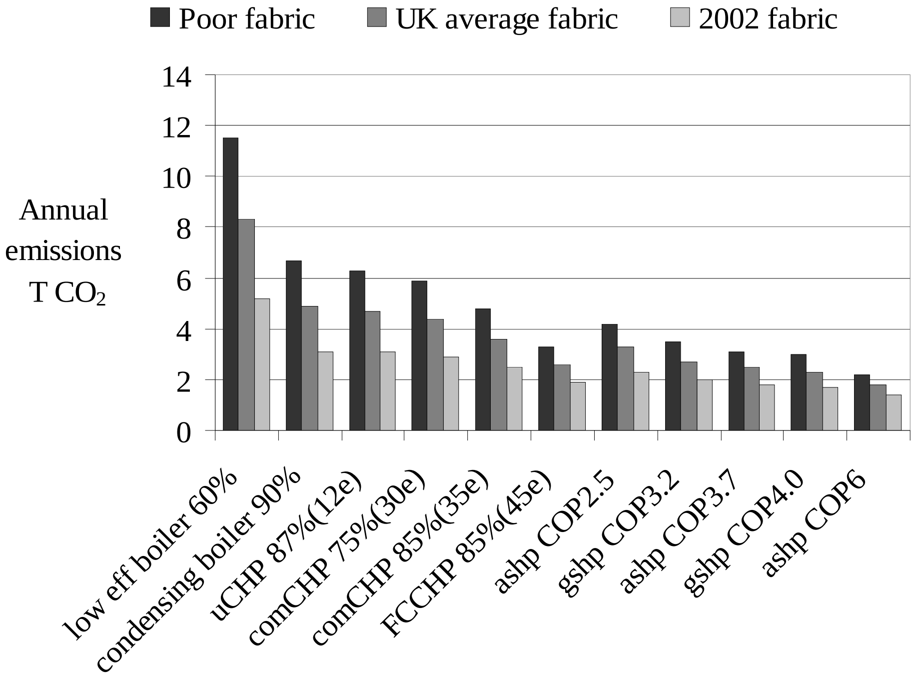


***Figure 5.5 Annual emissions associated with dwellings of poor, UK average and 2002 fabric and a range of heating systems for the 2050 grid.***

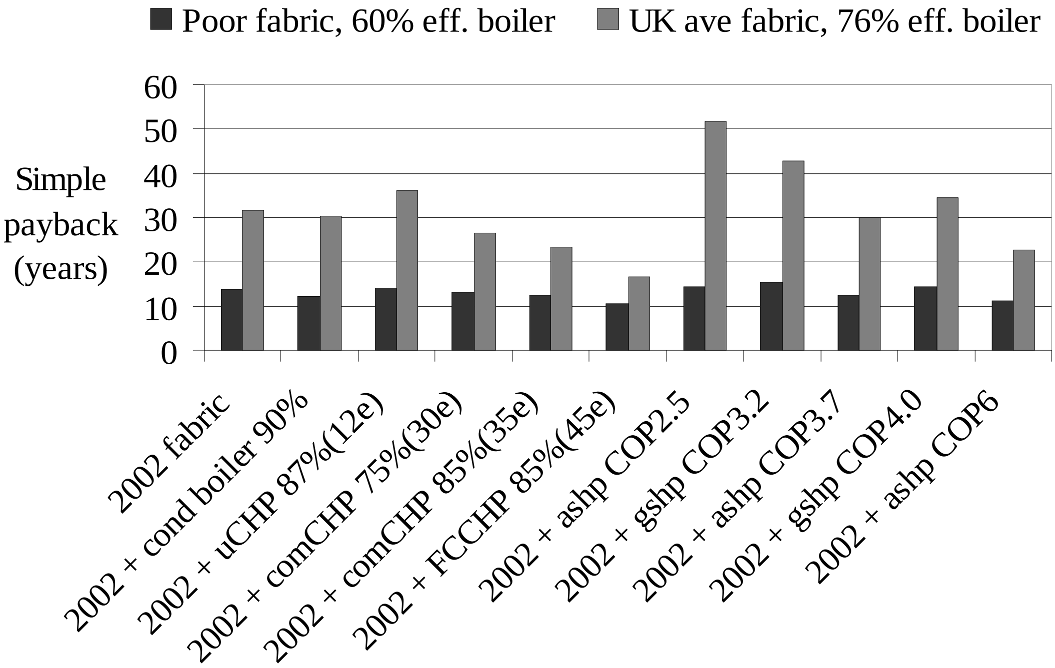


### 5.4.4 Policy: financial appraisal of upgrade options

The method was also test deployed for financial appraisal in support of policy. The BMT 2050 scenarios were analysed for both a medium feed-in tariff (locally generated electricity is exported to the grid at a tariff equal to half the electricity import price) and a high feed-in tariff (locally generated electricity is consumed locally or exported at a tariff equal to the import price). Here the upgrade was viewed as economic if the payback period is less than the expected lifetime (e.g. 20 years for a system, 40 years for fabric, 30 years if combined).

From this analysis (Figure 5.6) upgrades applied to the 'poor' dwelling (poor insulation and infiltration and 60% efficient gas boiler) are economic but the upgrades are marginal or uneconomic for a UK average dwelling except in the highest system efficiency cases. All of the upgrades evaluated included the improvement of the building fabric to '2002' i.e. approximately 2002 building regulation standards.

***Figure 5.6 Simple payback for a range of upgrades applied either to a dwelling with poor insulation/infiltration and 60% efficient gas boiler or a dwelling with UK average insulation/infiltration and 76% efficient gas boiler with a high electricity price paid for the local electricity generation (high feed-in tariff).***



Again the flexibility of the general deployment of the method and ability for the user to vary tariff information in the underlying data tables was highlighted as a positive. As with the previous policy example the geometry specifics of individual properties was not a limitation in this higher level application.

### 5.4.5 Policy: Impact of future buildings on energy demands by fuel

The method was tested for use to assess the potential impact on the electricity grid of different dwelling new build standards or different upgrades applied to existing stock. Various dwelling types were investigated including:

- A UK average dwelling with a 68% efficiency gas boiler and poor control,
- The same dwelling built to the current (2007) building regulations,
- The same dwelling built to meet the 2010 regulations (solar thermal hot water system and a heat pump system COP = 3.2 for space heating COP = 0.7x3.2 for water heating i.e. 30% reduction in COP for water heating c.f. space heating),
- The same dwelling built to meet the EU Passive House standard (including an air source heat pump compact unit (COP = 2.5) for space and water heating),
- The same dwelling built to the Passive House standard with a 2kWp PV panel.

Figures 5.7, 5.8 and 5.9 show: the energy demand by end use; the delivered energy by end use; and delivered energy by fuel type.

While the energy demand of the 2010 regs version is only reduced by the solar thermal contribution to the hot water supply, the delivered energy is significantly reduced through the use of the heat pump technology for space heating and hot water. This reduction in total delivered energy is combined with a fuel switch from gas to electricity. Figure 5.10 shows the delivered energy by fuel type. It is apparent that electricity demand hugely increases with the fuel switching from gas to electricity that may be one possible response to the 2010 regulations.

***Figure 5.7 Energy demand for semi-detached dwelling (kWh/m$^2$ p.a.)***

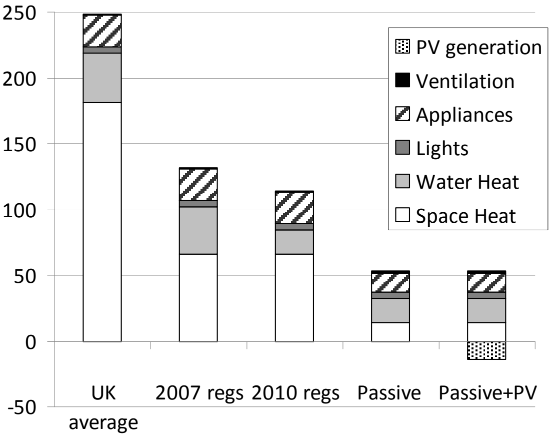


***Figure 5.8 Delivered energy for semi-detached dwelling (kWh/m$^2$ p.a.)***

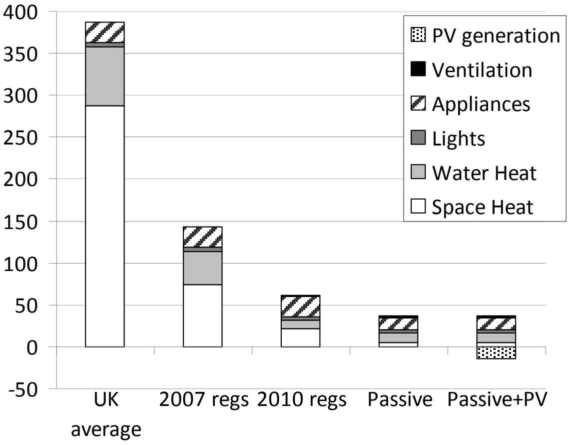
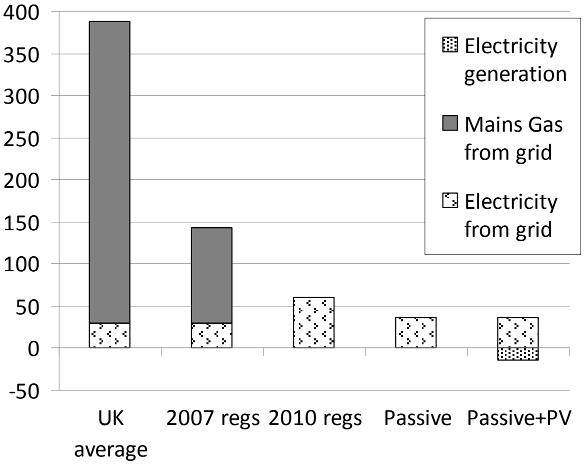


***Figure 5.9 Delivered energy by fuel for semi-detached dwelling (kWh/m$^2$ p.a.)***



The increased deployment of heat pump technology on otherwise unimproved UK average dwellings would have a much greater impact due to the higher demand for space heating in these cases (Figure 5.10,Table 5.3).

The Passive House building fabric, solar thermal water heating and efficient appliances approach act to mitigate the increased demand for electricity but even in combination with the adoption of passive house standards the switch to heat pumps would lead to an increase in electricity demand unless heat pump efficiencies could be significantly improved.

Again the ability of the method to quickly generate results for a range of customisable scenarios was highlighted as a strength. Each scenario could be easily saved as a category and re-used as the basis for further analysis.

***Figure 5.10. Delivered energy by fuel for semi-detached dwelling to different standards (showing upgrade of UK average dwelling with Heat Pump). (kWh/m$^2$ p.a.)***

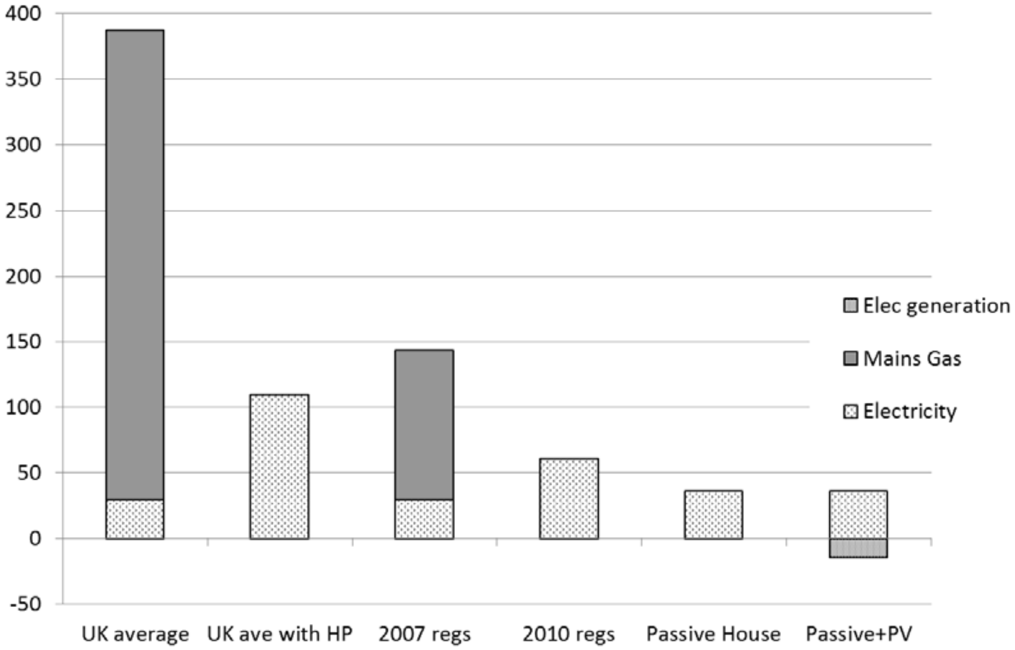


**Table 5.3 Delivered energy by fuel type (kWh/m$^2$ p.a.) for semi-detached dwelling to different standards.**

| | UK average | UK average with Heat Pump | 2007 regs | 2010 regs | Passive House | Passive+PV |
|---|---|---|---|---|---|---|
| Electricity | 29.5 | 109.5 | 29.5 | 60.9 | 36.7 | 36.7 |
| Mains Gas | 358 | 0 | 114 | 0 | 0 | 0 |
| Electricity generation | 0 | 0 | 0 | 0 | 0 | -14 |

### 5.4.6 Carbon neutrality - strategy for a Local Authority housing stock.

While the last three examples have been for application of the method to national strategy, the example in this section is of application to a Local Authority housing stock.

South Ayrshire Council requested that possible upgrade scenarios for their 7000 dwelling housing stock be evaluated as a test application, their objective being to gain insights to potentially inform a high level roadmap for carbon neutrality.

The stock was first decomposed using the Local Authority’s available property data. A range of possible upgrades were identified. Their preferred maximum fabric upgrades were to the Energy Savings Trust’s proposed upgrade to approximately 2002 building regulation standards (EST, 2007) rather than Passive House. The scenarios evaluated were:

0. ‘As is’: Current stock – no upgrades applied.
1. Low cost fabric improvement – where there is a pitched roof or a suspended wooden floor then loft insulation is increased and the suspended timber floors

are insulated. All dwellings to have basic double glazing and be brought up to a tight infiltration standard.

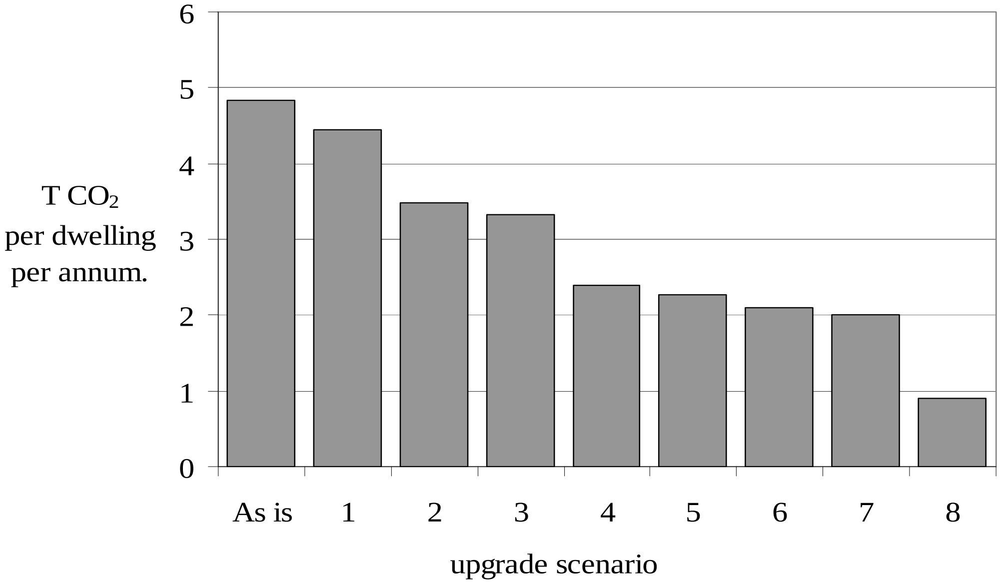
2. Major fabric upgrade – in addition to the low cost measures, flat roofs are upgraded to a U-value of 0.16 W/m$^2$K, cavity wall properties have insulation added to give a U-value of 0.35, solid wall properties are improved to a U-value of 0.6, and windows improved to a U-value of 1.5.
3. 2007 heating systems – gas, electricity and solid fuel heating systems are upgraded to meet the 2007 building regulation standards i.e. a condensing boiler with instantaneous water heating, an air source heat pump with radiators and a wood boiler respectively.
4. Upgrades 1+2+3.
5. Upgrade 4 plus solar hot water heating (delivering 920 kWh/yr useful energy applied to properties with an exposed roof).
6. Upgrade 5 plus local renewable energy generation (650kWh/yr) in the form of either PV (1kWp) or small scale wind turbines at appropriate locations.
7. Upgrade 5 with gas boilers replaced with Stirling engine CHP.
8. Upgrade 5 with heating through individual or community wood boiler systems.

Figure 5.11 shows the impact of each upgrade option on average carbon footprint. These results show the current carbon footprint per dwelling to be 4.9 tonnes of $CO_2$ per year, while future scenarios are presented with emissions below 1 tonne.

Net carbon neutrality was modelled for each case by quantifying the number of large scale wind turbines (similar to those at Whitelees wind farm) that would be required (to be placed on the adjacent Carrick hills). By upgrading the stock from its current condition to that proposed in scenario 8 the required number of turbines to offset emissions was reduced from 17 to 3 (Tuohy et al. 2006).

This application involved pre-processing the Local Authority database into the correct data input format for the method, then establishing categories representing each type of building / systems combination present in the stock, then applying the range of upgrades to each type, and re-compiling the whole stock from the individual records output from each of these operations. The use of spreadsheets to support this operation was not overly complex but it was highlighted that a ‘stock builder’ functionality would enable this kind of operation to be more conveniently supported within the method rather than being an additional spreadsheet function.

***Figure 5.11 Impact of upgrade options on the carbon footprint.***



### 5.5 Observations from test applications of the more general method.

The test applications of the general implementation of the method demonstrated that it was useful for:

- Option appraisal at the concept design stage.
- Scenario analysis to inform policy.
- Strategy analysis e.g. for a Local Authority housing stock.

Limitations highlighted were:

- Specific geometric details for detailed design analysis.
- Supporting spreadsheets required in the analysis of large building stocks.

The overall performance of the method for both the EPC application described in chapter 4 in addition to the more general applications described in chapter 5 is reviewed in the following section. Conclusions are drawn and future developments proposed.

## 5.6 Performance assessment and option appraisal method: discussion and general conclusions.

The starting hypothesis was that: *"A low cost simulation based method can be developed to usefully support real-time performance assessment and option appraisal by a range of users in the context of the EPBD."*

The desired characteristics for the proposed method were defined by decomposing this hypothesis and explained in chapter 2. In the method development (chapter 3) and the test applications (chapters 4 and 5) each of these desired characteristics have been demonstrated to some extent i.e.

1. The method accounts for the parameters required by the EPBD.
2. The method is based on dynamic simulation (DSM performance map).
3. The method has been encapsulated in a single easy to use format that facilitates real-time analysis (more than one format demonstrated).
4. The method does not require dynamic simulation expertise to carry out meaningful analysis.
5. The method supports direct use by building professionals with some limited amount of training.
6. The method supports direct use by non-professionals with some limited amount of training. (e.g. non engineering post graduate students)

Combining the outcomes from the test applications of chapter 4 and 5 the method has been tested and been proved useful in:

- Option appraisal at the concept design stage.
- Scenario analysis to inform policy.
- Strategy analysis e.g. for a Local Authority housing stock.
- Education and training.

The low cost aspect of the method has been demonstrated and can be related to a number of the desired characteristics. The method supports real-time analysis directly by the user instead of requiring the costly engagement of professionals and specialists in a lengthy iterative process.

The questionnaire based EPC test application gave insights into a potentially very low cost mechanism for energy rating as required by the EPBD that could also serve as a vehicle for the education of many individuals in energy performance.

Limitations highlighted through the test applications were:

- Requirement for a supporting education and quality assurance infrastructure if used for EPC generation based on questionnaire.
- Supporting spreadsheets required in in the analysis of large building stocks.
- Specific geometric details not being included limited the usefulness of the method for assessing specific upgrades in detail as part of either the EPC process or in detailed design.

Solutions to allow these limitations to be addressed in future have been proposed and are discussed in the next section.

Development of the method to include more dynamic simulation would appear to be an opportunity. The dynamic thermal modelling for space heating demand prediction used in the implementation here facilitates more physically explicit and realistic analysis compared to the simplified monthly or annual methods. However there are many other potential benefits of dynamic simulation that remain to be exploited. How this can exploitation can be achieved is discussed in the next section.

An overall conclusion is that the original hypothesis has been proved correct i.e. that a low cost simulation based method can be developed to usefully support real-time performance assessment and option appraisal by a range of users in the context of the EPBD. The general implementation of the method developed in this thesis has been usefully deployed and is made freely available for on-going use.

A secondary and potentially more important conclusion is that many useful insights have been generated through this research that can inform future developments and future research.

## 5.7 Addressing limitations, and future directions.

The test applications highlighted the potential for some enhancements to the proposed method, in particular:

- An education and quality assurance infrastructure for a robust questionnaire based application.
- A functionality to support stock modelling without the use of separate spreadsheets.
- An extension of the method to allow more detailed description of individual dwellings.

The educational infrastructure highlighted as a requirement for robust use of the questionnaire method has already been addressed to some extent through the provision of the technical manual (appendix B) and associated training and post-graduate modules developed around the more general method. Providing a publicly available education infrastructure for the questionnaire based method would be a useful extension of this work in future. One possibility would be to provide examples and on line examinations for accreditation of individuals to assist in quality assurance.

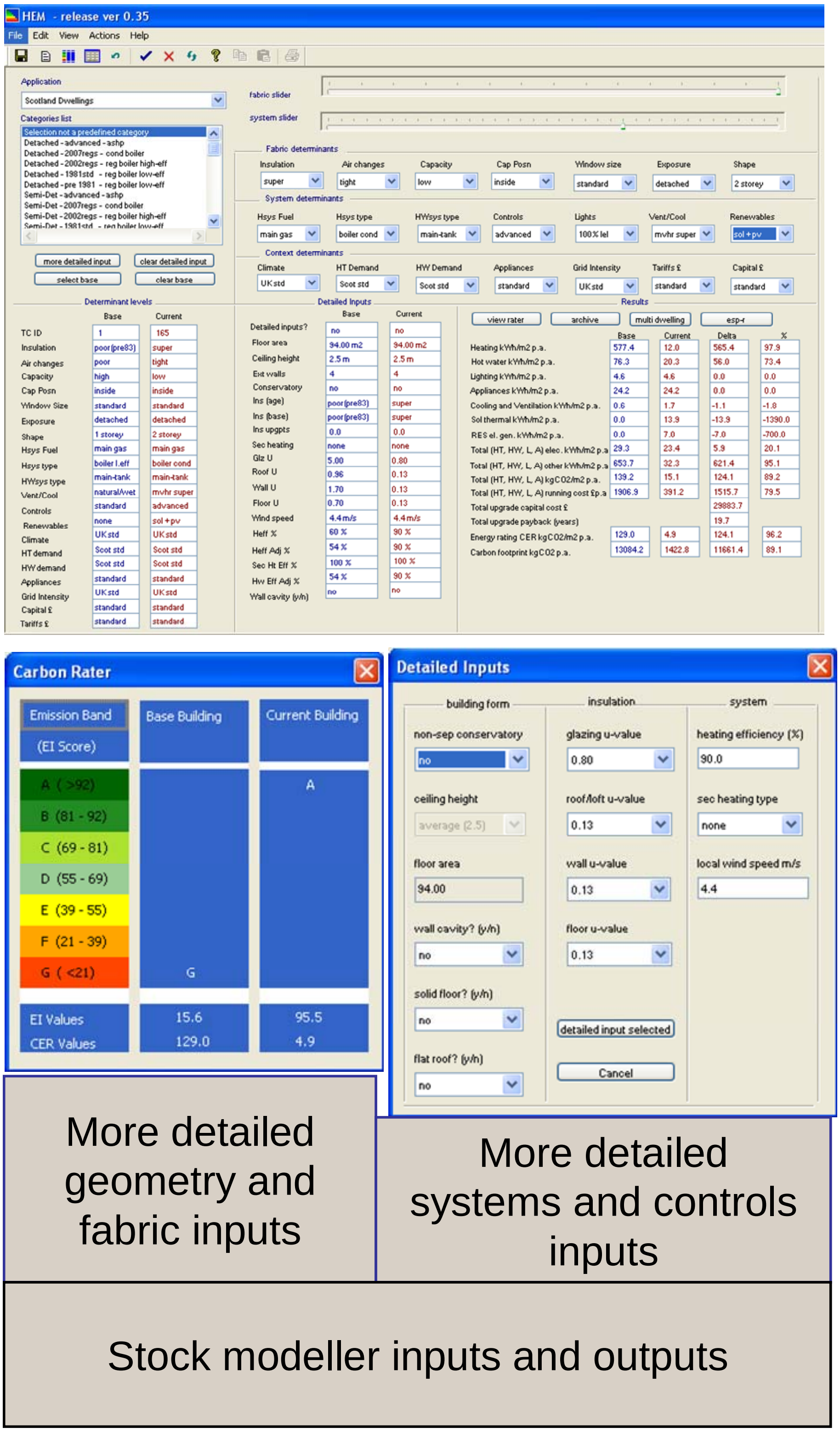
The provision of functionality to input multiple building types and their quantities to represent a building stock, and give cumulative results for upgrades across the stock could in future be relatively simply realised.

The potential extension of the proposed method to capture more detailed description of individual dwellings is more complex and is the subject of the following sections.

First the more detailed representation of geometrical and building fabric performance parameters is considered. Then other areas such as system type and controls are considered. In both cases further development of the use of dynamic simulation is proposed.

Figure 5.12 gives a mock up to illustrate how the proposed extensions of the method could be integrated as additional pop-outs in the tool interface.

***Figure 5.12. potential future development of tool incorporating more detailed inputs for geometry, fabric, systems, controls plus a stock modelling facility.***



Application: Scotland Dwellings

Categories list:
- Selection not a predefined category
- Detached - advanced - ashp
- Detached - 2007regs - cond boiler
- Detached - 2002regs - reg boiler high-eff
- Detached - 1981std - reg boiler low-eff
- Detached - pre 1981 - reg boiler low-eff
- Semi-Det - advanced - ashp
- Semi-Det - 2007regs - cond boiler
- Semi-Det - 2002regs - reg boiler high-eff
- Semi-Det - 1981std - reg boiler low-eff

Fabric determinants

| Insulation | Air changes | Capacity | Cap Posn | Window size | Exposure | Shape |
|---|---|---|---|---|---|---|
| super | tight | low | inside | standard | detached | 2 storey |

System determinants

| Hsys Fuel | Hsys type | HWsys type | Controls | Lights | Vent/Cool | Renewables |
|---|---|---|---|---|---|---|
| main gas | boiler cond | main-tank | advanced | 100% lel | mvhr super | sol + pv |

Context determinants

| Climate | HT Demand | HW Demand | Appliances | Grid Intensity | Tariffs £ | Capital £ |
|---|---|---|---|---|---|---|
| UK std | Scot std | Scot std | standard | UK std | standard | standard |

Determinant levels

| | Base | Current |
|---|---|---|
| TC ID | 1 | 165 |
| Insulation | poor (pre83) | super |
| Air changes | poor | tight |
| Capacity | high | low |
| Cap Posn | inside | inside |
| Window Size | standard | standard |
| Exposure | detached | detached |
| Shape | 1 storey | 2 storey |
| Hsys Fuel | main gas | main gas |
| Hsys type | boiler l.eff | boiler cond |
| HWsys type | main-tank | main-tank |
| Vent/Cool | natural/wet | mvhr super |
| Controls | standard | advanced |
| Renewables | none | sol + pv |
| Climate | UK std | UK std |
| HT demand | Scot std | Scot std |
| HW demand | Scot std | Scot std |
| Appliances | standard | standard |
| Grid Intensity | UK std | UK std |
| Capital £ | standard | standard |
| Tariffs £ | standard | standard |

Detailed Inputs

| | Base | Current |
|---|---|---|
| Detailed inputs? | no | no |
| Floor area | 94.00 m2 | 94.00 m2 |
| Ceiling height | 2.5 m | 2.5 m |
| Ext walls | 4 | 4 |
| Conservatory | no | no |
| Ins (age) | poor (pre83) | super |
| Ins (base) | poor (pre83) | super |
| Ins upgpts | 0.0 | 0.0 |
| Sec heating | none | none |
| Glz U | 5.00 | 0.80 |
| Roof U | 0.96 | 0.13 |
| Wall U | 1.70 | 0.13 |
| Floor U | 0.70 | 0.13 |
| Wind speed | 4.4 m/s | 4.4 m/s |
| Heff % | 60 % | 90 % |
| Heff Adj % | 54 % | 90 % |
| Sec Ht Eff % | 100 % | 100 % |
| Hw Eff Adj % | 54 % | 90 % |
| Wall cavity (y/n) | no | no |

Results

| | Base | Current | Delta | % |
|---|---|---|---|---|
| Heating kWh/m2 p.a. | 577.4 | 12.0 | 565.4 | 97.9 |
| Hot water kWh/m2 p.a. | 76.3 | 20.3 | 56.0 | 73.4 |
| Lighting kWh/m2 p.a. | 4.6 | 4.6 | 0.0 | 0.0 |
| Appliances kWh/m2 p.a. | 24.2 | 24.2 | 0.0 | 0.0 |
| Cooling and Ventilation kWh/m2 p.a. | 0.6 | 1.7 | -1.1 | -1.8 |
| Sol thermal kWh/m2 p.a. | 0.0 | 13.9 | -13.9 | -1390.0 |
| RES el. gen. kWh/m2 p.a. | 0.0 | 7.0 | -7.0 | -700.0 |
| Total (HT, HW, L, A) elec. kWh/m2 p.a | 29.3 | 23.4 | 5.9 | 20.1 |
| Total (HT, HW, L, A) other kWh/m2 p.a | 653.7 | 32.3 | 621.4 | 95.1 |
| Total (HT, HW, L, A) kgCO2/m2 p.a. | 139.2 | 15.1 | 124.1 | 89.2 |
| Total (HT, HW, L, A) running cost £p.a | 1906.9 | 391.2 | 1515.7 | 79.5 |
| Total upgrade capital cost £ | | | 29883.7 | |
| Total upgrade payback (years) | | | 19.7 | |
| Energy rating CER kgCO2/m2 p.a. | 129.0 | 4.9 | 124.1 | 96.2 |
| Carbon footprint kgCO2 p.a. | 13084.2 | 1422.8 | 11661.4 | 89.1 |

Carbon Rater

| Emission Band (EI Score) | Base Building | Current Building |
|---|---|---|
| A ( >92) | | A |
| B (81 - 92) | | |
| C (69 - 81) | | |
| D (55 - 69) | | |
| E (39 - 55) | | |
| F (21 - 39) | | |
| G ( <21) | G | |
| EI Values | 15.6 | 95.5 |
| CER Values | 129.0 | 4.9 |

Detailed Inputs

building form
- non-sep conservatory: no
- ceiling height: average (2.5)
- floor area: 94.00
- wall cavity? (y/n): no
- solid floor? (y/n): no
- flat roof? (y/n): no

insulation
- glazing u-value: 0.80
- roof/loft u-value: 0.13
- wall u-value: 0.13
- floor u-value: 0.13

system
- heating efficiency (%): 90.0
- sec heating type: none
- local wind speed m/s: 4.4

### 5.7.1 Dealing with geometry

The representation of geometry has been a significant point raised by the pilot applications; the approach taken here does not deal as explicitly with geometrical factors as the simple UK regulatory calculations. This lack of detailed geometrical inputs could for example, in some specific circumstances, lead to: overestimation of benefit of improvement measures; or an inability to represent more complex situations (e.g. different wall types, attic rooms, building shape).

In the definition of the method the geometry and fabric performance determinant parameters were incorporated in up to 4 ways:

- Fixed across the simulation model array e.g. orientation.
- Determinants varied across the simulation array e.g. insulation category.
- Applied through post simulation interpolation e.g. insulation element.
- Applied through post simulation scaling e.g. floor area.

It would be possible to include more determinant parameters directly into the simulation array (DSM performance map) in its current form as a full factorial matrix but at the cost of increasing the number of required DSM model replicates. Figure 5.13(a) summarises the approach taken in the proposed method tested in this thesis. Figure 5.13(b) illustrates a possible approach which incorporates all of the geometrical and thermal parameters at multi-level and supports interpolation to allow specific values to be represented.

The exposure parameter could be represented by 12 levels where for each of the 4 levels of roof/floor exposure (i.e. both exposed, roof only, floor only, neither) 3 levels of wall exposure would be represented (e.g. 4, 3, or 2 walls exposed). Then the actual wall exposure could be input as a length of heat loss perimeter (as in the UK Governments simple RDSAP method) and used to interpolate between the three set levels of wall exposure to return the result. If alternative wall types exist in the dwelling (as in the Victorian flat example given earlier) then separate lengths could be input.

Similar approaches could be taken for the floor area and the ceiling height, with a range of levels are set as model determinants and the actual value used to interpolate and return the correct value.

The floor plan effect on wall heat loss would already be covered to some degree by the representation of the length of heat loss perimeter in exposure; however the additional thermal bridging of a more complex shape could be represented by a model variant with larger thermal bridge losses.

Variation in solar gains could be represented by a range of determinant parameters plus interpolation to allow specific circumstances, three parameters: orientation (N/S, E/W, all 4); size (standard, small, large); and shading (none, heavy, average) could be used with interpolation based on actual input values.

Secondary building elements such as extensions, conservatories (if they are deemed to be ‘attached’ rather than stand-alone) and attic rooms could be represented by combining results for the main dwelling with the secondary element based on the specifics of geometry and fabric properties of each.

The implication of including all parameters explicitly in this way in a full factorial array is that the model array used to create the DSM performance map is now made up of >780,000 replicates (Figure 5.13(b)) which will place a logistical burden on the tool developers in organising and simulating for this large number of cases.

Opportunities exist for reducing this burden e.g. the parameters relating to solar gains (window orientations and shading) could potentially be combined into a single model parameter ‘solar gains’ etc. but this approach would still leave around 120,000 replicates.

A more sophisticated statistical approach rather than a full factorial array would be to use a blocked partial factorial or Response Surface Model (RSM) design (Wu and Hamada 2009, Montgomery 1999) for the simulation array to reduce the simulation burden without significant loss of data integrity. This would be the recommendation of the author for future implementations where this level of detail is a requirement.

*Figure 5.13. Fabric and geometry determinant parameter options*

### *(a) current implementation*

| | fixed in the simulation models | model determinant | post simulation interpolation | post simulation scaling |
|---|---|---|---|---|
| **fabric determinants** | | | | |
| insulation | | 5 | Y | |
| air changes | | 3 | Y | |
| thermal mass | | 2 | | |
| **geometry determinants** | | | | |
| exposure | | 6 | | |
| shape (storeys) | | 2 | | |
| floor area | Y | | | Y |
| ceiling height | Y | | | Y |
| shape (floorplan) | Y | | | |
| window orientation | Y | | | |
| window size | Y | | | |
| window shading | Y | | | |
| **DSM map replicates** | | 360 | | |

### *(b) one example of a possible future implementation*

| | fixed in the simulation models | model determinant | post simulation interpolation | post simulation scaling |
|---|---|---|---|---|
| **fabric determinants** | | | | |
| insulation | | 5 | Y | |
| air changes | | 3 | Y | |
| thermal mass | | 3 | Y | |
| **geometry determinants** | | | | |
| exposure | | 12 | Y | |
| shape (storeys) | | 3 | Y | |
| floor area | | 3 | Y | |
| ceiling height | | 3 | Y | |
| shape (floorplan) | | 2 | Y | |
| window orientation | | 3 | Y | |
| window size | | 3 | Y | |
| window shading | | 3 | Y | |
| **DSM map replicates** | | 787,320 | | |

### 5.7.2 Systems and controls – more detailed representation

In the pilot applications the thermal dynamic simulation results have been combined with simple calculation models representing systems and controls (Appendix B). These simple calculation models are limited in their representation of system performance often being based on limited monitoring and curve fitting.

Simulation provides the opportunity for prediction of system and control performance based on more detailed physical models. These predictions are already being used as an alternative for extensive field trials. Dynamic simulation models have been established representing a range of UK dwellings, systems and controls as a test bed for evaluating new controls and providing quantification of impacts for use in regulatory calculation methods (Cockroft, Samuel and Tuohy, 2007).

An approach to incorporate dynamic simulation results for plant and controls within the method would be to apply detailed system and plant modelling in a representative subset of the DSM performance map and extract the performance of the systems and control combination as a function of the thermal and context determinant parameters, this function would then be applied rather than the more generalised assumption of system and control performance currently used in the simple calculation models.

### 5.8 Concluding remarks.

The need for a method to support performance assessment and option appraisal to inform a range of decision makers in the context of the EPBD was identified.

A gap in previous literature in this area was highlighted. To address this gap the hypothesis was put forward that *"a low cost simulation based method can be developed to support real-time performance assessment and option appraisal by a range of users in the context of the EPBD"*.

A method was then proposed, developed and tested that addressed the hypothesis and the gaps in previous work.

The method was tested for a range of applications providing templates to be followed and identifying any limitations in scope of the proposed method.

A method for performance assessment and option upgrade appraisal based on simple questionnaire input data was developed and tested.

A more general application of the method was tested for a range of policy, strategy and individual building applications.

The hypothesis has been tested through these applications and has been found to be correct but with some limitations.

The limitations in scope identified in the test applications have been discussed and further extension of the method to address these limitations in future has been proposed.

Overall the method proposed here has proved useful in a wide range of applications, where limitations of the implementation of the method have been highlighted for some applications how these limitations could be addressed in future versions has been proposed.

### 5.7 References

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# PART B:

# Translating design intent into performance in practice

# Chapter 6. A Modular Control Mapping and FMEA based method to address gaps between intended and actual performance for low carbon buildings.

*The overall aim of this thesis is to contribute strategies, methods and insights that assist in the realisation of low carbon buildings in practice.*

*Two aspects of process were identified as problematic in chapter 2. The first was the assessment of design options. The second was the translation of design intent into performance in practice.*

*The thesis so far focussed on the first of these problem areas. Chapters 3, 4 and 5 presented research into a method to support assessment of options for policy, strategy and early design stage. Here the focus shifts to the second problem area, the translation of design intent into performance in practice.*

*Evidence of gaps between intended and actual performance were reviewed and the implementation of low carbon systems and controls identified as a particular problem.*

*The review highlighted that the Building Information Modelling (BIM) initiative had identified that processes from other sectors were worthy of consideration. Processes identified by the author as having potential were: (i) A modular design approach, and (ii) Failure Mode Effects Analysis (FMEA).*

*The hypothesis was advanced that a Modular Control Mapping and FMEA method could usefully address the gaps between intended and actual performance.*

*In this chapter such a method is proposed and tested through application to a low energy office.*

*In chapter 7 the method is applied to two low carbon domestic buildings, and then overall conclusions made.*

## 6.1 Introduction

The gap between intended and actual performance of buildings and in particular the performance of low carbon systems and controls has been highlighted in chapter 2 as a barrier to achieving intended low carbon performance in practice.

The current industry initiatives, if they address this issue, tend to do this through a requirement for expert inputs into the design process through staged reviews or the assignment of consultants such as ‘Commissioning authorities’ etc.

Comparison with Building Information Modelling (BIM) benchmark industries such as automotive, electronics, and aerospace suggests the potential for a different approach, with expert knowledge being augmented by, and incorporated within, a more formal modular design and quality systems approach. The design process in these industries is largely based on modular design methods with re-use of well understood, well documented modules. Risks of failure tend to be pro-actively managed through processes such as Failure Mode Effect Analysis (FMEA) with potential fail modes being managed so that they do not occur, or at worst case are detected and their impact minimised if their occurrence cannot be prevented.

In this chapter the modular design approach and FMEA process of BIM benchmark industries are leveraged in the formulation of a Modular Control Mapping and FMEA process aimed at addressing the systems and controls disconnects in the current buildings industry.

The objectives set for the method were:

- To support understanding of systems and controls and their associated failure modes.

- To provide a vehicle for common understanding and analysis between designers, controls and systems engineers, building operators and occupants.

- To provide a process for best practice to be incorporated, correct function verified, incorrect function detected, and support optimisations and enhancements.

- To support management of risks that captures expert knowledge of potential failure modes, their impacts, how they are detected, how they are avoided.

- To be integrated into the design process.
- To be in synergy with current buildings industry initiatives such as Building Information Modelling (BIM) and Soft Landings.

- To provide a vehicle for essential feedback (between and within projects) and feed forward (early to later stages within a project etc.) of information to enable intended low carbon performance to be achieved in practice.

## 6.2 The proposed Modular Control Mapping and FMEA method

Given the evidence that a major source of disconnects is in building systems and controls performance, the method proposed has this as its focus. Extending the scope of the method to cover other aspects of performance is possible and discussed in chapter 7 as future work.

### 6.2.1 High level concept for the proposed method.

To address the objectives it was proposed that key elements were to provide a vehicle for comprehending the systems and controls integration, and also a vehicle for comprehending the potential fail modes associated with that particular systems and control integration and how these fail modes can be avoided. It was proposed that these key elements associated with specific system and control integrations are captured in a library to facilitate a modular approach to design. It was envisioned that these elements (vehicle for comprehending systems and controls integration, vehicle for comprehending potential fail modes) would support and augment the Soft Landings expert review process throughout the design flow at concept, detailed design, implementation, commissioning, handover, and post occupancy stages. It was also envisaged that the BIM initiative would provide a data structure to facilitate the implementation of the proposed modular design approach.

The vehicle for comprehending system and controls integration developed in this work is labelled as the ‘Control Mapping’ method. The vehicle for comprehending failure modes is labelled as the ‘Fail Mode Effect Analysis (FMEA)’ method. The overall combination of these two within the modular design process is labelled as the ‘Modular Control Mapping and FMEA method’ which is the focus of this and he following chapter.

The high level concept for the proposed Modular Control Mapping and FMEA method is illustrated in figure 6.1. It is proposed that a modular design approach is supported by a design library implemented in BIM. When a module (i.e. a specific building type, system and control integration combination) is selected then documents associated with that module are available to facilitate the design and implementation process.

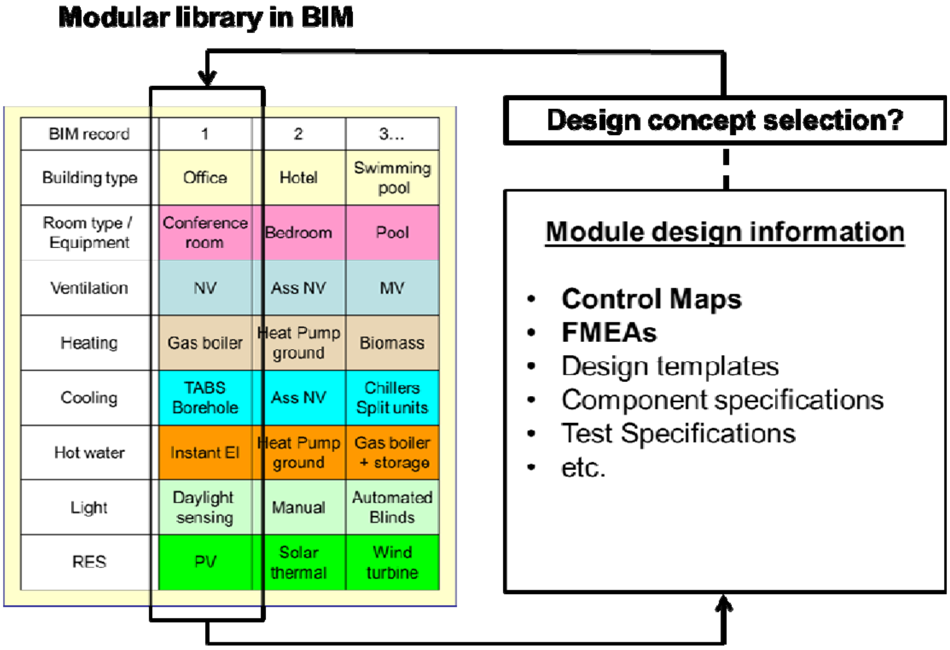
The two elements of documentation which form the focus of this work are (i) system and control map documentation for each module, and (ii) a set of FMEA documentation for each module.

The BIM library would also contain other data associated with that module such as design drawing templates, component specifications, best practice guidance documentation etc.

Where a new integration is proposed or one that doesn’t already exist in the modular design library then the control mapping and FMEA approach is applied as a method to capture the required information to create these documents. This can be achieved through expert reviews that capture relevant knowledge from previous projects or constructed based on best judgement if no precedent exists.

Each time a module and its associated control mapping and FMEA are selected and re-used the content will be reviewed through the various stages of that project and any new knowledge captured and the database updated with this new knowledge so it becomes available for future use.

**Figure 6.1 High level Modular Control Mapping and FMEA concept**



| BIM record | 1 | 2 | 3... |
|---|---|---|---|
| Building type | Office | Hotel | Swimming pool |
| Room type / Equipment | Conference room | Bedroom | Pool |
| Ventilation | NV | Ass NV | MV |
| Heating | Gas boiler | Heat Pump ground | Biomass |
| Cooling | TABS Borehole | Ass NV | Chillers Split units |
| Hot water | Instant El | Heat Pump ground | Gas boiler + storage |
| Light | Daylight sensing | Manual | Automated Blinds |
| RES | PV | Solar thermal | Wind turbine |

Module design information

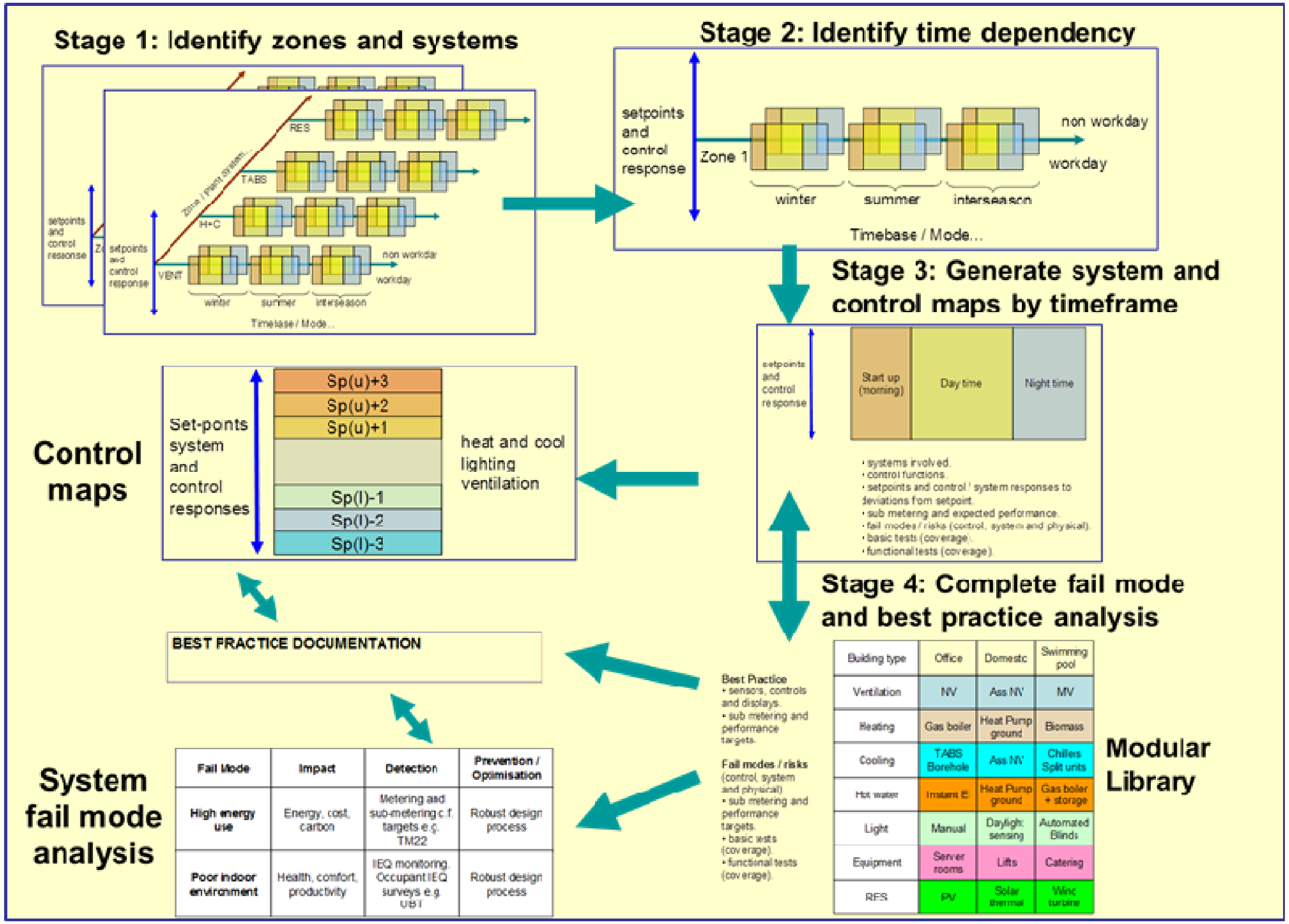
- **Control Maps**
- **FMEAs**
- Design templates
- Component specifications
- Test Specifications
- etc.

The concept and the application of the proposed Modular Control Mapping and FMEA method are described in more detail in the following sections. Then the method is tested by deployment to a low energy office (this chapter) and two domestic buildings intended to be low carbon (chapter 7) before some conclusions are made.

### 6.2.2 A template for the application of the proposed method.

A four stage approach for application of the proposed method is described here. Figure 6.2 gives a high level overview of the application process; the details of each stage are then explained in the following section.

*Figure 6.2. Overview of the Modular Controls Mapping and FMEA method.*



- systems involved.
- control functions.
- setpoints and control / system responses to deviations from setpoint.
- sub metering and expected performance.
- fail modes / risks (control, system and physical).
- basic tests (coverage).
- functional tests (coverage).

**Best Practice**
- sensors, controls and displays.
- sub metering and performance targets.

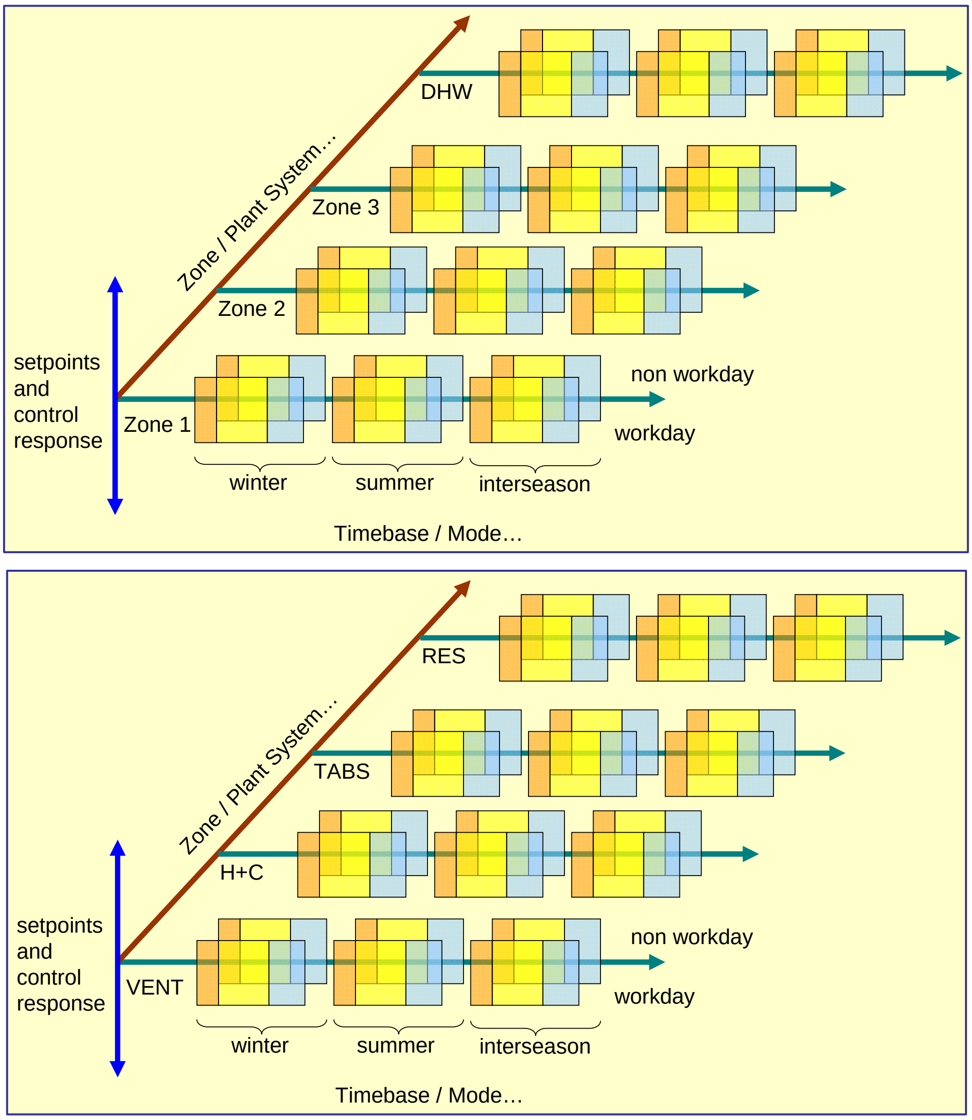
**Fail modes / risks**
(control, system and physical).
- sub metering and performance targets.
- basic tests (coverage).
- functional tests (coverage).

| Building type | Office | Domestic | Swimming pool |
|---|---|---|---|
| Ventilation | NV | Ass NV | MV |
| Heating | Gas boiler | Heat Pump ground | Biomass |
| Cooling | TABS Borehole | Ass NV | Chillers Split units |
| Hot water | Instant E | Heat Pump ground | Gas boiler + storage |
| Light | Manual | Daylight sensing | Automated Blinds |
| Equipment | Server rooms | Lifts | Catering |
| RES | PV | Solar thermal | Wind turbine |

| Fail Mode | Impact | Detection | Prevention / Optimisation |
|---|---|---|---|
| **High energy use** | Energy, cost, carbon | Metering and sub-metering c.f. targets e.g. TM22 | Robust design process |
| **Poor indoor environment** | Health, comfort, productivity | IEQ monitoring. Occupant IEQ surveys e.g. UBT | Robust design process |

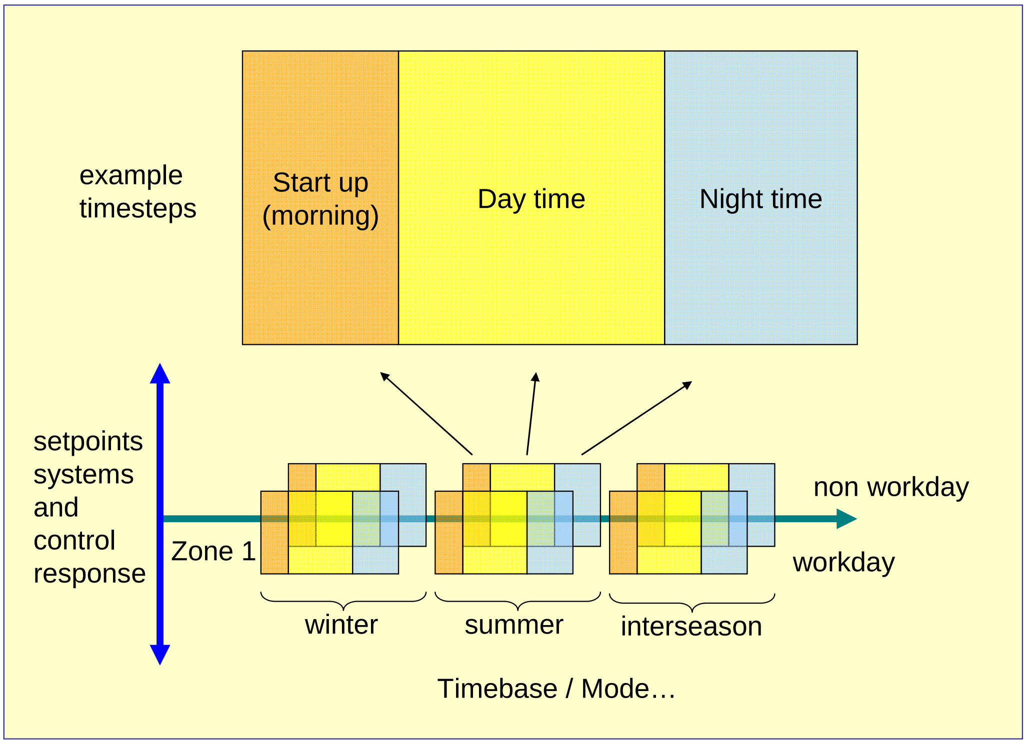
Stage 1 is to identify the building components, both zones and systems. Building zones are defined by physical location and activity e.g. 1st floor office, ground floor seminar room east etc. The plant systems are then the components of plant that service those zones e.g. heating, cooling, ventilation, hot water, renewable generation etc. (figure 6.3).

***Figure 6.3. Mapping of main components (zones and building systems), example shown is for a 3 zone building with hot water (DHW), space heating and cooling (H+C), thermally activated building systems (TABS) (e.g. thermal mass and borehole night cooling), and renewable energy generation (RES).***



Stage 2 is to determine the time dependency for mode of operation of that component (time of day, type of day, seasonal, operational mode etc.) (figure 6.4).

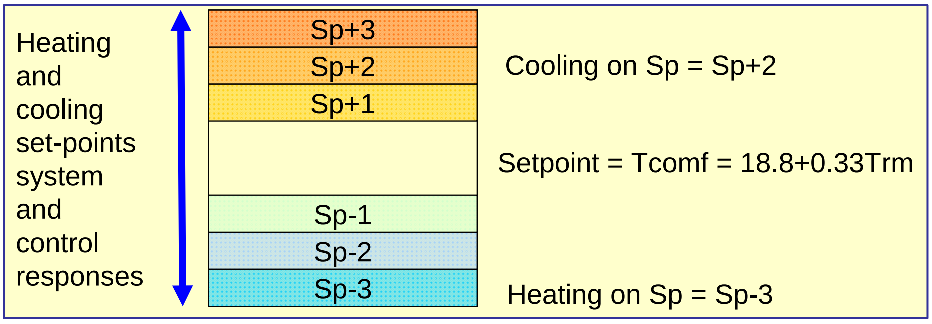
***Figure 6.4. Time dependency / operational mode maps.***



Stage 3 is to create system and control maps for each individual timeframe (e.g. zone 1, summer, workday, occupied period). For each timeframe the systems involved, controls, set-points and responses to deviations from the set-points are documented in a simple graphical form labelled here as a ‘Control Map’.

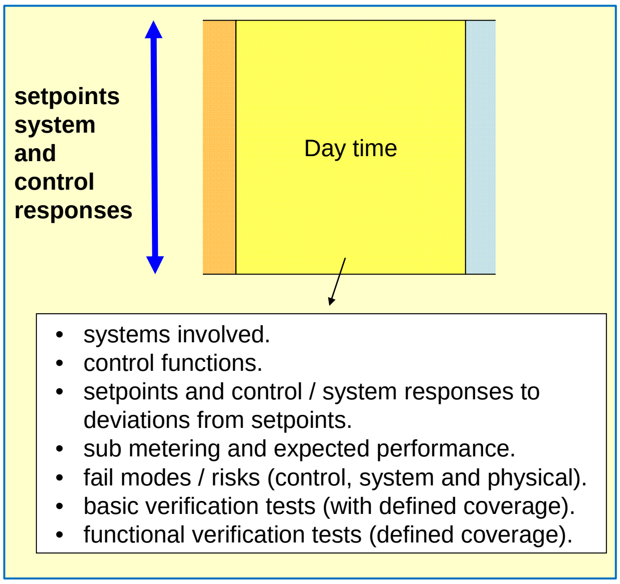
This Control Map is intended as a vehicle for common understanding and to provide the opportunity for discussion, review and for potential optimisation based on expert inputs. The process of review will involve iterations of review of best practice and risk analysis and possibly the use of simulation and other modelling tools. It should be available in a format suitable for discussion with clients and building managers etc. A possible format is illustrated in figure 6.5 for heating and cooling responses for a notional hybrid ventilated office in summer. More realistic examples are generated in the test applications.

*Figure 6.5. Simple example of a control map for a hybrid ventilated office in summer during occupied hours (Here Sp = set-point).*



For each timeframe in addition to creating a clear control map, the analysis should consider how correct operation can be verified through appropriate sub-metering, basic tests or functional tests i.e. comparison with expected values possibly established using simulation or from previous applications etc, (figure 6.6).

*Figure 6.6. System and control mapping for each timestep.*



- systems involved.
- control functions.
- setpoints and control / system responses to deviations from setpoints.
- sub metering and expected performance.
- fail modes / risks (control, system and physical).
- basic verification tests (with defined coverage).
- functional verification tests (defined coverage).

In stage 4 possible failure modes should be reviewed and how these would be detected and mitigated if they were to occur. To facilitate analysis of potential fail modes, their impacts, detection and prevention, it is proposed that a simplified template based on the FMEA risk management process common in other industries (Pyzdek 2003) is adopted. (figure 6.7)

*Figure 6.7. Example FMEA template.*

| **Fail Mode** | **Impact** | **Detection** | **Prevention / Optimisation** |
|---|---|---|---|
| **High energy use** | Energy, cost, carbon | Metering and sub-metering c.f. targets e.g. TM22 | Robust design process |
| **Poor indoor environment** | Health, comfort, productivity | IEQ monitoring. Occupant IEQ surveys e.g. UBT | Robust design process |

This template would be created with expert input, specific to a building or system type, would capture historical knowledge, and be updated when any new failure modes or improved detection methods come to light. The information captured in the FMEA template should then at appropriate intervals be used to inform the next iteration of best practice documentation.

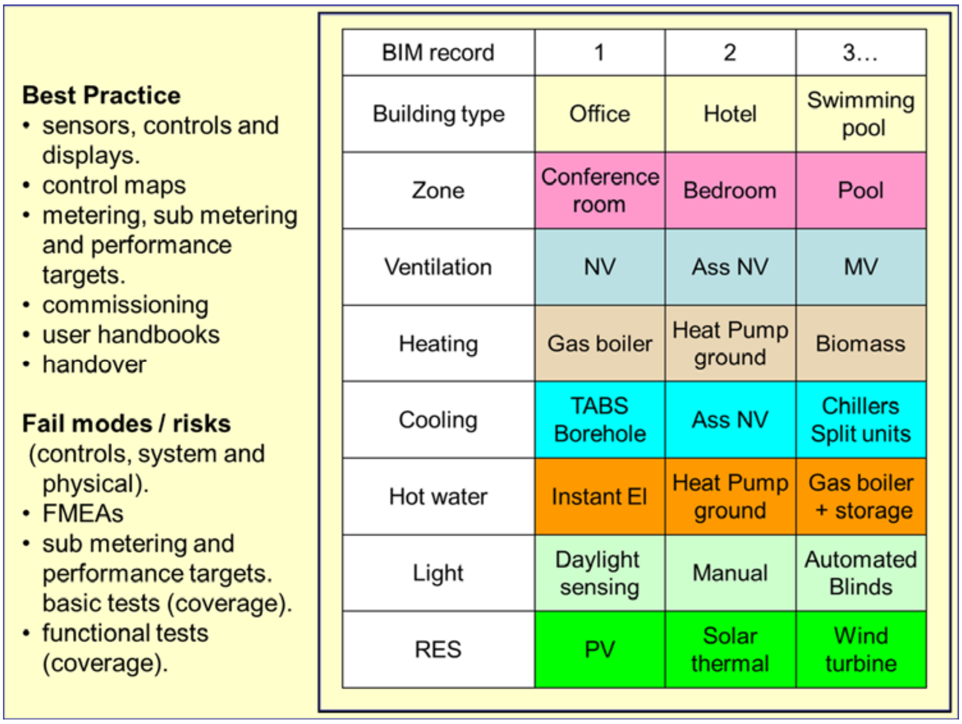
There should be some meaningful assessment of risk levels and greater efforts directed at higher risks. One example of a high risk item would be a novel solution not previously well proven, it would be appropriate in this case that great attention was paid to scoping of the potential fail modes and how these can be avoided (or at least eliminate the possibility they would be undetected if they did occur).

It should be noted that in the full FMEA method adopted in other industries there is a formal risk assessment process to assign a category to each risk, higher risks then require higher levels of management (assignment of management responsibility, reporting to clients etc). This full risk assessment and management process has not been adopted in the method as proposed here but could be added in future versions. An example of a more comprehensive FMEA template is given in Appendix C.

To facilitate the capture and re-application of knowledge it is proposed that a modular document library is created (and maintained) with best practice, design templates, control maps, failure mode analysis, and test information relevant to each specific building and systems modules or types (e.g. passive house dwellings, air source heat pumps, mechanical ventilation, solar thermal systems, night cooling etc.) a small selection of the possible categories is illustrated in figure 6.8.

This proposed Modular Control Mapping and FMEA processes are intended to fit within a modular design approach where knowledge appropriate to modules is captured enabling them to be re-used rather than each project being a ‘start from scratch’. The potential for such a library within the BIM framework is discussed later.

***Figure 6.8. Example categorisation of best practice and fail mode / risk analysis by building or system type (modular approach).***



**Best Practice**
- sensors, controls and displays.
- control maps
- metering, sub metering and performance targets.
- commissioning
- user handbooks
- handover

**Fail modes / risks**
(controls, system and physical).
- FMEAs
- sub metering and performance targets. basic tests (coverage).
- functional tests (coverage).

| BIM record | 1 | 2 | 3… |
|---|---|---|---|
| Building type | Office | Hotel | Swimming pool |
| Zone | Conference room | Bedroom | Pool |
| Ventilation | NV | Ass NV | MV |
| Heating | Gas boiler | Heat Pump ground | Biomass |
| Cooling | TABS Borehole | Ass NV | Chillers Split units |
| Hot water | Instant El | Heat Pump ground | Gas boiler + storage |
| Light | Daylight sensing | Manual | Automated Blinds |
| RES | PV | Solar thermal | Wind turbine |

Outputs from the application of the method are intended to be available for flexible re-use in future projects at various stages:

1. The simple control description to facilitate common understanding across the design team and users. This simple description can be generated at the design stage and / or generated based on the controls as implemented either at commissioning or post occupancy evaluation. If generated independently at each of these stages it provides a point of review and facilitates a check for

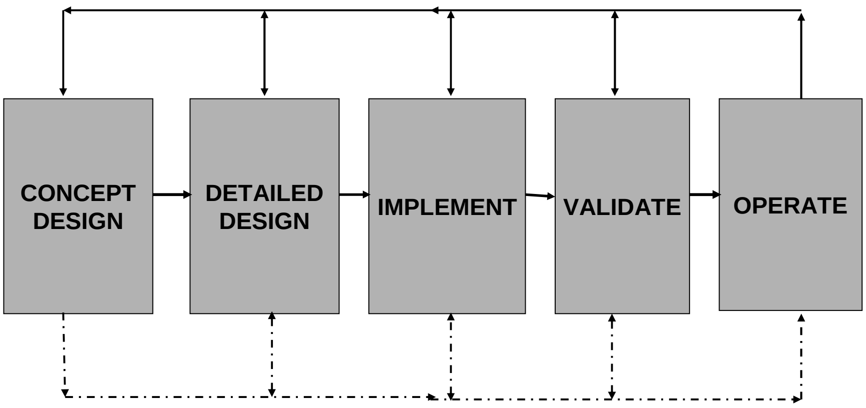
disconnects (errors, miss-understandings, logical gaps, approximations, substitutions etc.). Mapping the controls in this way is intended to allow them to be readily comprehended and reviewed and facilitate their optimisation e.g. using modelling tools. Control maps once established in one project can form the starting point for future projects using the same module so that knowledge is transferred and ‘start from scratch’ avoided.

2. The fail mode analysis is intended to aid the identification of potential disconnects for specific building types and technologies. It is intended for the capture and transfer of expert knowledge between projects and individuals so that potential disconnects can be prevented. This can be generated by the design team based on experience and with expert inputs and then revised and re-used in the commissioning or post occupancy evaluation phase. This is intended to be a living document which is updated based on findings, providing a vehicle for feedback and feed forward. Once mature the fail mode analysis would be expected to form an important input into robust best practice guidelines. The FMEA associated with a module would be re-used whenever that module is being considered or used in future projects ensuring that knowledge is transferred.

### 6.3 Integration with the industry process

Within the UK there are various definitions of the buildings industry design flow e.g. RIBA Plan of Work (RIBA 2011), Construction Industry Council work stages (CIC 2012) and the ‘Prepare-Design-Implement-Check-Operate’ flow of Bordass et. al. (2011). A model is used here which is similar but has more explicit representation of the validation, feedback and feed forward processes similar to those found in design flows of BIM benchmark industries such as the NASA Design Process for Complex Electronics (NASA 2012). These feed-forwards (e.g. installation instructions, commissioning tests, controls software and hardware specifications, user manuals etc. from the detailed design stage) and feed-backs (e.g. knowledge of systems application ranges and limitations, performance variations with patterns of use, fail modes and risk analysis etc. fed back to concept, detailed design or implementation stages from previous projects or characterisations) form part of the quality systems approach used in these BIM benchmark industries (Pyzdek, 2003).

***Figure 6.9. Model of design flow adopted in this work***



The proposed method is intended to fit within the design process for creating a new building and be integrated from the concept design stage through to the operation stage. Alternatively the method is equally intended to be useful as an investigation method in post occupancy evaluation (POE). These modes of intended application are documented in terms of the activities and intended outcomes against the stages of the design flow in table 6.1.

**Table 6.1 Intended applications of the Modular Control Mapping and FMEA method.**

| Stage | Activities | Outcomes |
|---|---|---|
| Concept design | o Concept design developed using method.<br>o Concept design documented in simple control map format to facilitate discussion, review, modelling and optimisation.<br>o Best practice and risk analysis (FMEA) carried out and documented (capturing expert inputs from previous projects).<br>o Required actions for verification (sub meters, basic and functional tests etc.) captured in project plans. | Clear communication of concept design.<br>Best practice incorporated.<br>Risk management incorporated.<br>Feedbacks from previous projects.<br>Modelling facilitated.<br>First pass user manual. |
| Detailed design | o Concept design control mapping, best practice and FMEA reviewed (and updated if required) with detailed design team, issues or new risks identified and resolved.<br>o Concept design translated into detailed specifications for implementation, verification and operation stages.<br>o Best practice and risk mitigation incorporated in detailed design.<br>o Review (and update if required) of detailed design specifications for best practice and FMEA and against concept design (bottoms up map c.f. concept map). Issues or new risks highlighted and resolved. (Review capturing expert inputs from previous projects). | Clear communication of concept and detailed design.<br>Detailed design aligned with concept, any deviations highlighted, risks assessed and if allowed, mitigations agreed.<br>User manual revision based on detailed plans for review with team and building managers / clients.<br>Feed forward of concept, detailed design specifications, best practice and FMEA to subsequent stages.<br>Issues raised captured in FMEA and Best Practice documents for use in this and future projects.<br>Modelling facilitated. |

| | | |
|---|---|---|
| | o Translation of detailed plans into revised user manual and review with clients / managers. | |
| Implementation | o Concept and detailed design control mapping, best practice and FMEA reviewed (and updated if required) with detailed design team, issues or new risks identified and resolved.<br>o Implementation phase verifications carried out based on specifications from detailed planning stage.<br>o Deviations from specifications raised and risk analysis carried out and appropriate actions taken to mitigate / verify. | Clear communication of concept and detailed design.<br>Implementation aligned with detailed design and concept, any deviations highlighted, risks assessed and if allowed, mitigations agreed.<br>Issues raised and managed then captured in FMEA and Best Practice documents for use in this (additional verifications feed forward to commissioning stage etc), and future projects (avoidance of issue). |
| Verification/Commissioning | o Verification plans based on detailed design stage best practice and FMEA analysis reviewed and any issues raised and resolved.<br>o Verifications carried out based on specifications from detailed planning stage (metering, basic and functional tests).<br>o Deviations from specifications raised and risk analysis carried out and appropriate actions taken to mitigate / verify.<br>o Review of systems and controls as implemented against concept design (bottoms up map from controls documentation c.f. concept map). Issues or | Clear communication of concept and detailed design.<br>Verification/commissioning (including seasonal commissioning) aligned with detailed design and concept, any deviations highlighted, risks assessed and if allowed, mitigations agreed.<br>Issues raised and managed then captured in FMEA and Best Practice documents for use in this (additional verifications, modelling etc), and future projects (avoidance of issue). |

|  |  |  |
|---|---|---|
|  | new risks highlighted and resolved. (Review to capture expert inputs from previous projects).<br>o User manual reviewed and updated. |  |
| Operation/POE | In operation the method provides the basis for clear user manual and building operator understanding.<br>The method can be deployed in POE in order to provide insights into: building overall performance, system and controls as intended and as implemented, and review the building against best practice and failure modes relevant to the building and systems type. Steps would be:<br>o Establish design intent (systems and controls map)<br>o Establish systems and controls as implemented (system and controls map plus FMEA process).<br>o Analyse disconnects in system and controls design, compare against best practice for relevant systems and controls, identify opportunities for optimisation (e.g. through modelling). | Clear understanding of building operation allowing informed decisions on shifting of setpoints etc by building managers.<br>In POE: Clear communication of intended concept, and also the systems and controls as implemented, through the control mapping.<br>Identification of disconnects in translating the concept into the controls implementation.<br>Identification of performance issues through application of FMEA analysis.<br>Identification of optimisations through comparison with best practice, use of modelling etc.<br>Modelling facilitated by the clear description of control implementation. |

| | | |
|---|---|---|
| | o Analyse actual building performance and diagnose problems using the FMEA method applied as relevant to the specific building and system type. | |

## 6.4 Test application of the Control Mapping and FMEA method to the BRE Environmental Office.

The first test application to the BRE Environmental office is described here. Further application to domestic buildings is described in chapter 7.

The test applications are at the post-occupancy evaluation (POE) stage. The availability of design process documentation and design targets, plus access to designers, systems and controls professionals involved allowed insights to be gained into the application of the method earlier in the design process i.e. at concept design, detailed design and implementation stages.

### 6.4.1 The BRE Environmental office.

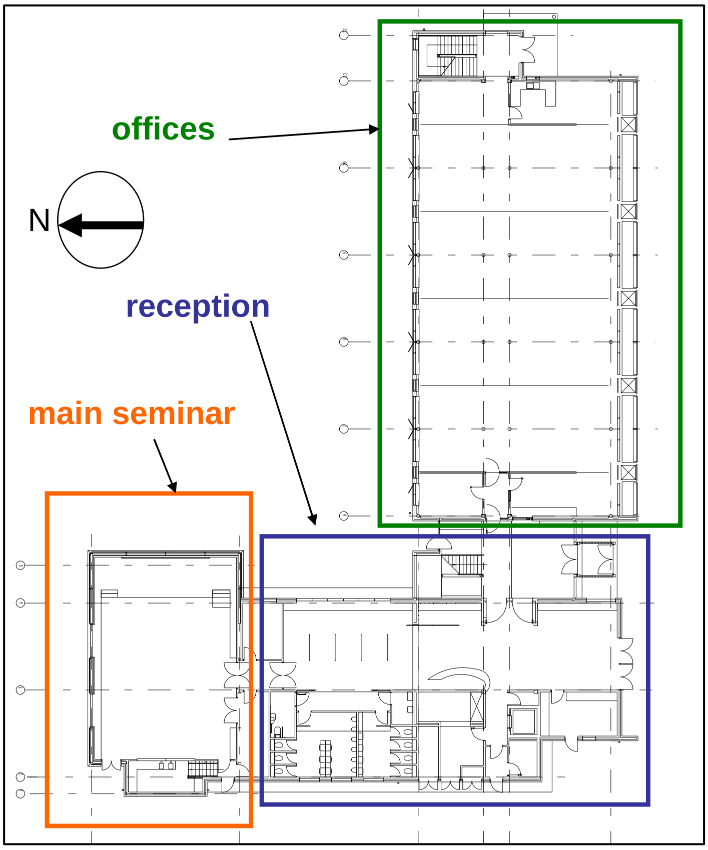
The Buildings Research Establishment (BRE) Environmental Office has assisted natural ventilation (ANV), high thermal mass, borehole cooling, and an automated Building Energy Management System (BEMS) and although completed in 1997 is consistently identified as an example to be followed (RAE 2010). The building is shown in figures 6.10 and 6.11.

Prior to the work of this thesis the building had been monitored after completion and found to perform reasonably well for occupant satisfaction and energy use compared to other office buildings of the time but the energy use in operation was reported to be 90% above the design target (Ní Riain et al. 2000). The BRE offered this as a case study building with the intent of identifying improvements in the operation of the building and gaining insights that could be applied elsewhere.

The proposed four stage Modular Control Mapping and FMEA process was tested using the BRE building. The method was applied post occupancy and to gain retrospective insights into the design process.

***Figure 6.10. BRE Environmental Office (south elevation of offices showing solar stacks and external shading systems).***

***Figure 6.11. BRE Environmental Office floorplan.***



### 6.4.2 Stages 1 to 3 and use of Control Mapping

Stage 1 of the method is to develop a high level understanding of the building and its component zones and plant systems.

The BRE Environmental Office has an office block, a main seminar room and a reception area. The office block consists of 3 self-contained floors. The ground floor office and first floor offices are very similar and have high thermal mass ceilings with automatically controlled slab and non-slab high level windows, solar assisted stack ventilation with automatically controlled hopper openings and a fan assist option, underfloor heating and cooling loops, and perimeter radiators. The upper floor has a similar floor (heating and cooling) and perimeter radiator system but does not have a high thermal mass ceiling or high level and stack automated window openings, instead having a high apex ceiling with roof windows to allow enhanced ventilation in warm periods.

There is a reception and stairway area to the west end of the offices with a public display area, 2 small seminar rooms and toilets. There is a large seminar room to the north of the reception area which seats around 100. This is heated through both underfloor and perimeter radiators and ventilated when occupied (control is through a $CO_2$ sensor) through opening a high level stack vent (to the north east of the building) and opening a low level vent (to the north west). There is a heater battery associated with the low level vent intended to pre-heat incoming air and avoid cold draughts.

The systems and controls mapping process identified the following components:

- Ground floor office.
- 1st floor office.
- 2nd floor office.
- Reception / stairs area.
- 2 small seminar rooms (in the reception block).
- Main seminar room.
- Ventilation systems (office and seminar rooms).
- Heating systems (office and seminar rooms).
- Cooling systems (assisted natural ventilation (ANV) and borehole).

- Lighting and shading systems.
- Renewable generation (large polycrystalline PV).

Each of these should be considered as a component for the system and control mapping of the building.

Stage 2 of the method is to understand the operation of the systems and controls for each component and for each time step. In POE there is the opportunity to approach this from the concept design perspective (based on architects descriptions), from the controls implementation perspective (from the BEMS manual), and from the controls as implemented (i.e. observed control responses). Here we take a look at all of these and attempt to identify any issues, disconnects, and potential improvements.

The controls are captured in the following descriptions taken from the 'Architects Description' document (Stevens 1997):

*"Winter Day Time Operation*

*The windows in to the ventilation ducts in the slabs in the offices will open to provide minimum fresh air; this allows the slab to pre-heat the air. Fresh air to the top floor is provided by manually operated trickle vents in the windows. The radiators and the underfloor heating will turn on to maintain a minimum temperature. The system will favour the underfloor heating coils over the radiators as this form of heating is slightly more efficient.*

*Winter Night Time Operation*

*Provide no ventilation to the building and only heat to prevent frost within the building.*

*Summer Day*

*Provide minimum ventilation to the building unless the building is above its summer temperature set point. In this case the automatic windows will open to cool the building and the borehole cooling will run. If the outside air is hotter than the internal air then the windows will remain in their minimum position. If it is windy then the windows will modulate towards the closed position. If it is windy and raining then the travel of the windows will be limited to 25% open. If it is raining the stack windows will close as these are top opening* *hopper type windows. If the temperature in the offices exceeds a second set point then the stack fans will switch on to increase the ventilation.*

*Summer Night*

*The windows will open to remove the excess heat which has built up in the building over the previous day, again only if it is cooler outside than inside. This free cooling is given a chance to lower the internal temperature. If it is not cooling the building fast enough then the borehole pump will run and additional cooling will be delivered to the underfloor coils.*

*The main seminar room operates in a very similar way to the offices except that the fresh air ventilation to the main seminar room is* $CO_2$ *controlled which will provide fresh air if it required by the occupants at all times. In winter this air will be heated to maintain a minimum supply air temperature.*

*Hot Water*

*The hot water is supplied from a central storage calorifier which is located in the plant room on the first floor. The calorifier is heated by a separate heating circuit from the gas fired boilers which are located on the ground floor of the plant room.*

*The water in the storage calorifier is heated up to 70°C once per day to ensure that there is no possibility of legionella growth. There is also an anti-stratification pump to ensure that the water in the cylinder is heated uniformly.*

*The heating system has one condensing boiler and one conventional high efficiency boiler. The condensing boiler will always be the lead boiler. Having a smaller condensing boiler also allows the condensing boiler to run nearer to maximum load, and so a higher efficiency, for more of the time. The condensing boiler is sized for 40% of the load and the conventional boiler 60%.*

*The borehole consists of a 100mm diameter hole drilled to a depth of 70m. This borehole is sited in the car park behind the new building. In the plant room the water from the borehole passes through two stainless steel heat exchangers where it cools the water in the offices and seminar room underfloor heating/cooling systems. The borehole water is heated by up to 5°C (providing about 35kW of cooling) and then it is discharged back to below ground."*

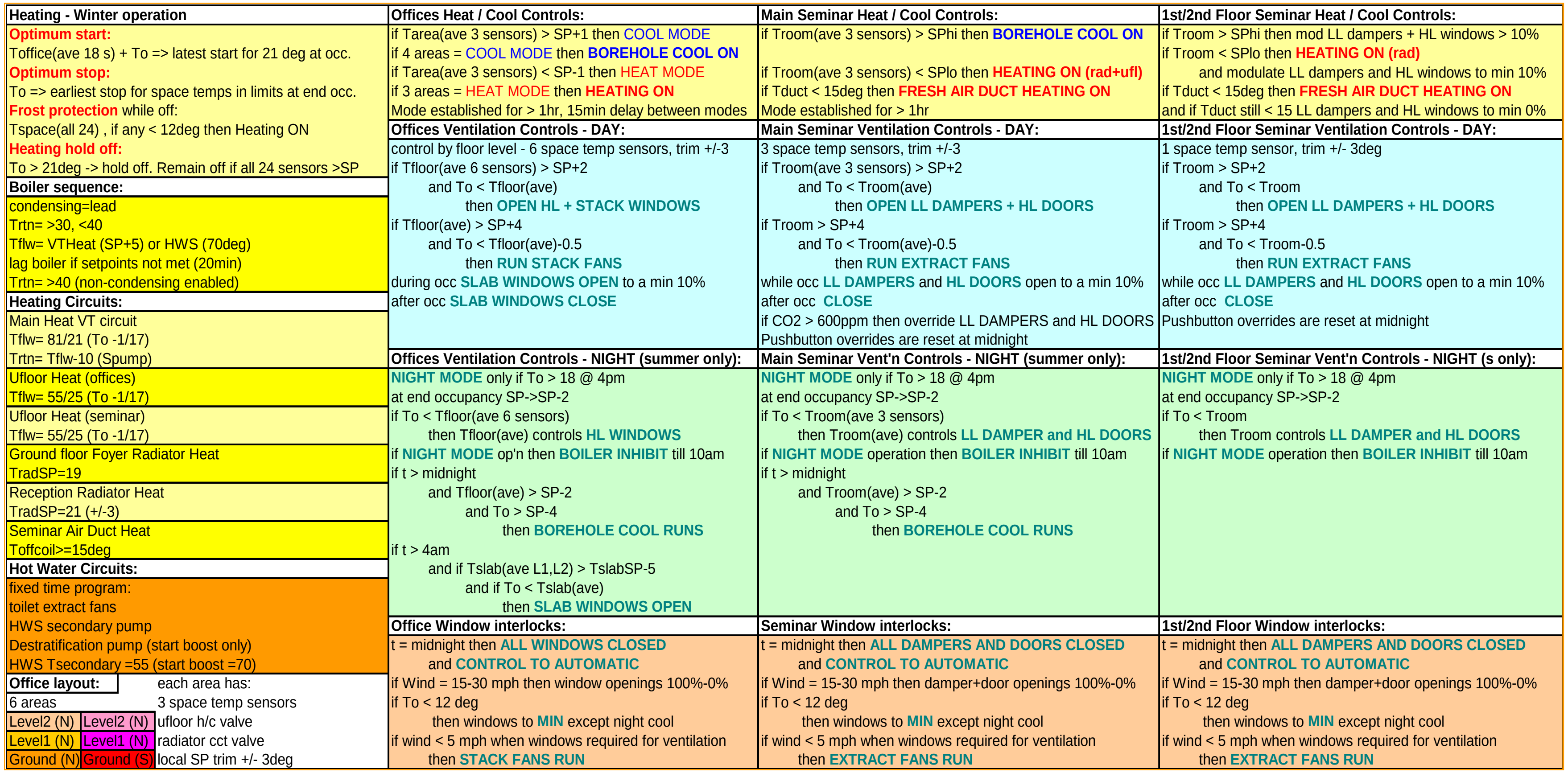
While these general descriptions are useful they are not sufficiently detailed to allow the controls to be mapped.

For a more detailed understanding of the controls the 84 page controls manual was analysed. The controls manual described each of the controls on a system by system basis rather than providing an overview or a clear representation of how any one zone was to be controlled through the combined systems.

The size of the manual and its complexity was a barrier rather than an aid to understanding without detailed study. This manual was the only information available to the building users, leading to a lack of clarity on the building operations and potential for uninformed decisions being made in response to requests for changes in local environments etc.

The information from the controls manual was extracted to allow control maps for individual components and timesteps to be constructed. An initial data extraction for the heating, ventilation, and cooling systems for the offices, main seminar and small seminar rooms is illustrated in figure 6.12. The subset of this focussed on only the office area is shown enlarged in figure 6.13. It was clear from this that the control map for a day could be separated into 3 timeframes: start-up, occupied, and night.

### *Figure 6.12. Controls extraction from 84 page BEMS manual.*



**Heating - Winter operation**

**Optimum start:**
Toffice(ave 18 s) + To => latest start for 21 deg at occ.
**Optimum stop:**
To => earliest stop for space temps in limits at end occ.
**Frost protection** while off:
Tspace(all 24) , if any < 12deg then Heating ON
**Heating hold off:**
To > 21deg -> hold off. Remain off if all 24 sensors >SP

**Boiler sequence:**
condensing=lead
Trtn= >30, <40
Tflw= VTHeat (SP+5) or HWS (70deg)
lag boiler if setpoints not met (20min)
Trtn= >40 (non-condensing enabled)

**Heating Circuits:**
Main Heat VT circuit
Tflw= 81/21 (To -1/17)
Trtn= Tflw-10 (Spump)
Ufloor Heat (offices)
Tflw= 55/25 (To -1/17)
Ufloor Heat (seminar)
Tflw= 55/25 (To -1/17)
Ground floor Foyer Radiator Heat
TradSP=19
Reception Radiator Heat
TradSP=21 (+/-3)
Seminar Air Duct Heat
Toffcoil>=15deg

**Hot Water Circuits:**
fixed time program:
toilet extract fans
HWS secondary pump
Destratification pump (start boost only)
HWS Tsecondary =55 (start boost =70)

| **Office layout:** | | each area has: |
|---|---|---|
| 6 areas | | 3 space temp sensors |
| Level2 (N) | Level2 (N) | ufloor h/c valve |
| Level1 (N) | Level1 (N) | radiator cct valve |
| Ground (N) | Ground (S) | local SP trim +/- 3deg |

**Offices Heat / Cool Controls:**
if Tarea(ave 3 sensors) > SP+1 then COOL MODE
if 4 areas = COOL MODE then **BOREHOLE COOL ON**
if Tarea(ave 3 sensors) < SP-1 then HEAT MODE
if 3 areas = HEAT MODE then **HEATING ON**
Mode established for > 1hr, 15min delay between modes

**Offices Ventilation Controls - DAY:**
control by floor level - 6 space temp sensors, trim +/-3
if Tfloor(ave 6 sensors) > SP+2
  and To < Tfloor(ave)
    then **OPEN HL + STACK WINDOWS**
if Tfloor(ave) > SP+4
  and To < Tfloor(ave)-0.5
    then **RUN STACK FANS**
during occ **SLAB WINDOWS OPEN** to a min 10%
after occ **SLAB WINDOWS CLOSE**

**Offices Ventilation Controls - NIGHT (summer only):**
**NIGHT MODE** only if To > 18 @ 4pm
at end occupancy SP->SP-2
if To < Tfloor(ave 6 sensors)
  then Tfloor(ave) controls **HL WINDOWS**
if **NIGHT MODE** op'n then **BOILER INHIBIT** till 10am
if t > midnight
  and Tfloor(ave) > SP-2
    and To > SP-4
      then **BOREHOLE COOL RUNS**
if t > 4am
  and if Tslab(ave L1,L2) > TslabSP-5
    and if To < Tslab(ave)
      then **SLAB WINDOWS OPEN**

**Office Window interlocks:**
t = midnight then **ALL WINDOWS CLOSED**
  and **CONTROL TO AUTOMATIC**
if Wind = 15-30 mph then window openings 100%-0%
if To < 12 deg
  then windows to **MIN** except night cool
if wind < 5 mph when windows required for ventilation
  then **STACK FANS RUN**

**Main Seminar Heat / Cool Controls:**
if Troom(ave 3 sensors) > SPhi then **BOREHOLE COOL ON**
if Troom(ave 3 sensors) < SPlo then **HEATING ON (rad+ufl)**
if Tduct < 15deg then **FRESH AIR DUCT HEATING ON**
Mode established for > 1hr

**Main Seminar Ventilation Controls - DAY:**
3 space temp sensors, trim +/-3
if Troom(ave 3 sensors) > SP+2
  and To < Troom(ave)
    then **OPEN LL DAMPERS + HL DOORS**
if Troom > SP+4
  and To < Troom(ave)-0.5
    then **RUN EXTRACT FANS**
while occ **LL DAMPERS** and **HL DOORS** open to a min 10%
after occ **CLOSE**
if CO2 > 600ppm then override LL DAMPERS and HL DOORS
Pushbutton overrides are reset at midnight

**Main Seminar Vent'n Controls - NIGHT (summer only):**
**NIGHT MODE** only if To > 18 @ 4pm
at end occupancy SP->SP-2
if To < Troom(ave 3 sensors)
  then Troom(ave) controls **LL DAMPER and HL DOORS**
if **NIGHT MODE** operation then **BOILER INHIBIT** till 10am
if t > midnight
  and Troom(ave) > SP-2
    and To > SP-4
      then **BOREHOLE COOL RUNS**

**Seminar Window interlocks:**
t = midnight then **ALL DAMPERS AND DOORS CLOSED**
  and **CONTROL TO AUTOMATIC**
if Wind = 15-30 mph then damper+door openings 100%-0%
if To < 12 deg
  then windows to **MIN** except night cool
if wind < 5 mph when windows required for ventilation
  then **EXTRACT FANS RUN**

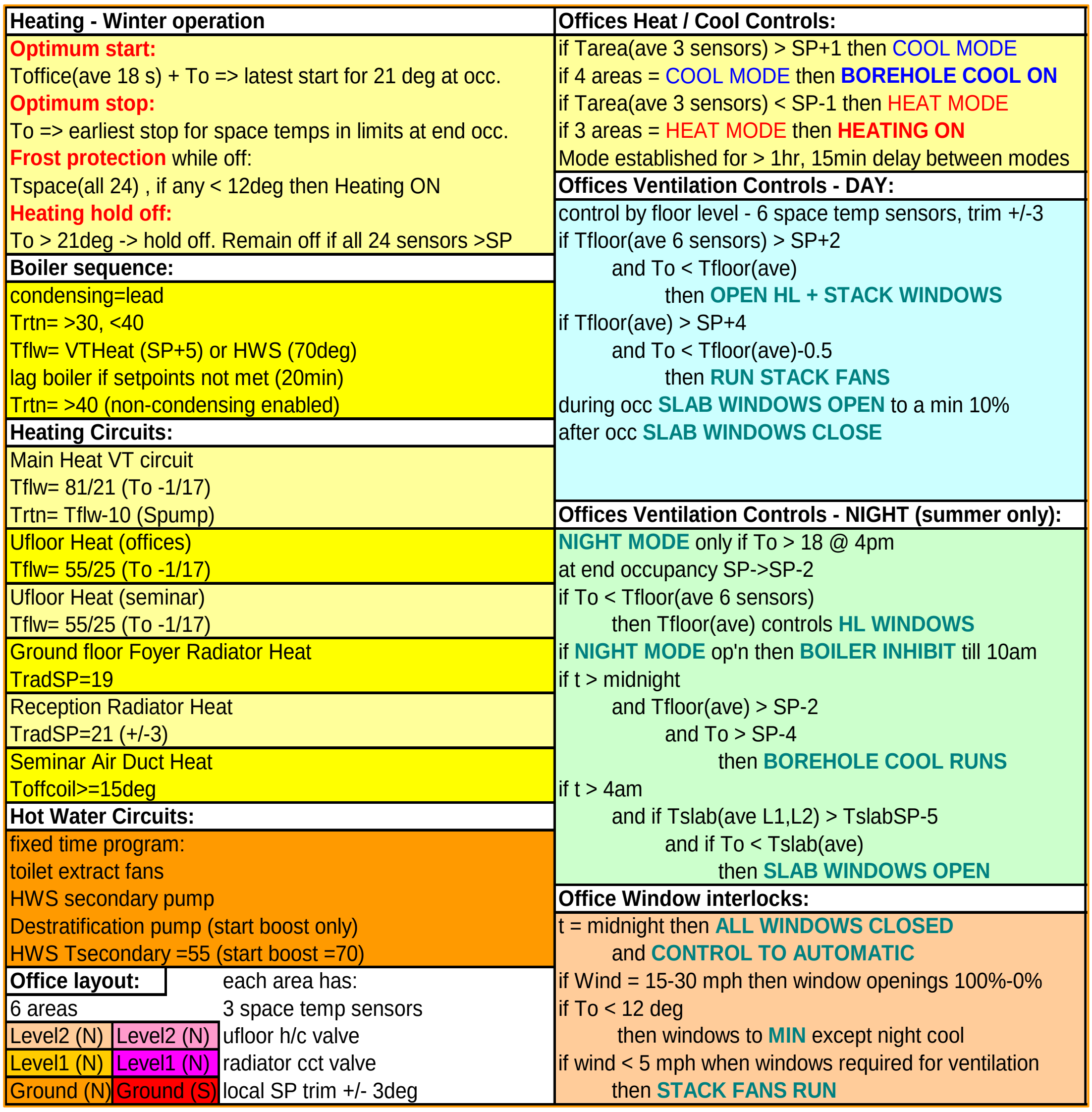
**1st/2nd Floor Seminar Heat / Cool Controls:**
if Troom > SPhi then mod LL dampers + HL windows > 10%
if Troom < SPlo then **HEATING ON (rad)**
  and modulate LL dampers and HL windows to min 10%
if Tduct < 15deg then **FRESH AIR DUCT HEATING ON**
and if Tduct still < 15 LL dampers and HL windows to min 0%

**1st/2nd Floor Seminar Ventilation Controls - DAY:**
1 space temp sensor, trim +/- 3deg
if Troom > SP+2
  and To < Troom
    then **OPEN LL DAMPERS + HL DOORS**
if Troom > SP+4
  and To < Troom-0.5
    then **RUN EXTRACT FANS**
while occ **LL DAMPERS** and **HL DOORS** open to a min 10%
after occ **CLOSE**
Pushbutton overrides are reset at midnight

**1st/2nd Floor Seminar Vent'n Controls - NIGHT (s only):**
**NIGHT MODE** only if To > 18 @ 4pm
at end occupancy SP->SP-2
if To < Troom
  then Troom controls **LL DAMPER and HL DOORS**
if **NIGHT MODE** operation then **BOILER INHIBIT** till 10am

**1st/2nd Floor Window interlocks:**
t = midnight then **ALL DAMPERS AND DOORS CLOSED**
  and **CONTROL TO AUTOMATIC**
if Wind = 15-30 mph then damper+door openings 100%-0%
if To < 12 deg
  then windows to **MIN** except night cool
if wind < 5 mph when windows required for ventilation
  then **EXTRACT FANS RUN**

*Figure 6.13. Controls extraction from 84 page BEMS manual – office areas.*



**Heading - Winter operation**
**Optimum start:**
Toffice(ave 18 s) + To => latest start for 21 deg at occ.
**Optimum stop:**
To => earliest stop for space temps in limits at end occ.
**Frost protection** while off:
Tspace(all 24) , if any < 12deg then Heating ON
**Heating hold off:**
To > 21deg -> hold off. Remain off if all 24 sensors >SP

**Boiler sequence:**
condensing=lead
Trtn= >30, <40
Tflw= VTHeat (SP+5) or HWS (70deg)
lag boiler if setpoints not met (20min)
Trtn= >40 (non-condensing enabled)

**Heating Circuits:**
Main Heat VT circuit
Tflw= 81/21 (To -1/17)
Trtn= Tflw-10 (Spump)
Ufloor Heat (offices)
Tflw= 55/25 (To -1/17)
Ufloor Heat (seminar)
Tflw= 55/25 (To -1/17)
Ground floor Foyer Radiator Heat
TradSP=19
Reception Radiator Heat
TradSP=21 (+/-3)
Seminar Air Duct Heat
Toffcoil>=15deg

**Hot Water Circuits:**
fixed time program:
toilet extract fans
HWS secondary pump
Destratification pump (start boost only)
HWS Tsecondary =55 (start boost =70)

| **Office layout:** | | each area has: |
|---|---|---|
| 6 areas | | 3 space temp sensors |
| Level2 (N) | Level2 (N) | ufloor h/c valve |
| Level1 (N) | Level1 (N) | radiator cct valve |
| Ground (N) | Ground (S) | local SP trim +/- 3deg |

**Offices Heat / Cool Controls:**
if Tarea(ave 3 sensors) > SP+1 then COOL MODE
if 4 areas = COOL MODE then **BOREHOLE COOL ON**
if Tarea(ave 3 sensors) < SP-1 then HEAT MODE
if 3 areas = HEAT MODE then **HEATING ON**
Mode established for > 1hr, 15min delay between modes

**Offices Ventilation Controls - DAY:**
control by floor level - 6 space temp sensors, trim +/-3
if Tfloor(ave 6 sensors) > SP+2
    and To < Tfloor(ave)
        then **OPEN HL + STACK WINDOWS**
if Tfloor(ave) > SP+4
    and To < Tfloor(ave)-0.5
        then **RUN STACK FANS**
during occ **SLAB WINDOWS OPEN** to a min 10%
after occ **SLAB WINDOWS CLOSE**

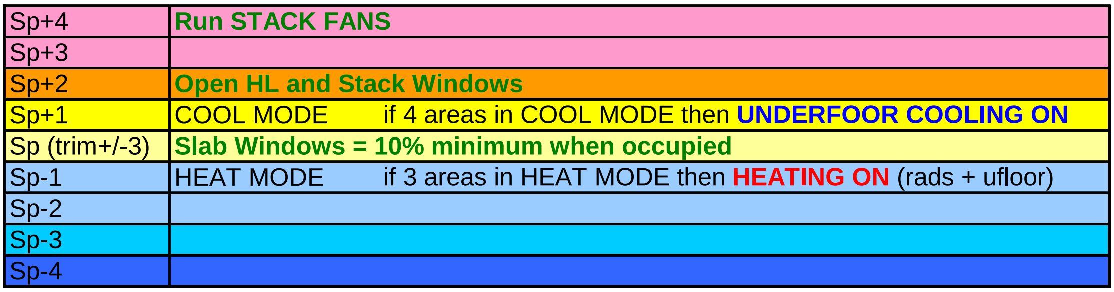
**Offices Ventilation Controls - NIGHT (summer only):**
**NIGHT MODE** only if To > 18 @ 4pm
at end occupancy SP->SP-2
if To < Tfloor(ave 6 sensors)
    then Tfloor(ave) controls **HL WINDOWS**
if **NIGHT MODE** op'n then **BOILER INHIBIT** till 10am
if t > midnight
    and Tfloor(ave) > SP-2
        and To > SP-4
            then **BOREHOLE COOL RUNS**
if t > 4am
    and if Tslab(ave L1,L2) > TslabSP-5
        and if To < Tslab(ave)
            then **SLAB WINDOWS OPEN**

**Office Window interlocks:**
t = midnight then **ALL WINDOWS CLOSED**
    and **CONTROL TO AUTOMATIC**
if Wind = 15-30 mph then window openings 100%-0%
if To < 12 deg
    then windows to **MIN** except night cool
if wind < 5 mph when windows required for ventilation
    then **STACK FANS RUN**

Stage 3 of the process was then to use the available data to create the control maps for individual areas and timeframes as called for in the method. Two examples are shown here, the first is for the office heating, cooling and ventilation operation during occupied hours, the second is for the operation of the same office in night cooling after occupied hours.

When the combined system and control responses are mapped out for the daytime operation of the offices heating cooling and ventilation systems the situation highlighted in figure 6.14 becomes apparent. The simple format here is intended to bring clarity to the actual system and control regime so that informed discussion and analysis can then be done. The analysis could include expert review, comparison with best practice, failure mode analysis, or modelling, potentially leading to improvements. (It should however be borne in mind that at this stage the representation of the controls is as documented, not necessarily as implemented – this possible disconnect will be addressed at a subsequent stage).

***Figure 6.14. Control map for offices daytime heating cooling and ventilation as implemented.***



| | |
|---|---|
| Sp+4 | **Run STACK FANS** |
| Sp+3 | |
| Sp+2 | **Open HL and Stack Windows** |
| Sp+1 | COOL MODE if 4 areas in COOL MODE then **UNDERFOOR COOLING ON** |
| Sp (trim+/-3) | **Slab Windows = 10% minimum when occupied** |
| Sp-1 | HEAT MODE if 3 areas in HEAT MODE then **HEATING ON** (rads + ufloor) |
| Sp-2 | |
| Sp-3 | |
| Sp-4 | |

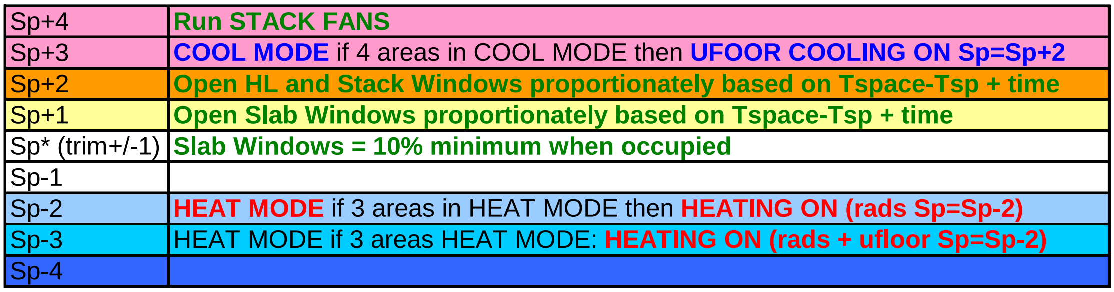
In this case the simple control map representation of the system and controls servicing the daytime offices highlights a number of potential issues and possible improvements including:

- Only +/- 1 degree between heating and cooling on.
- Mechanical cooling triggered before free cooling.
- Full heating (radiators plus underfloor) activated at 1 degree below setpoint.
- Large user adjustment (+/- 3 degrees) compared to deadband (+/- 1).

From reviewing this and discussing with experts an alternative control strategy could be proposed with potential for reduced energy use, an example produced by the author is given in figure 6.15. Here, as the building has opportunities for the occupants to adjust their surroundings in an adaptive manner (e.g. through window opening) an adaptive setpoint based on the adaptive comfort temperature (CEN 2007) is proposed. An increased deadband is proposed based on the same adaptive comfort standard, a smaller trim allowed, free cooling implemented before mechanical cooling, mechanical cooling given an increased setpoint, graduated turn-on of heating with the fast response radiator system activated initially in summer and intermediate seasons before the underfloor activated.

This proposed improved strategy is provided as an example to illustrate the value of the proposed process. In reality the control strategy would be discussed further, reviewed against best practice and fail modes, and modelled thoroughly before a finalised optimum strategy was then determined for deployment. Whatever strategy is finally adopted should of course ultimately be presented in a clear control map format to facilitate communication and a common understanding.

***Figure 6.15. Proposed improved control map for offices daytime heating cooling and ventilation.***



| | |
|---|---|
| Sp+4 | **Run STACK FANS** |
| Sp+3 | **COOL MODE** if 4 areas in COOL MODE then **UFOOR COOLING ON Sp=Sp+2** |
| Sp+2 | **Open HL and Stack Windows proportionately based on Tspace-Tsp + time** |
| Sp+1 | **Open Slab Windows proportionately based on Tspace-Tsp + time** |
| Sp* (trim+/-1) | **Slab Windows = 10% minimum when occupied** |
| Sp-1 | |
| Sp-2 | **HEAT MODE** if 3 areas in HEAT MODE then **HEATING ON (rads Sp=Sp-2)** |
| Sp-3 | HEAT MODE if 3 areas HEAT MODE: **HEATING ON (rads + ufloor Sp=Sp-2)** |
| Sp-4 | |

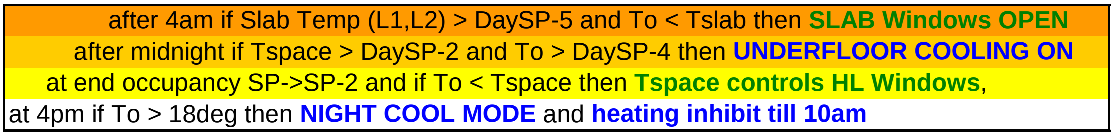
The combined system and control responses for the offices during the night in the summer are shown as a second example of control mapping in figure 6.16.

Again the simple control map representation of the system and controls servicing the offices at night in summer highlights a number of potential issues and possibilities for improvements including:

- Night cooling not triggered by internal temperature (slab or resultant) but only by external temperature at 4pm (often afternoon showers in hot periods temporarily reduce outside temperatures at this time).
- Mechanical borehole cooling triggered 4 hours before free cooling of slab through opening of slab windows.
- Control primarily based on temperature of the space rather than the slab temperature (experience elsewhere has suggested that controlling the temperature of the mass is most important in high mass buildings (Tovey and Turner 2006)).

- Stack fans not activated.

*Figure 6.16. Control map for offices night-time summer cooling and ventilation as implemented (SP = set-point).*

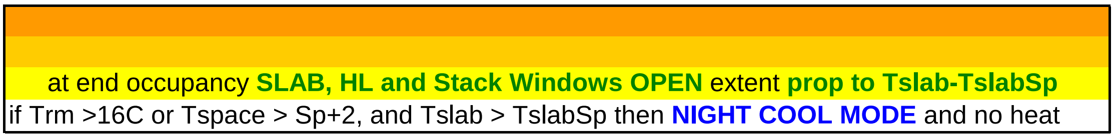


after 4am if Slab Temp (L1,L2) > DaySP-5 and To < Tslab then **SLAB Windows OPEN**
after midnight if Tspace > DaySP-2 and To > DaySP-4 then **UNDERFLOOR COOLING ON**
at end occupancy SP->SP-2 and if To < Tspace then **Tspace controls HL Windows**,
at 4pm if To > 18deg then **NIGHT COOL MODE** and **heating inhibit till 10am**

Again a more appropriate and energy efficient regime can be envisaged where control is triggered based on a running climate factor such as that used in the adaptive comfort standard or high internal and slab temperatures. Control would be through free cooling based on a target slab temperature which can be calculated based on the maximum that can be stored to offset internal gains without compromising morning thermal comfort. Any use of mechanical cooling would only be as a last resort and would be part of the pre-conditioning at start up (optimum start).

As with the earlier case the example described here and presented in figure 6.17 is to illustrate the proposed process. Again, in reality the control strategy would be discussed further, reviewed against best practice and fail modes, and modelled thoroughly before a finalised optimum strategy was then determined for deployment. Whatever strategy is finally adopted should ultimately be presented in the clear control map format to facilitate a common understanding.

*Figure 6.17. Proposed improved Control map for offices night-time summer cooling and ventilation.*



at end occupancy **SLAB, HL and Stack Windows OPEN** extent **prop to Tslab-TslabSp**
if Trm >16C or Tspace > Sp+2, and Tslab > TslabSp then **NIGHT COOL MODE** and no heat

### 6.4.3 Stage 4 of the method

Stage 4 of the process involves the review of best practice guidance and implementation of an FMEA approach targeted at the building type, systems and technologies as appropriate to the case study building. The FMEA includes as a potential fail mode the failure of the controls to work as intended and can be used to facilitate functional verification testing leading to a further version of the control map based on the 'as found' controls.

The use of the FMEA approach is the focus here. It is intended that FMEA will be used as an active tool, be applied to new innovative solutions, and be developed iteratively. It is proposed then that FMEA can be used as a vehicle for capturing knowledge and experience to provide updates for the generation of best practice guidelines.

In this case study building the FMEA approach would cover the following elements:

1. Overall building performance.
2. Ventilation through assisted natural ventilation (ANV), natural ventilation (NV) and infiltration.
3. Cooling through Borehole plus ANV plus NV.
4. Heating systems.
5. Hot water systems.
6. High mass, assisted naturally ventilated (ANV) building types.
7. Highly insulated building types.
8. Lighting and shading.
9. Special loads and equipment.

The last two items were not considered in the case study presented here.

The FMEA approach was applied as follows. First, preliminary FMEAs were created appropriate to each of the aspects listed above. Potential fail modes were postulated based on literature review, including best practice guidelines where available, and knowledge of issues seen in other buildings or systems of similar type. How these fail modes could be detected was proposed and how they could be avoided or mitigated in future also proposed. These FMEAs were then used to target the investigation of the building performance and to assist in detection and diagnosis of problems.

The preliminary FMEA process highlighted the complexity involved in this building, for example, systems involved in ventilation and cooling include: thermal mass, slab windows, high level windows, hopper windows (to the solar stacks), solar stacks, stack fans, borehole cooling, natural ventilation through occupant use of main windows, night cooling, and $CO_2$ and temperature triggered vents in the seminar room.

The FMEAs were used to inform the post occupancy evaluation. The potential fail modes and detection methods were investigated. Where new fail modes were detected or potential fail modes became apparent then the FMEAs were updated to capture these also. Table 6.2 gives the FMEAs generated and used in the investigation; the text in red *italic* was not part of the initial FMEA but was added through insights gained during the POE.

The idea is that the FMEAs including these updates will be used to inform the design, implementation and validation stages of future projects, and have increased effectiveness when used in future POE. In theory, once the process is established it should not be necessary to create an FMEA from scratch except where some novel solution is being proposed.

Table 6.2 FMEA for the BRE Environmental Office

| Fail Modes | Impact | Detection | Prevention |
|---|---|---|---|
| **1. Overall building performance** | | | |
| - Fails to meet intended performance | Energy and cost compromised. Comfort compromised. Remediation expense and disruption. | Monitoring of energy performance (main and sub-metering) against targets (e.g. TM22).<br>Monitoring of occupant experience (e.g. UBT/SL).<br>Monitoring of summer comfort performance. | Robust design and verification processes. |
| - *Building performance invisible. No response to alarms or faults etc.*<br>- *Faults occur that turn on backup systems that don't get recovered.* | *Energy and cost potentially compromised. Comfort potentially compromised.* | *Check for availability of performance data – ideally public display of real time and historic performance against targets for each sub metered point.*<br>*Create fault conditions and observe fault recovery process.* | *Robust design and verification processes: Building performance visibility planned in and executed correctly. In building, web and phone apps should be considered. Fault response and recovery to be planned in design and verified.* |
| - *Building operations not clearly understood – leading to uninformed responses and* | *Energy and cost potentially compromised. Comfort potentially compromised*. | *Check for availability of clear operations guide describing system and control responses by timeframe.* | *Robust design and verification processes: Building performance map based operations manual and user* |

| | | | |
|---|---|---|---|
| *adjustments. Faults not recognised and so undetected.* | | | *manual to be planned in and made readily available. (e.g. SL)* |

| Fail Modes | Impact | Detection | Prevention |
|---|---|---|---|
| **2. Ventilation – ANV, NV, extracts, infiltration.** | | | |
| - Ventilation system doesn't operate as intended:<br>o ANV components (offices and seminars)<br>o Manual operable windows.<br>o Extracts etc. | IEQ issues if under ventilation.<br>Energy issues if over ventilation.<br>Comfort / productivity issues. | Observe actual operation against intended operation.<br>Monitor actual operation against intended operation (possibly using BEMS if independently verified).<br>Monitoring of occupant experience (UBT/SL). | Robust design and verification process. |
| - Heating season daytime ventilation rates higher than planned. | Energy use for heating increased.<br>Heating system size potentially insufficient.<br>(quantification of energy and heating load potential impacts can be modelled).<br>Potential comfort issues due to cold air / air velocity. | Measure air velocities and weather conditions / ventilation settings. Measure tracer gas dispersion rates for range of outside conditions. Extrapolate results using modelling for range of expected weather conditions. | Robust design and verification process. Ventilation controls to be sensitive to driving factors and adjust to maintain intended ventilation rates across full range of expected variations (pressure, temperatures (in and out), wind speed and direction etc.). Modelling to establish weather dependencies for controls (models calibrated on previous projects). |

| | | | |
|---|---|---|---|
| - Heading season daytime ventilation rates lower than planned. | Potential IEQ and productivity issues.<br>Potential increased use of manual window opening with less controlled ventilation leading to higher energy use. | Measure air velocities and weather conditions / ventilation settings. Measure tracer gas dispersion rates for range of outside conditions. Extrapolate results using modelling for range of expected weather conditions. | Same as above. |
| - Heating season out of hours ventilation / infiltration rates higher than planned. | Energy use for heating increased.<br>Comfort compromised (Temp or draught). | Observe / monitor out of hours operation. (windows / doors left open, other openings). Tracer gas tests (as above). Blower door and smoke test. Monitor temperature decay curves for end of occupancy compared to expected (model). Co-heating test. | Robust design and verification process. Infiltration detailing, workmanship and verification processes. Clear user instructions on out of hours operation and checking / feedback procedures. |
| - Local comfort problems caused by cold draughts and/or high air velocities. | Comfort and productivity issues.<br>Compensatory energy use for heating etc. | Monitoring of occupant experience (UBT/SL). | Robust design and verification process. Local environments accounted for in design (modelling) and local control of window settings and other adaptive mechanisms ideally to be provided. |
| - *Overly coarse control results in step changes to indoor environment and* | *Comfort compromised. (draught)*<br>*Energy use compromised* | *Check capabilities of window actuators and controls.* | *Robust design and verification process. (see above)* |

| | | | |
|---|---|---|---|
| restricts ability to address local comfort issues. | through reduced ability to control ventilation rates.<br>Possible compensatory use of personal comfort appliances. | | |
| - Noisy window actuators. | Comfort compromised (audio)<br>Productivity potentially impacted. | Check noise levels for window actuators. | Robust design and verification process. Specify actuation noise levels < 25dB etc.<br>Maintenance requirements need to be determined and applied. |
| - Louvers on ventilation ducts have poor thermal performance when closed (air-tightness and insulation) | Higher than planned energy uses.<br>Cold draughts.<br>Heat losses through infiltration and direct transmission. | Check specifications of louvers when closed.<br>Observe louver operation.<br>Thermographic camera.<br>Co-heating test.<br>Airtightness test.<br>U-value measurement.<br>Surface temperature measurement. | Robust design and verification process.<br>Maintenance requirements need to be determined and applied. |

| Fail Modes | Impact | Detection | Prevention |
|---|---|---|---|
| **3. Cooling – Borehole, ANV, NV. Night cooling.** | | | |
| - Cooling systems do not work as intended:<br>o Offices ANV: slab, HL, hopper windows and stack fans.<br>o Offices NV: occupant window use.<br>o Offices borehole.<br>o Offices night cooling.<br>o Seminar room ANV: high and low.<br>o Seminar room borehole.<br>o Seminar room night cooling. | Comfort and productivity issues.<br>Compensatory energy use for increased mechanical cooling etc. | Observe actual operation against intended operation.<br>Monitor actual operation against intended operation (possibly using BEMS if independently verified). Where required modelling to support with expected responses for comparison with observed.<br>Monitoring of occupant experience (UBT/SL). | Robust design and verification process.<br><br>Modelling to establish weather dependencies for controls (models to be calibrated based on previous real projects).<br>Modelling to support development of verification tests. |
| - Cooling systems active when not required. | Potential increased energy use for mechanical cooling.<br>Potential increased heating energy if during a heating period. Potential discomfort (draughts, cold temperatures) if | Observe actual operation against intended operation.<br>Monitor actual operation against intended operation (possibly using BEMS if independently verified). | Robust design and verification process. |

| | | | |
|---|---|---|---|
| | inappropriately applied. | | |
| - Cooling systems cause discomfort (draughts, cold areas, cold surfaces, cold times of day etc). | Comfort and productivity. Possible increase in energy use due to occupants using personal appliances to restore comfort (e.g. electric fires, fan heaters etc). | Monitoring of occupant experience (UBT/SL). | Robust design and verification process. Local environments accounted for in design (modelling) and local control of window settings and other adaptive mechanisms ideally to be provided. |
| - *Heating and cooling systems in conflict e.g. shared underfloor system always calls for heating systems to be ON when pump activated even in cooling mode.* | *Energy use compromised. Comfort compromised.* | *Testing for correct response when cooling system enabled.* | *Robust design and verification procedures.* |

| Fail Modes | Impact | Detection | Prevention |
|---|---|---|---|
| **4. Heating – Rads + Ufloor + air pre-heat (seminar). Gas boilers (60:40 condensing + non condensing).** | | | |
| - Heating systems do not work as intended:<br>o Condensing lead boiler.<br>o Non condensing back-up boiler<br>o Office radiators<br>o Office underfloor<br>o Seminar perimeter<br>o Seminar underfloor<br>o Seminar air heater | Comfort compromised.<br>Energy use compromised. | Observe actual operation against intended operation.<br>Monitor actual operation against intended operation (possibly using BEMS if independently verified). If required - modelling to support with expected responses for comparisons with observed.<br>Monitoring of occupant experience (UBT/SL). | Robust design and verification process. |
| - Heating systems on when not required. | Energy use compromised. | Observe actual operation against intended operation.<br>Monitor actual operation against intended operation (possibly using BEMS if independently verified). | Robust design and verification process. |

| | | | |
|---|---|---|---|
| - *Fault conditions requiring turn-on of back up boiler not detected and not resolved.* | *Energy use compromised (backup boiler always on standby).* | *Create fault conditions and observe operation.* | *Robust design and verification process. Fault conditions to be tested and route back from fault on recovery planned.* |
| - *Air heating at louver allows heat loss unless closed louver has good thermal and airtightess properties.* | *Energy use compromised.* | *Check louver specifications. Observe in operation.* | *Correctly specify louver properties in design and verify performance on site.* |

| Fail Modes | Impact | Detection | Prevention |
|---|---|---|---|
| **5. Hot water systems – storage for reception toilets area (from gas boilers).** | | | |
| - Hot water systems do not work as intended:<br>o Condensing lead boiler.<br>o Non condensing back-up boiler<br>o Storage tank.<br>o Distribution system. | Energy use compromised.<br>Comfort impact. | Observe actual operation against intended operation.<br>Monitor actual operation against intended operation (possibly using BEMS if independently verified). | Robust design and verification process. |
| - Insufficient hot water. | Comfort impact. | Observe / Monitor. | Robust design and verification process. |
| - Hot water systems on when not required. | Energy impact. | Observe / Monitor. | Robust design and verification process. |
| - Legionella prevention not adequate (per HSE L8) | Potential health impact. (Health issue for vulnerable individuals inhaling water spray particles with bacteria.) | Observe / Monitor. | Robust design and verification process. |

| Fail Modes | Impact | Detection | Prevention |
|---|---|---|---|
| **6. Building type – high mass natural plus assisted natural ventilation plus TABS (borehole cooling).** | | | |
| - Thermal mass not available to interact with the space. | Comfort impact (thermal) – i.e. intended benefit not achieved. | Observe locations of thermal mass and access to the rooms. | Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Acoustics problems due to exposed concrete surfaces. | Comfort impact (audio). | Observe acoustics (out of scope for this investigation).<br>Occupant satisfaction survey (e.g. UBT/SL). | The design process should include detailed modelling of the thermal mass and its control regime across the expected variations in climate and pattern of use. |
| - High thermal mass difficult to control due to high time constant. | Comfort impact (thermal).<br>Potential for higher energy use due to increased use of mechanical systems to counter poor control of mass. | Observe / Monitor / Model building in operation. Compare with best practice guidelines. | Similar attention to detail in the design of the room acoustics to account for the high mass surfaces. |

| Fail Modes | Impact | Detection | Prevention |
|---|---|---|---|
| **7.1 Insulation envelope – junctions**<br>- Thermal bridges (service penetrations)<br>- Thermal bridges (window / door attachments)<br>- Thermal bridges (all other junctions) | Heat losses<br>Annual heating energy<br>Heat load too high<br>Comfort compromised<br>Local condensation damage | Thermographic camera.<br>Co-heating test.<br>Air tightness test (+/-).<br>Surface temperatures.<br>Design details / inspection of as built details. | Design details and specifications.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure.<br>Instructions for subsequent work on building (e.g. extensions / services). |
| **7.2 Insulation envelope – surfaces**<br>- Timber fraction too high due to structural elements.<br>- EIFS insulation compromised due to fixings or gaps.<br>- Elemental u-values too high. | Heat losses<br>Annual heating energy<br>Heat load too high<br>Comfort compromised<br>Local condensation damage | Thermographic camera.<br>Co-heating test.<br>Surface temperatures.<br>Design details / inspection of as built details. | Design details and specifications.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |

| | | | |
|---|---|---|---|
| **7.3 Insulation envelope – glazing and doors.**<br>- Poor thermal performance (U values too high, g_solar or g_light values too low, thermal bridges too high, seals not airtight). | Excessive energy use.<br>Comfort compromised. | Check specifications.<br>Thermographic camera.<br>Co-heating test.<br>Air tightness test (+/-).<br>Surface temperatures.<br>Design details / inspection of as built details. | Design details and specifications.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |

The POE of the BRE building involved several short visits to observe the building in operation and interrogate the building management system. The focus was on the systems and controls aspects of the buildings operation and their influence on performance. Given this narrow focus, the application of the FMEA approach is described here for elements 1 to 5 from the list above:

FMEA element 1: Overall building performance.

- It was immediately apparent that there was a lack of visibility in current or historical performance.

- No clear targets for building overall performance or by sub-meter were established.

- Sub-meter energy readings were not available either physically or through the BEMs. Overall performance visibility was only through the fuel bills as received in the finance office.

- In discussions with the buildings manager it became apparent that there was a lack of understanding as to how the building was intended to be operated. The 84 page building operations manual did not aid understanding as it went into great detail on each of the sub-systems without providing a clear picture of combined operations.

- The building manager had been making tweaks to building controls to address immediate issues without being able to assess the longer term impacts.

- Issues such as the lack of sub meters had been raised but budget was not readily available to address this and other subsequent issues found.

### FMEA element 2: Ventilation through assisted natural ventilation (ANV), natural ventilation (NV) and infiltration.

- The ventilation mechanisms were observed to be operating as described in the control manual.

- The controls were observed to be very coarse with all of the numerous windows of each type acting in ganged fashion with no control possible over individual windows except to disconnect them from the actuators.

- The actuators which opened and closed the mechanically operated windows were observed to be noisy.

- Several windows had been disabled through physical disconnection of the actuator in response to complaints of noise or draughts.

- The seminar room low level air intake louver was observed to have a poor seal when closed such that warmed indoor air from the heater battery was being released to the outside (this louver appeared not to seal tightly when closed and did not appear to have good thermal performance characteristics being apparently of mainly aluminium construction). The high level seminar room louver was not accessible for close inspection but appeared to have similar construction.

- The release of warm air to the outside through this louver was in part due to the prevailing pressure across the building from the south to north sides. With this louver in the seminar room being to the north side of the building it is to be expected that in general air will tend to flow out through this opening, a more detailed study of this situation could be done.

- It was not possible to measure the ventilation rates achieved.

FMEA element 3: Cooling through borehole plus ANV plus NV plus night cooling.

- The cooling FMEA was followed (Table 6.2). Initially the operation of each of the different cooling systems was observed.

- The control actuation sequencing was observed to be as in the controls manual. The office cooling and night cooling issues highlighted by the control mapping exercise were observed (mechanical cooling applied before free cooling, poor control of night cooling).

- The issues highlighted in the ventilation section applied also to the ventilation aspects of the cooling function (noisy actuators, coarse control).

- In summer the borehole system actuation was observed and the response of the sensors in the office floor and in the offices observed. It was found that despite the borehole running as intended and water flowing through the underfloor system there was no noticeable cooling effect with water circulating around the underfloor loops at 25 degrees. Further investigation identified that the pumps running for the underfloor circuit had been set to trigger the heating circuits to turn-on and heat the water to the outside compensated setpoint of 25 degrees. So both heating and cooling systems were running with no positive cooling effect. Checking the history of the system this situation was confirmed to have existed since the original implementation of the controls. The cooling and heating modes for operation of the underfloor circuit were incorrectly implemented.

FMEA element 4: Heating systems, radiators, underfloor, air pre-heater, gas boilers.

- The co-incident use of the radiators (fast response) and underfloor (slower response) systems was highlighted as potentially less than optimal in the control mapping process.

- It was observed that both of the boilers were constantly running in stand by mode even during periods of no demand. Further investigation highlighted that the condensing boiler had at some time tripped off causing the back-up boiler to be activated and run at an 85 degree setpoint (normal hot water setpoint 60 degrees). The condensing boiler had been reset but the backup was still enabled and constantly running. Fault condition and recovery logic did not appear to be adequate.

- The main seminar room air heater louver situation was previously highlighted (by the ventilation FMEA). During heating periods this heater battery was set to be on so that whenever there was a requirement for ventilation air this could be satisfied by opening the louver. A sequenced control could be envisioned which would potentially be more efficient e.g. heater off until $CO_2$ or room temperature threshold reached, then heater on to compensated temp if required, then louver opened.

FMEA element 5: Hot water (gas boiler, storage, primary and distribution circuits)

- The legionella control destratification pump was observed to be continuously running when ideally it would only be enabled once per day. In combination with the higher temperature required by the boiler fault condition this was leading to a much higher than needed energy use.

## 6.5 Conclusions on the application of Control Mapping and FMEA to the BRE Environmental Office.

Both the control mapping and the FMEA elements of the approach when applied to the Environmental office provide some useful outcomes.

The control mapping highlighted clearly how the building was being controlled which had been unclear to the building manager and controls service engineers. This provided a useful baseline for further investigations as well as for future operation of the building.

From the simple control map representation it became possible to identify areas where the controls could be optimised to improve building performance.

The Control Mapping and FMEA approach proved to be a useful methodology for planning a post occupancy evaluation focussed on the specifics of the building type, its systems and their controls.

Through this POE, conducted using the Control Mapping and FMEAs as a framework, it was possible to determine whether the systems and controls were operating as intended or identify disconnects where this was not the case.

The fail modes identified a-priori formed a useful template but the FMEA format was also useful in capturing additional fail modes or potential fail modes highlighted during the conduct of the POE.

This updating of FMEAs illustrates the evolutionary function of the documents and their potential role in capturing information to be used earlier in the design process on future buildings to ensure that the failures occurring in current buildings are not replicated.

Similarly these updated FMEAs are now available for further POE use on similar buildings or buildings with similar system types.

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# Chapter 7. Test application of the Modular Control Mapping and FMEA method to low energy domestic buildings and systems; and overall conclusions on the method.

*The hypothesis has been advanced that a Modular Control Mapping and FMEA method could be useful to address gaps between intended and actual performance for low energy systems and controls.*

*The previous chapter described the proposed method and a test application of the method to a low energy office.*

*In this chapter the Modular Control Mapping and FMEA method is applied to two low energy domestic buildings with a range of low carbon systems.*

*Then overall conclusions and general applicability of the proposed method are discussed.*

## 7.1 Introduction

The domestic sector has seen increasing promotion and use of low carbon technologies such as heat pumps, solar thermal systems, mechanical ventilation systems with heat recovery, photovoltaic systems, biomass boilers, combined heat and power (CHP) etc. As in the non-domestic sector, in cases where there has been scrutiny of the actual performance, it has often been poorer than intended (EST 2012).

The control mapping and FMEA process described in the previous chapter is intended for use across domestic as well as non-domestic sectors to address these problems.

For the domestic sector two case study buildings were used to test the hypothesis. One was the first Scottish Passive House in Dunoon. This has mechanical ventilation with heat recovery, an air-source heat pump and a solar thermal hot water system.

The second test application for the domestic sector was the Glasgow House, an exemplar low energy house with mechanical ventilation and a solar thermal hot water system.

Both of these dwellings and their low carbon systems are intended to be pilot building projects for future replication. While not the main objective of this work, it is however very appropriate to investigate their actual performance so that knowledge gained can inform the intended replications.

## 7.2 Application of Control Mapping and FMEA to a Scottish Passive House.

The Passive House standard has since 1998 been promoted through EU funded projects as a suitable advanced standard for buildings across central and northern Europe (CEPHEUS 2012). The Passive House standard has however only recently become popular in the UK and Scotland.

The control mapping and FMEA test application to the Scottish Passive house was carried out in 2011 / 2012. The work formed a subset of a larger investigation by the author into performance of three dwellings in Dunoon, on the west coast of Scotland. The three dwellings are within 250m of each other with similar orientation and occupancy but were built to different standards representative of: Passive House standards; 1950's Scottish building standards; and approximately 2010 Scottish building standards (labelled 'code 4' or 'low energy' by the architect). The Passive House included mechanical ventilation with heat recovery (MVHR), air to air heat pump and solar thermal hot water heating systems which are in general being encouraged by Government for new build and retrofit. The monitoring was carried out over 1 year and included indoor environment (relative humidity (RH), carbon dioxide ($CO_{2)}$, and temperatures T)) outdoor conditions (Solar illuminance, T, RH), energy use (Watts, kWh), operation schedules, and hot water system temperatures (T). The focus here is on the application of the method to the Passive House but to aid understanding some of the Passive House results and findings are shown in relation to results from the the other monitored dwellings in the Dunoon study.

**Figure 7.1. Location in Scotland of the three monitored dwellings: 1 = Passive House, 2 = 2010 regulations house (labeled 'code 4' or 'low energy' by the architect), 3 = 1950's house; the low energy development; the Passive house.**

The Modular Control Mapping and FMEA method was applied to the Passive House in the four stages described in the previous chapter.

### 7.2.1 Stages 1 to 3 and use of Control Mapping

Stage 1 of the method is to develop a high level understanding of the building and its zones and plant systems.

The 1st Scottish Passive House is an end terrace family home with 2 bedrooms situated in Dunoon Scotland. The project has been highly publicised and won a number of awards. The Architect and Services Designers as well as the Developers and the Occupant were all interested in having the building's actual performance assessed through a POE exercise.

The novel features of the Dunoon Passive House include a highly insulated building envelope, high performance glazing, a mechanical ventilation and heat recovery unit, an air source heat pump and solar thermal hot water system. The solar thermal system consists of a flat panel collector connected to the bottom half of a vertical storage tank with a back-up electrical heater available to heat the top half of the vertical storage tank. The storage tank has two temperature sensors positioned half way up each section (upper and lower).

The Designers and Architects supplied the plans, including the Passive House Planning Package (PHPP) calculations for the building and its services. The main components of the building to be included in the mapping process were determined to be:

- A single building zone.
- The heating system.
- The ventilation system.
- The hot water system (including the solar thermal system).
- Lighting and shading systems.

A single zone was selected to represent the building as the Passive House design approach treats the internal area as one zone due to its relative connectedness through internal walls, doors and ventilation paths compared to its isolation from the outside environment through high external fabric airtightness and insulation. Lighting and shading systems were not considered in the current case study as there was no automated system in place.

Stages 2 and 3 of the method are to understand the operation of the systems and controls for each component and for each time step and then to create control maps to allow these to be readily comprehended.

In post occupancy there is the opportunity to approach this from three different perspectives: from the concept design perspective (if the design concept is available), from the controls intended implementation perspective (if the system and control plans are available), and from the controls 'as observed' perspective.

The system and controls mapping for the Passive House was expected to present a much simpler task than for the Environmental Office. One difficulty encountered however, was the lack of any specification of controls in the design documentation. Rather this had been delegated to the suppliers and installers of the systems themselves. It was however possible to postulate the 'intended' control regime from general Passive House guidance and accreditation documentation and industry standards (PHI 2012, CEPH 2012). This intended system and controls operation map is shown in figure 7.2. The map has assumed that the building is a single zone and that there is only one time period (a day) for each of summer, winter and intermediate season cases.

The Passive House approach is to minimise the demand for space heating and the size of the heating system required. One consequence of this approach is that the space heating system is sized to be controlled from a central thermostat and be available constantly to come on during periods when heat is demanded as there is no over sizing of the system to facilitate intermittent heating schedules during cold periods.

The system sizing is based on the averaged worst case weather periods (of the order of a week) rather than an absolute worst case low temperature. This is justified based on the slow response of the highly insulated and airtight Passive House. The Passive House sizing method also includes the probability of solar gains during these colder periods. Again, this sizing is only appropriate where heating is set to be constantly available rather than on an intermittent schedule (PHI 2012).

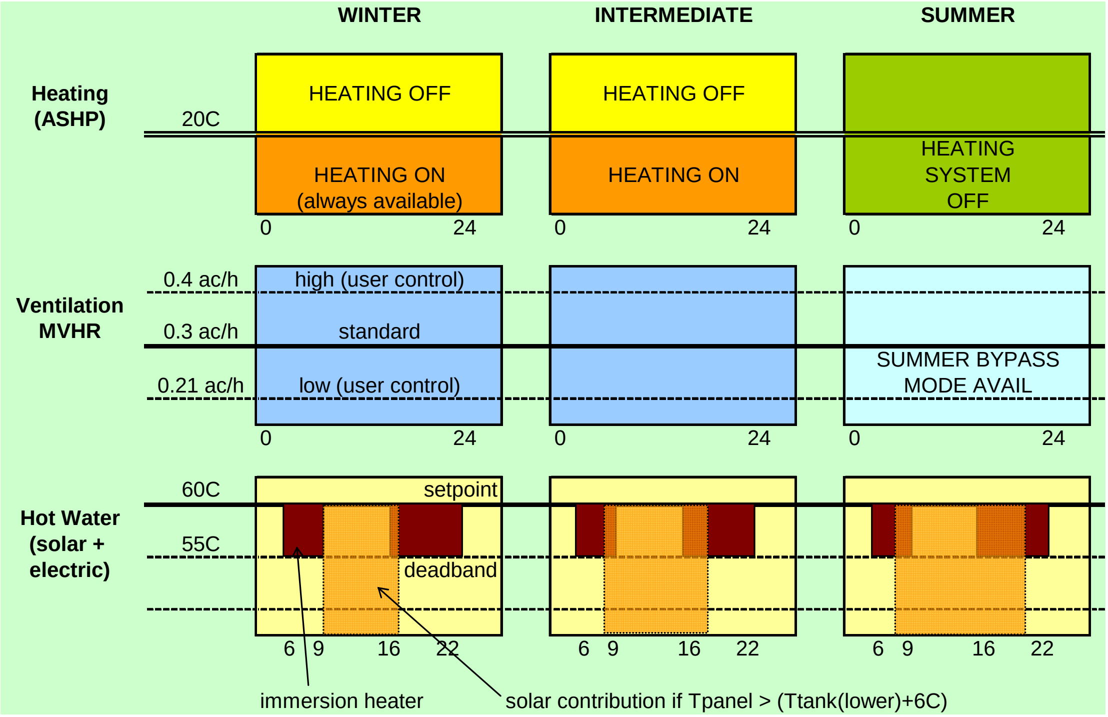
The planning for ventilation in a Passive House generally assumes air is delivered continuously through a whole house system with a controlled ventilation rate. The planning process includes the requirement for 30 $m^3$/h per person of outdoor air or 0.3 ac/h whichever is higher. For the Dunoon Passive House the 0.3 ac/h criteria was applied. The ventilation is planned to run at this standard setting continuously but the user is able to adjust as required to suit their circumstances. It is mandatory to have at least ‘low’ and ‘high’ user settings of 0.7x and 1.3x relative to the standard setting. In the summer worksheet of the PHPP it was entered that ventilation would be by window opening but since the internal bathrooms had no access to windows it is assumed here that the unit would run continuously in summer. The unit has the option of running in bypass mode which excludes the heat exchanger from the ventilation paths and saves some fan energy. It was not clear whether this was intended to be used but it was noted on the control maps as an option.

The hot water system assumptions in the PHPP are simply that water is delivered at $60^oC$. There are no prescriptions about timings of the back-up electrical heater. UK

Energy Savings Trust documentation (CE131, EST 2011) suggests that the back-up heating should be left to come on as 'normal' after a solar thermal installation so in the as intended / design concept control map this has been represented as backup heating on from 6am till 9am and from 4pm till 10pm. The hot water backup heater is positioned so as to heat the top half of the storage tank only. These settings for the hot water backup heater will be discussed more later (section 7.2.2).

The solar panel feeds a heat exchanger in the bottom half of the solar thermal tank and the solar system circulation pump is assumed here to be activated if the panel temperature is 6$^{o}$C above the water in the centre of this bottom solar portion of the tank. This first pass assumption is based on standard industry practice (Duffie and Beckman 2006).

***Figure 7.2. 'As intended' control map constructed for the heating, ventilation and hot water system components of the Passive House.***



This initial control map was then used as a basis for discussion with the occupant, architect, designer, and the installers of the systems and also as a starting point for the POE. An intended outcome of the POE is a control map representing the controls as implemented (and potentially a further control map to illustrate possible improvements).

### 7.2.2 Stage 4

Stage 4 of the process involves the review of best practice guidance and implementation of an FMEA approach targeted at the appropriate building type, systems and technologies for the case study building. The same Passive House guidance and industry best practice information used in constructing the initial control maps was used in constructing the FMEAs for the appropriate elements for the Passive House POE. The author also completed accreditation as a Passive House Designer and Trainer through the EU CEPH project (CEPH 2012) and visited a range of Passive Houses in Germany and Austria. The elements covered by FMEA approach for this test case were:

1. Overall building performance.
2. Building fabric including summer temperatures.
3. Space Heating (ASHP).
4. Ventilation (MVHR).
5. Hot Water (Solar thermal with electric backup).

The work presented here is focussed on the systems and controls aspects of building performance. Some initial general observations on the overall building performance are made here based on element 1, followed by some more detail on the findings generated from the use of elements 3, 4 and 5 of the FMEA. Element 2 of the FMEA was generated and included in the FMEA documentation but is not reported on in detail here. The initial FMEA generated for the Passive House and the appropriate technology elements is given in table 7.1.

***Table 7.1 FMEA for the Dunoon Passive House.***

| Fail Modes | Impact | Detection | Prevention |
|---|---|---|---|
| **1. Overall building performance** | | | |
| - fails to meet intended performance | Energy and cost compromised.<br>Comfort compromised.<br>Remediation expense and disruption. | Checking of occupant understanding of building systems, controls, system performance, and system maintenance requirements and how to meet these.<br>Fuel bills compared to targets (adjusted by weather).<br>Monitor energy performance (main and sub-metering) against targets (e.g. TM22).<br>Monitor occupant experience (UBT/SL).<br>Monitor summer comfort performance (Tresultant etc). | Robust design and <u>verification processes.</u><br><u>Clear performance feedbacks to occupant.</u><br><u>Clear communication of operation, performance, controls for systems and maintenance specifications and why / who / when / how.</u> |

| | | | |
|---|---|---|---|
| **2.1 Fabric: Insulation envelope – junctions**<br>- Thermal bridges (service penetrations)<br>- Thermal bridges (window / door attachments)<br>- Thermal bridges (all other junctions) | Heat losses<br>Annual heating energy<br>Heat load too high<br>Comfort compromised<br>Local condensation damage | Thermographic camera.<br>Co-heating test.<br>Air tightness test (+/-).<br>Surface temperatures.<br>Design details / inspection of as built details. | Design details and specifications.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure.<br>Instructions for subsequent work on building (e.g. extensions / services). |
| **2.2 Fabric: Insulation envelope – surfaces**<br>- Timber fraction too high due to structural elements.<br>- EIFS insulation compromised due to fixings or gaps.<br>- Elemental u-values too high. | Heat losses<br>Annual heating energy<br>Heat load too high<br>Comfort compromised<br>Local condensation damage | Thermographic camera.<br>Co-heating test.<br>Surface temperatures.<br>Design details / inspection of as built details. | Design details and specifications.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |

| | | | |
|---|---|---|---|
| **2.3 Fabric: Insulation envelope – glazing and doors.** | | | |
| - Poor thermal performance (U values too high, g_solar or g_light values too low, thermal bridges too high, seals not airtight). | Excessive energy use.<br>Comfort compromised. | Check specifications.<br>Thermographic camera.<br>Co-heating test.<br>Air tightness test (+/-).<br>Surface temperatures.<br>Design details / inspection of as built details. | Design details and specifications.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |
| **2.4 Fabric: Summer performance** | | | |
| - Summer window ventilation not sufficient / not secure / not accessible / not possible. | Thermal comfort compromised.<br>Potential for installation of mechanical cooling with associated energy use. | Check PHPP assumptions on ventilation openings and patterns of use against physical implementation and also understanding and behaviour of occupants. | PHPP design calculations to capture realistic assumptions on window opening, blind and external shade use etc (including security, pollution, privacy constraints) for summer performance ensuring all components (usable controls, secure openings, shades etc) get translated into specifications and user instructions.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Shading of S,E and W windows and glazed doors not sufficient. | | Check PHPP assumptions on shading against physical implementation and understanding and behaviour of occupants. | |
| - Summer MVHR use not | | Similar to above but for | |

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| as planned. |  | summer MVHR use. | Plus – detailed calculations for all rooms assessed as high risk of overheating (dynamic simulation assessment of thermal comfort with range of appropriate range of climate and behavioural variations). |
| - Thermal mass planned but not available to moderate temperatures. |  | Similar to above but for thermal mass (e.g. was tiled concrete floor planned but implemented as timber on insulation layer etc). |  |
| - High internal gains e.g. from poorly insulated hot water systems etc. |  | Check for high gain situations e.g. poor insulation on hot water system or primary / solar / distribution pipe-work. | Design details and specifications.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Individual rooms or spaces suffer from overheating. |  | Check for rooms with high gains / poor ventilation etc.<br>Monitor temperature (air and radiant) and ventilation performance. Monitor summer comfort conditions.<br>Carry out simulation study. |  |

| | | | |
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| **3.1 Space heating system – general.** | | | |
| - Insufficient capacity for intermittent heating. (PHPP heating system sizing is for constantly available heating with a remote thermostat). | Inability to maintain comfort temperature with primary system Excessive use of backup heating.<br>Overall higher energy use.<br>User comfort compromised. | Check design intent.<br>Check available controls.<br>Check user understanding and patterns of use.<br>Monitor / observe system performance against targets. | Clear design strategy – if using PHPP system sizing – heating must be always on and controlled by a remote sensor.<br>Clear communications to occupants and user manual. |
| - Insufficient distribution of heat throughout building. (PH system may rely on air movement, supply /extract/transfer openings etc.). | Comfort compromised (thermal).<br>Excessive use of backup heating.<br>Overall higher energy use. | Check air transfer (see ventilation FMEA).<br>Check / observe room by room gains and losses and resultant temperatures (air and radiant) performance. | Consider room by room gains / losses and patterns of use.<br>Provide appropriate occupant controls / systems for comfort adjustments. |
| - Excessive use of bathroom electric towel rails. (PH design generally includes heated towel rails in bathrooms). | Energy use increased. | Check user understanding and patterns of use.<br>Check system controls.<br>Monitor / observe system performance. | Provide “user on / timed off” control of bathroom towel rails – sufficient for towel dry and comfort but limits energy use.<br>Design specification.<br>Verification / witness procedure. |
| - Controls not optimised | Comfort compromised. | Check occupant understanding | Clear control strategy specified |

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| for demands, tariffs etc. | Excessive use of back-up heating.<br>Excessive energy use. | and user guidance.<br>Check controls settings.<br>Monitor / observe system perf. | for optimum performance seasonally considering tariffs etc.<br>Quality of work on site.<br>Verification/witness procedure.<br>Clear communications to occupants and in user manual.<br>Usable controls. |
| **3.2 Space heating system – air to air heat pump with electric fire backup.** | | | |
| - Heat pump poor performance. | Energy and comfort compromised. | Monitor system performance against targets. (Heat, el, Tout, RHout, Tin). | Design in performance feedbacks. |
| - Heat pump undersized for cold weather conditions.<br>- Heat pump defrost mechanism not appropriate to Scottish climate. | Problem maintaining comfort conditions without alternate heating.<br>Poor efficiency in cold weather conditions (potentially below 6 degrees) | Check manufacturers cold weather (-2, -7 etc) performance data (including defrost cycle) against PHPP load calc.<br>Monitor / observe system performance against targets (Heat, el, Tout, RHout, Tin). | Correctly specified HP for full range of outside and supply temperatures including defrost and part load operation. Sized for intermittent or constant winter heating use as appropriate. |
| - Heat pump sized for constantly on mode but operated in intermittent | Compromised thermal comfort. | Check occupant understanding and control settings against heat pump sizing used in | Design intent clearly translated into controls and users guidance. |

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| mode. |  | design PHPP. (+ monitor HP perf). | Quality of work on site.<br>Verification/witness procedure. |
| - Heat pump oversized especially for milder periods giving short cycling and inefficiency. | Excessive on/off cycling with efficiency penalties (unless variable speed compressor control capability). | Check manufacturers part load performance data and whether variable speed compressor has been specified. (+ monitor HP). | Correctly specified HP for full range of outside and supply temperatures including defrost and part load operation.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Heat pump short cycling due to temperature sensor too close to heat delivery point (possibly integrated into indoor unit - should be in another room). | Reduction in effective capacity due to short cycling.<br>Comfort compromised as local rather than whole house temperature controlled. | Check thermostat and programmer placement for space heating. | Design intent clearly translated into controls and users guidance.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Heat pump poor performance because in need of maintenance. | Energy.<br>Comfort. | Check maintenance records.<br>Check understanding of occupant.<br><u>Check / monitor system performance.</u> | Ensure system self monitors and alarms; and occupant fully aware of system alarms and maintenance schedules and source of maintenance service. |

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| **3.3 Space heating system – wood fuel stove.** |  |  |  |
| - No separate air supply from outside air. | Unbalancing of MVHR, need for infiltration through a wall vent compromising heat recovery and heat losses etc. | Check for separate air supply to room sealed appliance. | Correct specification of sealed appliance with outside air supply.<br>Quality of workmanship.<br>Verification/witness procedure. |
| - Overheating due to over specified system. (should normally be small space heat contribution and large water heating). | Overheating leading to energy waste through compensatory use of free cooling. | Check appliance ratings for heating and hot water against heat loads (PHPP).<br><u>Observe / monitor operation (Temps).</u> | Correct specification of sealed appliance with outside air supply.<br>Quality of workmanship.<br>Verification/witness procedure. |

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| **4. Ventilation system (MVHR)** |  |  |  |
| - MVHR system specification (HR < 75%, el > 0.45Wh/m3, db > 25) | Heat losses<br>Annual heating energy<br>Heat load too high<br>Comfort compromised | Check manufacturers specification for installed system.<br>Monitor / observe system performance. (CO2, RH, Texh/sup, El etc). | Specification.<br>Verification/witness procedure. |
| - Duct system and components not to standard (rigid duct, size, insulation, deltaP, terminals, layout/zoning, filters, frost protection, air heating, transfer openings, silencers (mc/x-talk), fire). | Heat losses<br>Annual heating energy<br>Heat load too high<br>Comfort compromised (thermal and audio)<br>Electricity use increased.<br>Air quality compromised. | Check all design elements against PH specs.<br>Check installed system against design.<br>Monitor unit electricity use. | Design details.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Duct system airflows insufficient or not correctly balanced. | Air quality compromised | Balometer measurement within 10% of design airflows for each room at standard setting.<br>Check total airflow against design specs (30m3/p/h or 0.3ac/h at standard, 0.7x at low, 1.3x at high). | Design airflows correct.<br>Design details.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |

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| - System noise levels > 25db.<br>- room to room audible x-talk (privacy)<br>- fan noise to outside. | Comfort compromised (audio). | Inaudible at standard setting (0.3 ac/h or 30m$^3$/h/person).<br>Just barely audible at boost (1.3x standard vent rate.<br>Check room to room audio isolation. | Machine and duct system / component specification.<br>Machine silencers. X-talk silencers. Efficient duct layout with low pressure drops. Supply / transfer / extract openings with low pressure drop. |
| - Ducts to outside - too long or insulation not sufficiently thick. | Heat losses<br>Annual heating energy<br>Heat load too high<br>Comfort compromised (thermal) | Inspection.<br>Surface temperature (probe or thermographic camera). | Ducts to outside short as possible.<br>Insulation and vapour barrier correctly specified in design and PHPP.<br>Design details. |
| - Ducts to outside – insulation not completely sealed with vapour barrier. | Local condensation damage.<br>Loss of insulation properties (same impact as insulation not sufficiently thick or missing). | Inspection.<br>Check materials specifications (particularly vapour barriers and all connecting tapes/gaskets). | Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure.<br>Instructions for subsequent work on building. |
| - Supply air ducts not insulated if supplying heating. | Heat losses<br>Comfort compromised (thermal, overheating in some areas and not sufficient heat delivered to others) | Inspection.<br>Surface temperature (probe or thermographic camera). | Design details.<br>Robust materials, sequencing and systems.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Filters not F7/G4 int/ext.<br>- Filters not maintained. | Air quality compromised.<br>Fan power increased. | Check filter spec and condition. | Correct specifications in design and installed (verified). |

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| | Fan noise increased. | Check for user understanding, user log, maintenance records. | Clear user instructions. |
| - Outside air intake / exhaust placement poor (fumes, frosting, entrainment, noise). | Air quality compromised. | Check placement and terminal type suitable to application.<br>Check outside fan noise levels. | Design details and specifications.<br>Robust materials, components, and connections / sequencing.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Controls not sufficient to allow correct operation. (v.low/low/std/high/boost, summer bypass, extract only etc).<br>- User instructions for operation not sufficient to allow correct use. | Higher than required energy use.<br>Compromised air quality.<br>Potential loss of free cooling assumed in planning (summer comfort). | Check user understanding and controls / actual use pattern against PHPP assumed patterns of use.<br>Monitor / observe system performance. (CO2, RH, Texh/sup, Tres, El etc). | Design details.<br>Quality of work on site.<br>Verification/witness procedure.<br>Clear and simple user instructions. |
| - Defrost control set to run too often. | Electricity use increased. | Check setting against spec.<br>Check / monitor actual operation. | Correct design.<br>Verification/witness procedure. |
| - Maintenance requirements of system not carried out. | Higher than required energy use.<br>Compromised air quality. | Check for user understanding, user log, maintenance records.<br>Maintenance contractor details.<br>Access for maintenance. | Clear user instructions on requirements for user and service company interventions.<br>Source for parts for user maintenance. Source(s) identified for servicing.<br>Maintenance access designed. |

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| **5.1 Hot water system – general.** | | | |
| - Storage system or attached pipework (primary, distribution, solar etc) not correctly insulated. | Heat losses.<br>Comfort (Potential overheating due to unintended gains). | Check insulation against correct specifications (BS, PHPP).<br>Monitor / observe store temp decay curve against planned. | Design details.<br>Robust materials, components, and connections / sequencing.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Legionella risk. (storage and significant distribution lengths to be sterilised per HSE 8. | Health issue for vulnerable individuals inhaling water spray particles with bacteria. | Check legionella regime against HSE 8 requirements (controls).<br>Monitor / observe system performance. (heat flows, temperatures, electricity use). | Design to account for legionella.<br>Quality of work on site.<br>Verification/witness procedure. |
| - Controls not optimised for demands or tariff etc. | Excessive energy use. | Check user understanding and settings compared to user patterns of use.<br>Monitor / observe system performance against targets (heat flows, store temp decay curve, temperatures, electricity). | Consider patterns of use and tariffs in design and implementation of controls.<br>Verification/witness procedure.<br>Clear user instructions. |

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| **5.2 Hot water system – solar thermal with electrical backup.** | | | |
| - Solar system and backup system controls not optimised.<br>- Solar system interaction with backup heating unclear to occupant. | Potential increased energy use.<br>Potential legionella risk. | Check user understanding, control settings and pattern of use.<br>Monitor / observe system performance (heat flows, temperatures, electricity use against targets). | Consider seasonal and day to day solar patterns, occupant patterns of use and tariffs in design and implementation of controls.<br>Verification/witness procedure.<br>Clear user instructions.<br>Performance of system to be clearly displayed to user. |
| - Solar system malfunction not visible to occupant. Maintenance operations not carried out. | Potential increased energy use.<br>Potential legionella risk. | Check visibility and user understanding of solar system performance.<br>Check performance against expectations.<br>Check for regular maintenance schedule. | Design in visibility of solar system performance.<br>Clear user instructions on controls, operational performance, maintenance requirements and service companies. |
| - Solar system pipework incorrectly insulated (Temp rating 150 degrees, or insulation missing).<br>- Outdoor insulation and | Missing or melted insulation:<br>Heat losses.<br>Comfort (Potential overheating due to unintended gains). | Check insulation against correct specifications (BS, PHPP) Note: 150 degrees or higher temp rating on solar thermal systems. | Design details.<br>Robust materials, components, and connections / sequencing.<br>Quality of work on site.<br>Verification/witness procedure. |

| | | | |
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| connections to be appropriate (for UV and weather). | | | |

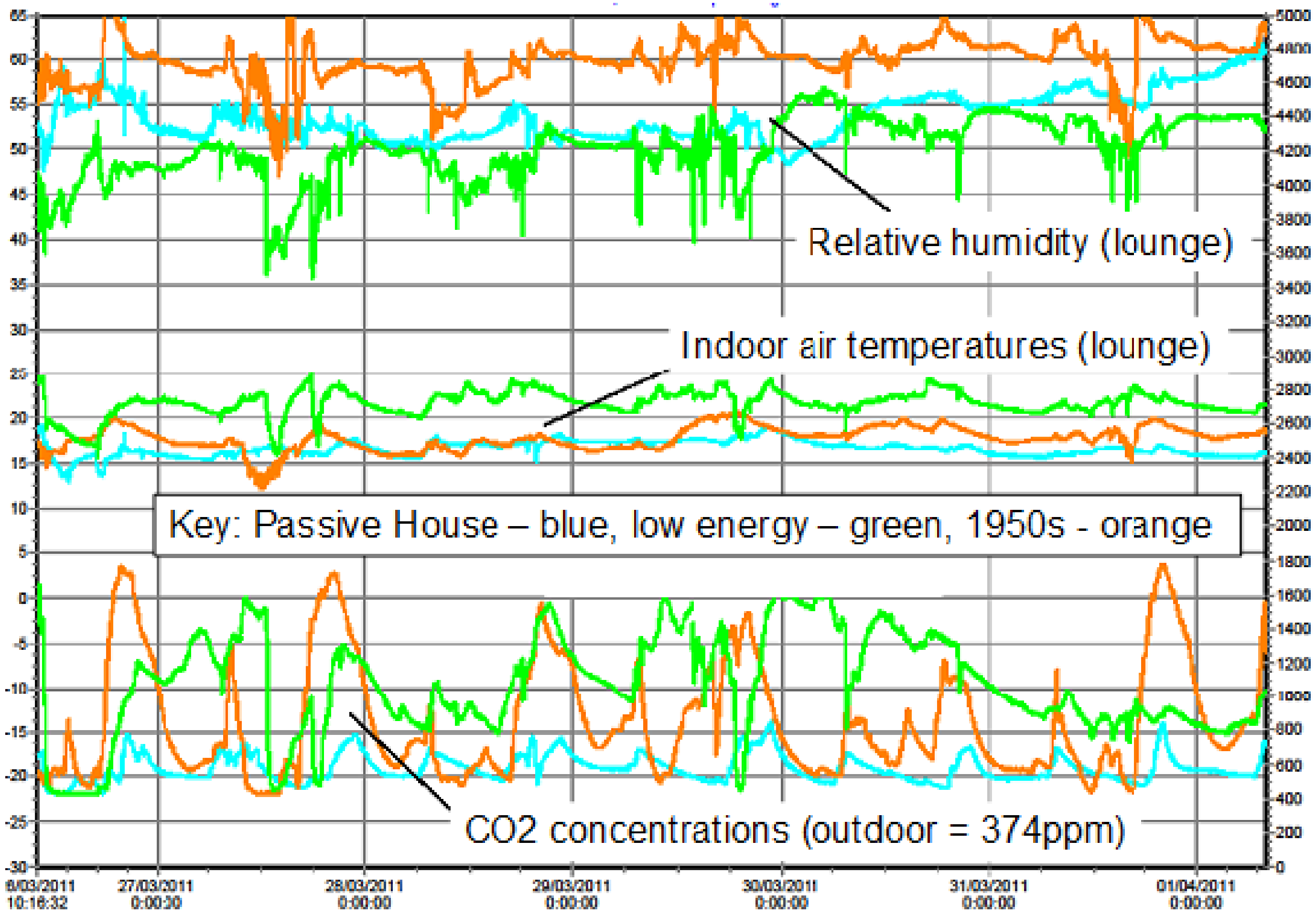
The findings generated from the use of elements 1, 3, 4 and 5 of the FMEA are listed below:

FMEA element 1: General observations on overall performance.

The occupant was interviewed and provided the following insights:

- The building was cold and difficult to heat to comfortable temperatures (the observation of low temperatures was backed up by initial monitoring data which showed the Passive House to be colder than the ‘low energy’ dwelling and similar to or colder than the 1950s dwelling (figure 7.3)).
- The heat pump was stated to be ‘not working’ when it was cold outside, just blowing cold air rather than delivering heat.
- An air heater had been provided as a temporary measure but even with this in place the building was cold.
- Electric towel rails for the two bathrooms had been recently supplied (they had been originally specified but omitted from the build).
- The occupant had a very poor understanding of operation and performance of the systems, system controls, system maintenance requirements or potential sources for maintenance and parts (e.g. filters). There was no useful house manual available with this information.
- There was no useful performance indication for the heat pump or solar thermal systems and only a complicated display for the MVHR.
- The fuel bills the occupant was experiencing were much higher than expected, reported as being similar to those experienced in their previous property (a two bedroom 1920s sandstone flat with electric storage heating).

***Figure 7.3. An example of monitored data in November for the Passive House (blue), 2010 regulations (code 4) house (green), 1950's house (orange). $CO_2$ (bottom 3 lines, right axis), Indoor temp and RH (both left axis).***



### FMEA element 3: Space heating systems (Air source heat pump)

Based on reviewing the building against the FMEA sections 3.1 (general space heating) and 3.2 (space heating with an air to air heat pump) the following observations were made:

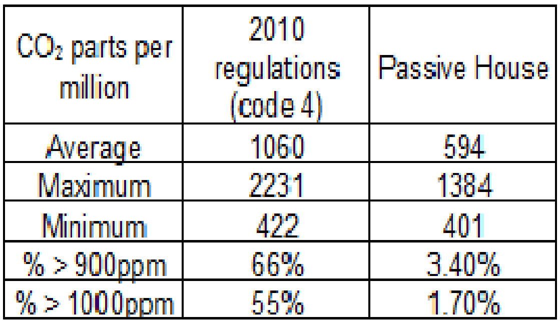
- The heating was being operated in intermittent mode (user switching on and off) which in cold periods could potentially lead to under-heating as system was sized based on PHPP criteria for constantly available heating.
- The system control was based on the heat pump indoor unit's built in thermostat rather than a remote thermostat as called for in the Passive House design guidance. This would be a potential cause of short cycling of the system and restrict the ability to perform as a whole house heating mechanism.
- The heat distribution through ventilation air depends on free airflow from supply rooms to extract rooms which requires air transfer openings through or around doors (normally a door undercut or architrave air transfer duct) – there appeared to be no provision of these transfer openings. If they had been provided, door undercuts had been compromised by subsequent floor coverings.
- The specification of the towel rails for the bathrooms did not include any timed-off function which would be ideal to ensure that excessive electricity is not used.
- The specification of the heat pump was checked with the manufacturer. Performance data at low outdoor temperatures such as 2C, 0C, -2C, -7C were requested. The supplier could give values for performance only at 7C. Defrosting is normally required below 6C and can significantly impact performance. The manufacturer could not give any indication of the performance of the system in defrost mode. It was concluded that the system could not be verified to be fit for purpose in this application.

### FMEA element 4: Ventilation (mechanical ventilation with heat recovery)

Reviewing the installed systems against the FMEA allowed the following observations:

- The MVHR system was of a type certified for Passive House use with heat recovery of 92%.
- Monitoring of $CO_2$ levels in the Passive House and the other 2 dwellings showed the Passive House to have consistently lower $CO_2$ levels indicating adequate fresh air flows (figure 7.3, table 7.2).
- The duct system when inspected had many faults (figure 7.4);
    - The cold ducts (intake and exhaust) were very long. The MVHR unit was placed in a central cupboard requiring around 12m of cold duct within the thermal envelope leading to very large heat losses unless unfeasibly thick insulation was applied and moisture sealed.
    - The insulation on these ducts was missing or where applied was inadequate (loose with open joints, 19mm v. 140mm specification, not vapour sealed) leading to huge heat losses.
    - As reported above, there were no transfer openings to allow airflow (these openings should be sufficient for < 1Pa pressure drop).
- The inadequate insulation on the cold ducts caused condensation made visible on removing ceiling panels. If undetected this could have resulted in moisture damage to the structure and reduction in wall insulation effectiveness. Where there was duct insulation of a mineral wool type its effectiveness was completely compromised by being wet – leading to very high heat losses.
- The operations manual for the MVHR was around 60 pages and was not in a format that allowed the occupant to understand it.

**Table 7.2 Comparison of $CO_2$ monitoring results for the Passive House (which has mechanical ventilation with heat recovery) and the 2010 regulations dwelling (intermittent extracts and window trickle vents) over a 3 month period.**



| $CO_2$ parts per million | 2010 regulations (code 4) | Passive House |
|---|---|---|
| Average | 1060 | 594 |
| Maximum | 2231 | 1384 |
| Minimum | 422 | 401 |
| % > 900ppm | 66% | 3.40% |
| % > 1000ppm | 55% | 1.70% |

***Figure 7.4. Issue with the ventilation system: missing transfer openings under doors, missing and inadequate cold duct insulation, moisture problems due to inadequate insulation and sealing of cold ducts.***

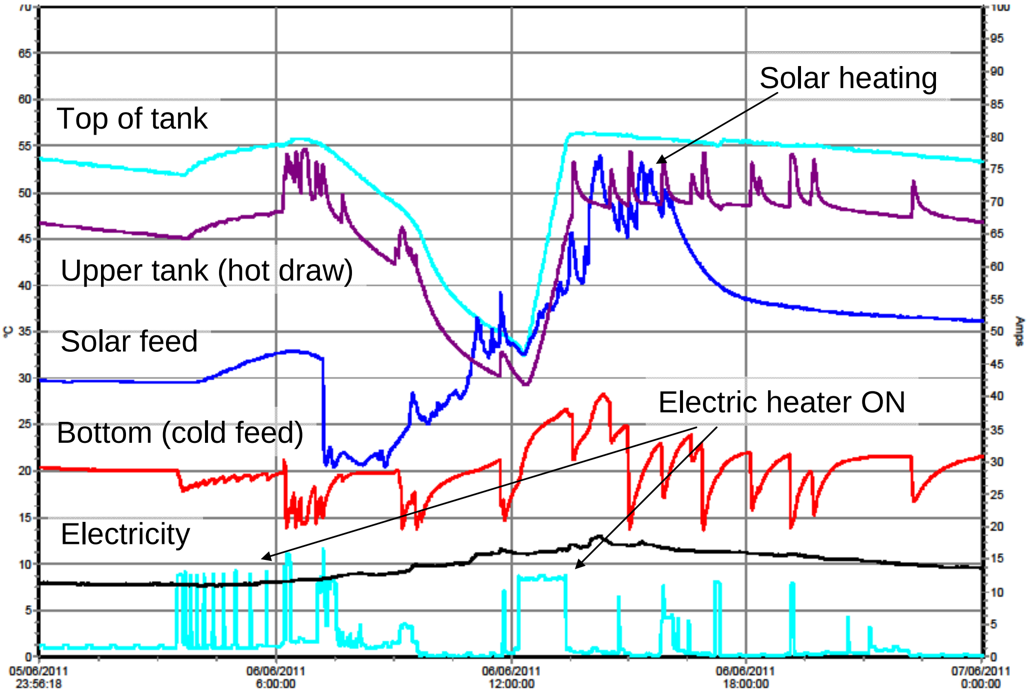
FMEA element 5: Hot water systems (solar thermal with electric back-up)

Based on reviewing the building against FMEA sections 5.1 (general hot water heating) and 5.2 (water heating with solar thermal system with electric back-up) of the FMEA the following observations could be made:

- Pipework associated with the thermal store was not fully insulated – some lengths of pipework attached to the storage tank were un-insulated leading to higher than planned heat losses.
- Legionella had not been explicitly considered. Solar system installers had instructed occupant to 'leave the back-up heating on at normal setting' but the back-up electric heater will only sterilise the upper portion of the tank leaving the bottom portion un-sterilised in winter when the solar thermal system does not raise temperatures above around 40C.
- Off peak tariffs for the back-up heater had not been considered.
- It was found that the back-up heater was programmed to come on in an 'economy 10' pattern with 'on' period between midnight and 5am, 1pm to 4pm and 8 to 10pm all year round. This could be expected to reduce the gains possible from solar heating of this upper portion of the tank in summer when high temperatures are possible from the solar system (figure 7.5).
- The occupant had no awareness of system performance, controls or maintenance requirements.

- It was observed that on some occasions the water leaving to return to the solar panels was warmer than that flowing from the panels into the tank heat exchanger.

***Figure 7.5. Observed performance of the solar thermal and storage system temperatures (various colours) and back-up heating electricity use (light blue, bottom, right hand scale (Amps)). The top of the tank (l.blue), upper tank (hot water draw, purple), solar feed from panel (inputs half way up tank, navy blue) and cold feed from mains (inputs at bottom of tank, red) temperatures were monitored (left scale, $^{o}$C). The outside temperature is also shown (black).***



Control maps

Carrying out the POE allowed the control maps to be created for the controls as they were found to be implemented.

The ‘as implemented’ map for the heating system is shown in figure 7.6 which can be compared with the as intended map of figure 7.2 allowing useful comparison. It is possible to postulate an improved system and control map as shown in figure 7.7, this would require installation of a more capable heat pump controlled by a remote thermostat and also improved controls on the towel rails. The transfer openings for air movement would also require to be remedied, as would the high heat losses due to the problems with the MVHR cold ducts. (In fact based on these findings the MVHR unit was moved to be directly adjacent to the outside wall of the dwelling and the remaining very short cold ducts properly insulated and sealed). The new controls regime and also other user information would require to be clearly communicated to the occupants.

***Figure 7.6. Heating system control map 'as implemented'.***

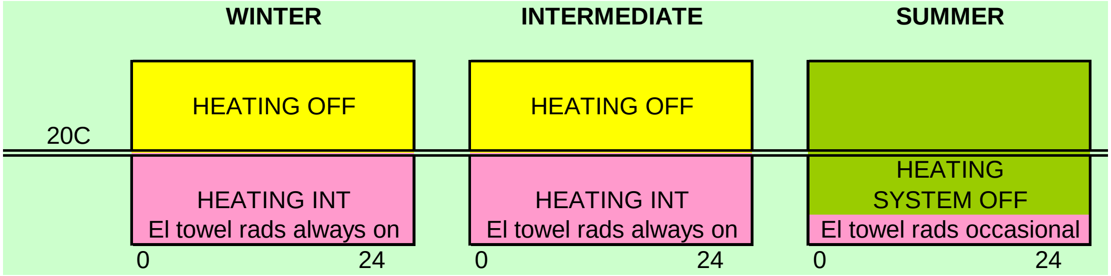
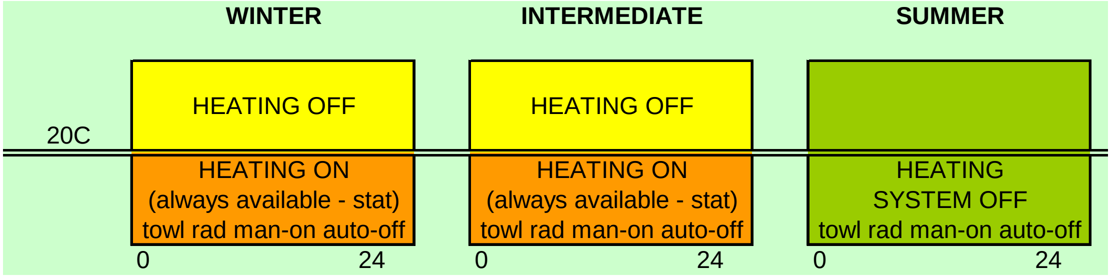


***Figure 7.7. Heating system control map 'proposed improvements'.***



The same information for the 'as implemented' and 'possible improvements' versions of the ventilation control map are shown in figure 7.8 and 7.9 which again can be usefully related back to the as intended controls of figure 7.2. It was found that rather than having a constant ventilation rate the MVHR unit had been programmed to perform at 'boost' during expected occupied hours in the morning and evenings and have a 'low' setting during the daytime. The instructions to the occupant were not to adjust the system unless there was a problem. It is postulated here however that it would be reasonable to use the 'summer bypass' mode which bypasses the heat exchanger and reduces the fan power requirements in the summer period when heat recovery is not required (normal fan power is around 30W, in summer bypass this could be expected to be around 20W).

*Figure 7.8. Ventilation system control map ‘as observed’.*

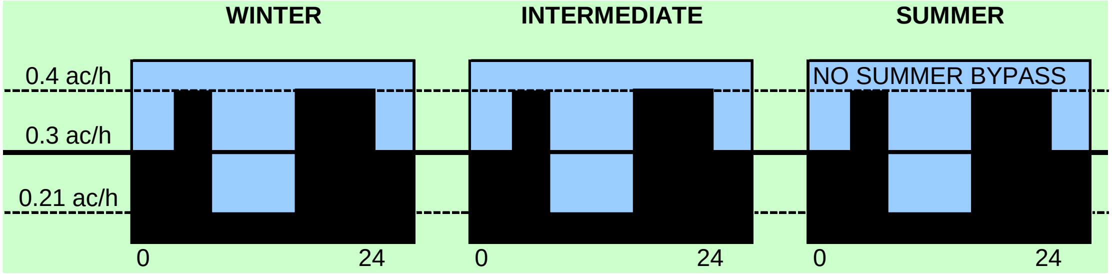
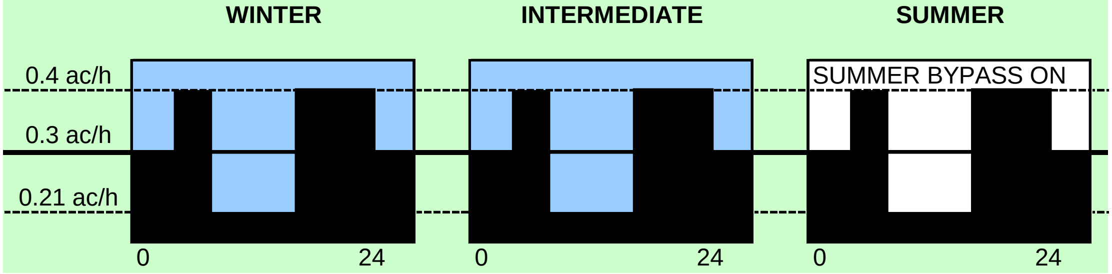


*Figure 7.9. Ventilation system control map with proposed improvements.*



Similar ‘as implemented’ and ‘possible improvement’ control maps are shown for the hot water systems in figures 7.10 and 7.11. The excessive use of the immersion heater identified in this work was addressed. A new schedule with two hours of immersion use per day (5am – 6am, and 5pm – 6pm) was implemented which the occupants reported did not cause any reduction in their perception of the availability of hot water. It would be possible in theory to have an adaptive controller which adjusted the timing of immersion use based on demands and possibly weather forecast. In the summer period when the whole tank had been warmed on the previous day it would appear that immersion use in the morning could be unnecessary. The sterilisation of the tank (through a de-stratification pump operating in tandem with the immersion heater) could be carried out only as required, again orchestrated by a smart controller. The issue of legionella in domestic systems is however a subject of debate and this sterilisation may or may not become a requirement (CE131 EST 2011).

Figure 7.10. Hot water system control map 'as observed'.

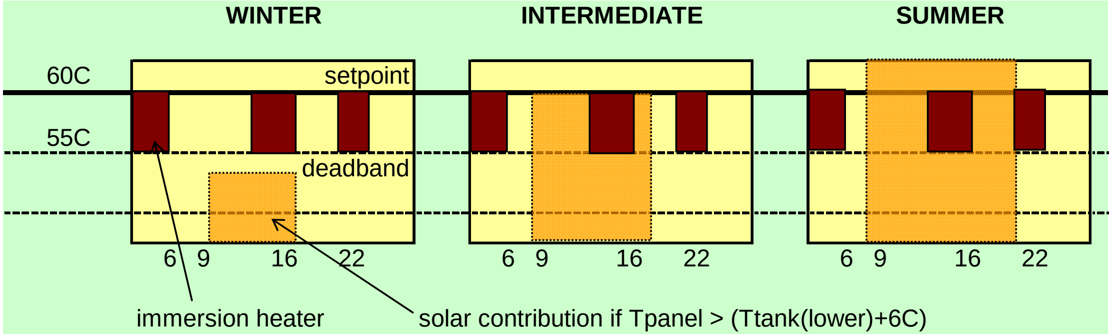
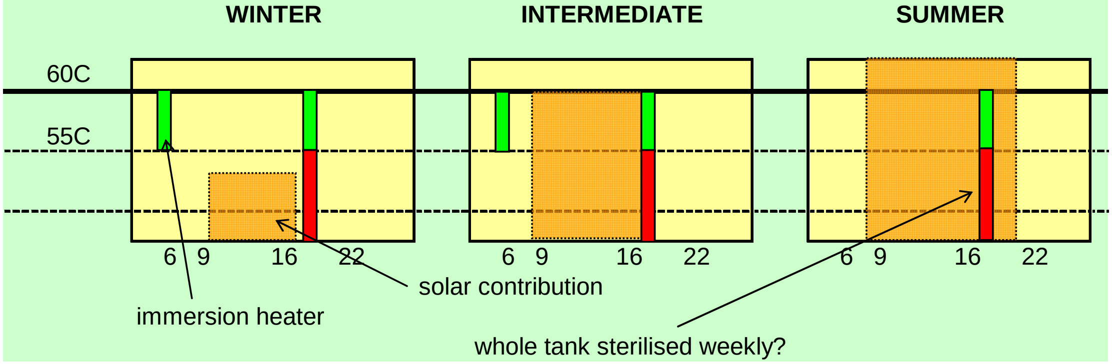


Figure 7.11. Hot water system control map as proposed.



### 7.2.3 Conclusions on the application to the Passive House.

The hypothesis was proved generally correct in this test application. Both the control mapping and the FMEA elements of the approach, when applied to the Passive House, provided some insights and useful outcomes.

The control mapping exercise was used at the outset to capture the Passive House intended approach to systems and controls and this straight away highlighted to the occupants and the architect and designers some shortcomings and areas where there was a lack of clarity or common understanding, particularly in the control regime around space heating.

The control mapping based on the observed operation again provided a vehicle for insights particularly into the operation of the solar thermal system where the three times a day immersion heater setting was unexpected and the periods where the tank was heating the panel highlighted potential control issues.

The control mapping process facilitated discussions and allowed improvements to the systems control regime to be documented. Ultimately these control maps could form a useful component of a user guide for the operation of the dwelling.

The FMEAs constructed a-priori were found to be comprehensive in this application and not many additional issues were added through the course of the investigation, this is testament to the amount of information available on Passive House design and leveraged in the FMEA construction.

The FMEA approach was found to be a very useful framework for the POE exercise. It was found that many of the potential failure modes identified as possible had in fact occurred and were detected in this test case. The number of issues detected highlights that despite all the available information on Passive House design and implementation this information was not effectively used in this case. It is proposed that this gap can be effectively filled by the control mapping and FMEA process of this thesis.

The many issues identified through this test application to the Passive House and its associated low carbon technologies (HP, MVHR, Solar thermal) took around 14 months to remedy. The building will be subject to another POE to confirm the outcomes of the remediation.

The control mapping and FMEA templates created for the Passive House case study are intended to be suitable for re-use in other projects, and for inclusion in a modular library to support re-use. A second low energy house case study was used to test this approach. This is the subject of the next section.

## 7.3 Application of the Control Mapping and FMEA method to Solar Thermal and MVHR Systems in the Glasgow House.

To further test the method, an investigation into the solar thermal system installed in the Glasgow House was carried out in October and November 2012. While the primary objective was to investigate the method applied to the solar thermal system some observations were able to be made on the MVHR system installation.

The Control Mapping and FMEA process was used as the template for this, with the FMEAs developed for the hot water heating, solar water heating and ventilation systems of the Passive House being directly applicable (Table 7.1 elements 5.1, 5.2 and 4 respectively).

The house was unoccupied during the period of the investigations but all services were set to run to normal occupancy schedules (space heating timed to come on twice per day with thermostat set around 21$^{o}$C, water heating also timed to the same schedule etc). The solar thermal system configuration was similar to that of the Passive House except that the back-up heating was provided by a gas boiler rather than by an electric immersion system. The system again had a vertical storage tank with a lower portion intended to be heated by the solar panels, and an upper portion heated by the gas boiler.

An initial 'as intended' control map for the Glasgow House solar hot water system was constructed, similar to that shown for the Passive House hot water system in figure 7.2.

The investigation carried out consisted of a physical inspection of the system plus a monitoring exercise. The monitoring exercise was non-invasive using external temperature probes only to give insight into the system operation. Some hot water draws were made by the author during the monitoring period to allow system operation to be studied.

The MVHR system was only superficially inspected against the FMEA developed for the similar system installed in the Passive House and some observations made. No monitoring of its operation was done.

The findings had many similarities with the previous study of the Dunoon Passive House. Details are given below.

### 7.3.1. Application of the method and results

FMEA element 5.1 Hot water heating – general.

Using the FMEA developed for the hot water heating system in general (Table 7.1) led to the following observations:

- The insulation on the primary pipework between the gas boiler and the vertical storage tank was missing adjacent to the boiler in the downstairs utility room and was poorly applied in the service room containing the thermal store leading to energy losses and risk of overheating. Insulation of primary pipework is encouraged in building regulations and SAP calculations (BRE 2012). Where applied it should be of a type rated for the appropriate temperatures (BS5422, BSI 2012).

- The temperature in the services room with the solar thermal store was seen to rise by around 6$^{o}$C during the 2 hour periods when the gas boiler was running to heat the upper portion of the storage tank, indicative of unintended heat gains to the building and potential summer overheating risk.

- The cold-water feed to the thermal store had poor insulation with the potential for condensation and localised water damage. Insulation and vapour barrier could be applied to eliminate this risk in line with BS5422.

FMEA element 5.2 Hot water heating – solar thermal with gas boiler backup.

Using the FMEA developed for the solar hot water heating system (table 7.1) led to the following observations:

- The solar thermal system pipework insulation showed poor workmanship, missing from large sections and where present had in large sections melted and fallen away from the solar thermal pipes (figure 7.12). The pipe insulation observed is not in compliance with BS5422 which states that solar thermal pipe insulation must be able to withstand 150$^{o}$C.

***Figure 7.12. Solar system pipework in the attic of the Glasgow house showing poor specification and poorly applied thermal insulation. Much of the insulation was found to have melted and fallen away from the pipes.***

- This poorly insulated solar thermal pipework will emit significant amounts of heat inside the buildings insulation envelope, providing significant heat gains in summer. This situation would appear to have very high probability of creating significant overheating issues for the internal living spaces especially the bedrooms in the upper floors. The lengthy routing of the poorly insulated pipework over the false ceiling and through the walls of the upper floor bedroom exacerbates the problem. A lesser issue is the loss of heat intended for hot water heating but lost to the indoor environment reducing slightly the solar system performance.

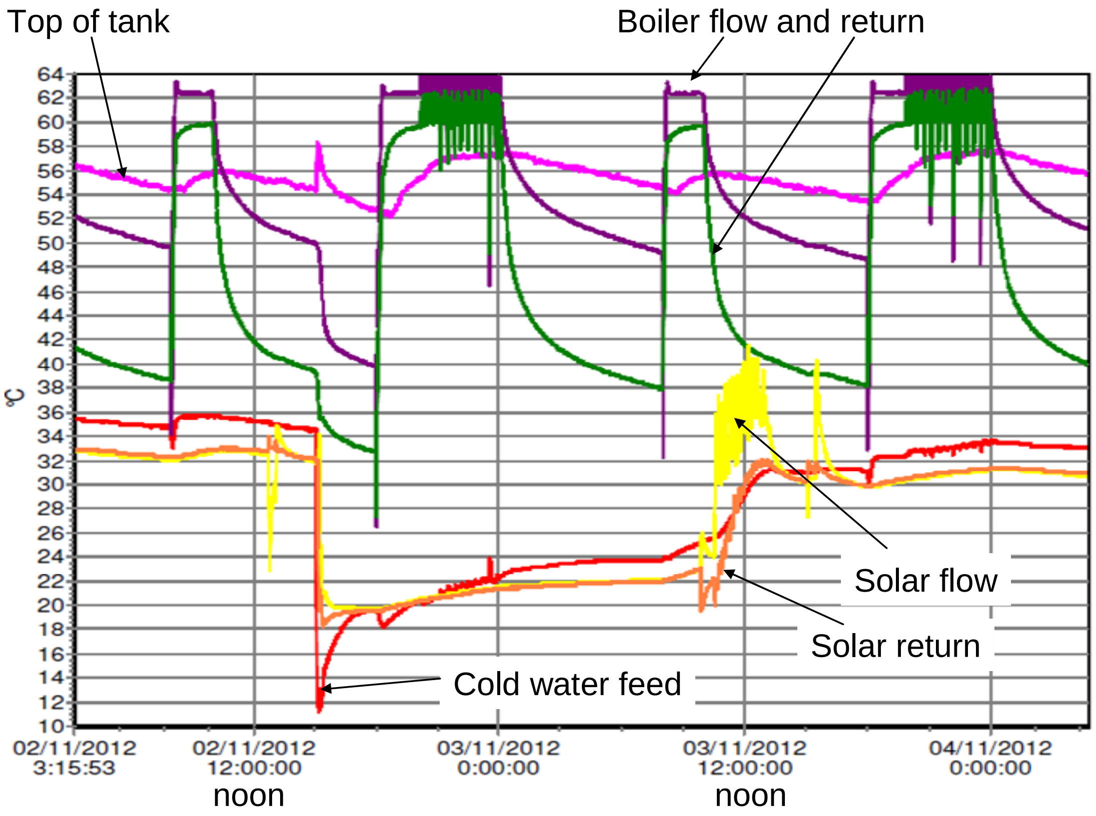
- The insulation on the solar thermal pipework and the other pipework in the service room containing the hot water storage vessel was also sub-standard leading to heat losses and high risk of overheating in this area. Much of the exposed solar pipework was un-insulated (figure 7.13).

***Figure 7.13. Uninsulated and poorly insulated pipework in the plant room.***

- The operation of the gas boiler system to heat the upper portion of the thermal store was set for 2 hours in the morning and 6 hours in the evening. Even with no water being drawn by occupants for successive days the boiler was seen to run constantly for 2 hours during each period. There would be potential for energy savings if controls could be optimised for periods of absence. These fixed timings of water heating do not take account of the hot water use, in this case leading to inefficient cycling of the boiler in the evening period, or the solar potential in summer to heat this upper portion of the tank i.e. the heating periods could be better matched to the demands and in summer the morning heating period could potentially be eliminated – with potential for savings.

- Figure 7.14 below shows the operation of the solar thermal and backup systems. The house was unoccupied during the monitoring period but some water draw-offs were made by the author so that operation of the system during and after these events could be observed. In the figure below a hot water draw off was made (bath fill) around 3pm which dropped the temperature of the bottom of the tank (red) and the middle of the tank (the solar flow and return are attached to the lower portion of the tank) due to the influx of cold water at the bottom and the shifting upwards of the thermocline. It can be seen that the solar system turns on the following day due to sunshine raising the panel temperature above the turn-on threshold (bottom tank temp + 6 degrees) heating the water in the bottom and middle of the tank to around 30 degrees.

***Figure 7.14. Monitored data showing the operation of the hot water system controls. The cold feed, solar flow and return are all connected to the lower portion of the water tank.***



- The bottom of the tank during the unoccupied periods was seen to float between 20 to 40$^{o}$C. There is a potential risk of legionella build up at this temperature in this lower portion of the tank. Legionella will be sterilised in the top of the tank if it is resident during a period when this portion is heated to 60$^{o}$C by the gas boiler, however the potential exists for the occupants to return from an extended period abroad, run a bath using up the top sterilised portion of the tank, and then have a shower with non-sterilised water from the bottom of the tank. There has been debate on the scale of this risk. HSE guidelines recommend sterilising the whole tank regularly to deal with this risk but solar thermal guidelines from EST (EST CE131 2011) identify that this sterilisation will reduce the potential solar gains. Applicability of the HSE (HSE 2012) guidelines: *"The water temperature at the base of the calorifier (ie under the heating coil) will usually be much cooler than the water temperature at the top. Arrangements should therefore be made to heat the whole water content of the calorifier, including that at the base, to a temperature of 60°C for one hour each day"* to private domestic dwellings appears to be a grey area. It is important this is resolved as solar thermal becomes more prevalent.

- Similar to the Passive House case an improved control regime could be postulated as in the control map of figure 7.11.

### FMEA element 4: Mechanical Ventilation and heat recovery (MVHR) system

The MVHR unit installation was briefly inspected against the criteria highlighted by the FMEA and the following observations made:

- The door undercuts to allow air to move between the supply rooms and the extract rooms were insufficient (figure 7.15), the UK specification is for 10mm clear opening above the floor finishes, in general this guidance appeared to have been ignored as no significant free areas were observed (Building regulations 2012).

- Some more general comments on MVHR were also made: it is a requirement that filters are changed regularly – the positioning of the unit in the attic means that this is somewhat inaccessible; the MVHR should ideally be inaudible at the standard setting i.e. have a specification of less than 25dB but was observed to be audible.

***Figure 7.15. Insufficient air transfer opening between rooms.***

### 7.3.2 Conclusions from application of the control mapping and FMEA process to the Glasgow House solar thermal and MVHR systems.

The application again proved a useful vehicle for carrying out the evaluation of the house and for communicating the issues and potential improvements.

The re-application of the Control Maps and the FMEAs developed initially for the Dunoon Passive House proved to be a very useful approach.

## 7.4 Conclusions on the application of Control Mapping and FMEA to the domestic test cases.

The application to the Dunoon Passive House and the Glasgow House showed that the methods can be usefully applied in a domestic context as well as the office used for the first test application.

The transfer of knowledge from the first to the second domestic project worked well with the control maps and FMEAs developed in the Passive House application providing a sound foundation for the Glasgow House project.

## 7.5 Overall conclusions on the Modular Control Mapping and FMEA method.

Overall the outcomes from the test applications indicate that the hypothesis made at the outset is correct i.e. the Modular Control Mapping and FMEA method can contribute to reducing the gaps between intended and actual performance associated with building systems and controls. Issues were successfully identified using the method and solutions described to resolve these issues.

In the test applications the Control Mapping method has shown potential benefits including: a clear representation of the systems and controls, an effective communication vehicle, and a basis for clear user documentation.

Control Mapping has been used in a variety of modes:

- To capture system and control responses as intended by the Architect i.e. from the Architects building description.
- To capture system and control intended operation from available best practice and design guidance e.g. Passive House.
- To capture system and control responses as intended to be implemented in detail e.g. from the BEMs manual.
- To capture systems and controls responses as physically implemented, based on observation and monitoring of actual building performance.
- To develop and represent possible future system and control responses which may better meet the intended performance criteria.

These different uses of the Control Mapping method demonstrate its use at various stages of the design process i.e. the first two modes being equivalent to application at the concept design stage, the third being similar to deployment at the detailed design stage, and the fourth being similar to deployment at the implementation or validation stages. The fifth mode of application could be applied at any stage; in this mode the Control Mapping method would facilitate the transfer of design information to and from building simulation as part of the optimisation process.

The inter-comparison between the maps generated at these different stages has allowed disconnects to be identified and potential improvements proposed. The simple representation of the building operation in the control maps could be used to facilitate analysis such as modelling using dynamic simulation. An ‘as modelled’ or ‘as simulated’ control map will be a useful extension, as often modelling assumptions will vary from the ‘as intended’, ‘as designed’ or ‘as implemented’ scenarios due to limitations in the models used etc.

While the FMEA approach in the test applications has been applied to a post occupancy situation the use of the method has been demonstrated in a variety of modes which point to more general applications:

- To capture expert knowledge at the beginning of a project.
- To provide a framework for project planning and management.
- To provide a framework for project reviews and risk / issue management.
- To capture knowledge generated during the progress of a project for potential use later on in the same project or on subsequent projects.
- To provide feed forward and feed back of information from different stages so that disconnects can be resolved.
- As a repository of knowledge to be re-used on similar projects.

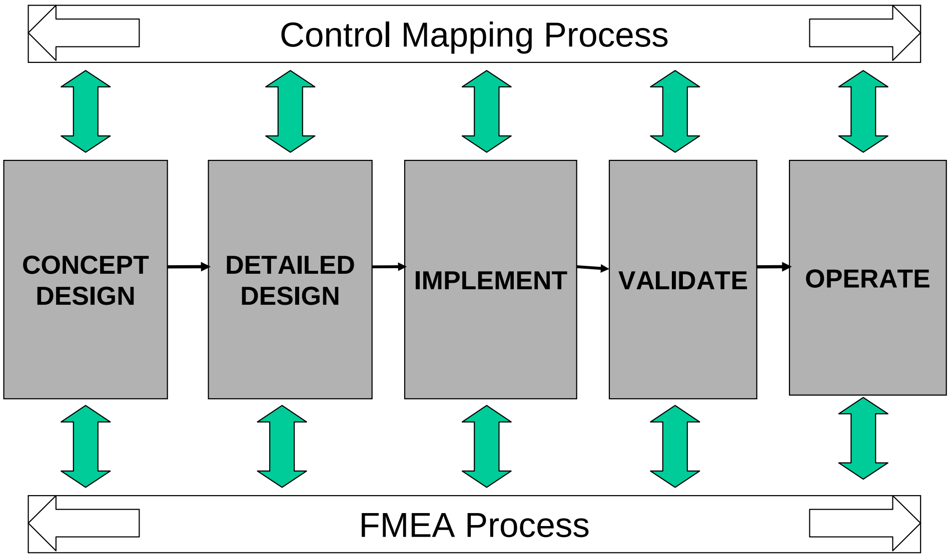
Both the Control Mapping process and the FMEA process have shown great potential as a vehicle for capturing knowledge from expert review and provide a baseline for risk management and project planning and management at various stages of the building industry process. This is consistent with the vision for the method proposed in table 6.1.

It is proposed that modular libraries of Control Map and FMEA documents are created to be selected as appropriate to inform projects, providing feedbacks from project to project. As Building Information Modelling (BIM) becomes more established it would potentially provide a mechanism for this approach. These modular libraries in BIM could be developed either internally in a large business or through some more open organisations e.g. CIBSE, Government.

The control maps and FMEAs developed in the test applications of this work are to be made publically available and can be seen as the start of the proposed modular library.

The intended broad range of application of the method is illustrated in figure 7.16 overlaid on the model of the industry process described earlier. It is proposed that the formal application of the Modular Control Mapping and FMEA process would support and add value within the framework of expert reviews proposed in the Soft Landings and NABERS processes.

***Figure 7.16. Control Mapping, FMEA and reviews integrated into the buildings industry process. Control Maps and FMEAs being reviewed at each stage of the buildings process. The Control Maps and FMEAs are also provide a vehicle for knowledge transfer for appropriate modules between projects.***



The modular approach and the adoption of FMEA in the method proposed here borrow to some extent from the BIM benchmark automotive, electronics and aerospace industries. In the following chapter the possibility for other methods from these industries to be useful in the building industry is discussed in the context of current building industry initiatives.

The combination of the modular control mapping and FMEA method with the option appraisal method of earlier in this thesis is discussed later (chapter 8).

## 7.6 References

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# Discussion and Conclusions

# Chapter 8. Discussion and future work: Possible further lessons from a BIM benchmark industry.

*Proponents of the BIM initiative have suggested that other industries have improved productivity due to improved processes. One example given is the electronics industry. The analogy between the electronics and building industries is explored in this chapter. Some of the issues found in the realisation of low energy buildings highlighted earlier in this thesis are reviewed, and techniques from electronics explored as potential solutions.*

*Opportunities identified include: adoption of a more integrated process, use of standard cells, inclusion of controls and operational code in the design, generation of building commissioning tests with high coverage from simulation, generation of building operational control code (including self-test) from simulation, inclusion of variation and uncertainties in the design process,  use of a quality systems approach with processes such as indices for design robustness, formal risk analysis (e.g. FMEA) and continuous improvement methods.*

*The possible integration of these techniques within a building information model (BIM) flow is reviewed. How the Option Appraisal Method (Chapter 3) and the Control Mapping and FMEA methods (Chapter 6) fit with the range of suggested future improvements is also discussed.*

*A major feature of the electronics industry has been the highly competitive nature of that market and industry sector, It is proposed that the industry has been largely driven by the availability of public domain performance data.*

*The extent to which current building industry initiatives are aligned with the electronics industry processes is explored and some suggested improvements put forward to form the basis of possible future work.*

## 8.1 Introduction to processes from a BIM benchmark industry

The BIM initiative is promoted at least in part as a method for productivity improvement in the buildings industry based on adoption of successful techniques from other industries (BSI 2012). The initial focus of BIM has been on automation of logistical processes rather than on performance, here we take a look at the drivers of performance in a BIM benchmark industry. The extent to which these are relevant to the buildings industry is then discussed.

The BIM initiative suggests comparison with industries such as consumer electronics (e.g. PCs, mobile phones, mobile computing) or automotive (e.g. family cars). Many of these industries have developed processes which enable them to create products that work 'straight out of the box' meeting specified performance (most of the time).

The BIM benchmark industries are in general driven by a plethora of public domain performance data (energy, user experience, features, cost, reliability etc.) often organized in the form of performance rankings and league tables. Esteem awards in these industries are to a large extent based on this public domain performance data e.g. manufacturer of the year, product of the year for different categories. Manufacturers who have performance issues that are not immediately addressed find it very difficult to be successful. In these industries it is also very important to bring new technologies to market quickly without compromising performance.

While the industrial engineering approaches of these industries have historically been developed to manufacture a 'one-size-fits-all' product, the creation of a customer specific product from a library of available modules (Freescale 2012) is also increasingly common, particularly in fields such as custom electronic systems where modular designs are configured and then translated to match with available manufacturing processes or meet different performance requirements or new environmental or emissions standards (e.g. consumer or military temperature ranges etc).

It is this custom electronics approach which is explored here as a parallel for the buildings industry process. This 'custom' modular industrial engineering approach is arguably already evident in the some specialist areas of the buildings industry such as off-site modular construction, large apartment blocks, hotels, large cruise ships, and the air conditioning industry, where combinations of standardized modules are used.

The electronics industry has been subject to rapidly evolving expectations of performance including functionality, quality, cost, energy use, and robustness. The industry has been the focus of global competition and its end products have been the subject of extreme public scrutiny.

Investments required in product development and new technologies are extremely large and market opportunities are very narrowly time bounded with first to market with the required performance achieving huge returns and correspondingly huge financial penalties for any delayed market entry due to performance or other issues. These market technical and economic factors create a ‘survival of the fittest’ environment where only those organizations that evolve robust design and build processes have been able to succeed and many large organizations have failed.

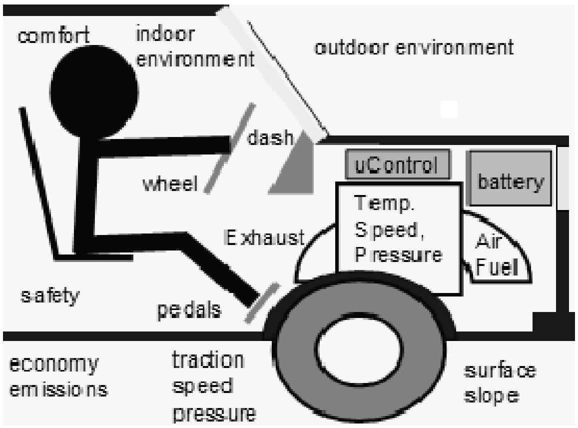
The electronic systems embedded in many products are highly complex. A typical system has several hundred analogue and digital inputs and outputs and many modules with specific functions such as processors, timers, communications, signal processors, monitors, or alarms and may be used in critical applications in dynamically variable environments such as in automotive or aeronautic industries. Energy consumption of microcontrollers is often highly critical for battery sensitive applications such as automotive, military, space, mobile computing and communications.

The challenge facing designers of automotive electronic systems, for example, can be compared to the challenge of realising a complex building. In both cases the system must maintain comfortable and safe conditions, operate and monitor plant, respond to variations in occupant behaviour, internal and external environments, while minimising energy use and emissions.

Both systems are required to accept changes in settings from the user and display performance parameters and alarms, detect and take appropriate actions for different modes of operation (accelerating, braking c.f. heating, cooling etc.) and respond appropriately in fault conditions. Figure 8.1 illustrates in simple terms the key elements of the automotive system.

The proposal made here is that there are sufficient similarities between electronic systems and building systems to make comparison worthwhile. There has been some exploration of the 'six sigma' quality systems approach from electronics in buildings design within a BIM framework (INPRO, 2010) but only at a very superficial level.

***Figure 8.1 The Automotive Environment***



The performance and quality of electronic systems and the products they are integrated into are the subject of great scrutiny and public interest with performance data (e.g. cars $CO_2$ emissions etc.) and reliability ranking tables regularly published in the public domain. This is in contrast with the buildings industry where companies reputations can be largely unrelated to the actual performance or quality of their buildings. Some limited progress is being made in this area with the implementation of energy labelling in public buildings based on actual energy use in England and Wales for example providing public feedback on some very high profile buildings.

The electronic systems design and implementation process has evolved to meet the challenges in a highly dynamic and rapidly evolving marketplace. Extreme competition, high cost of fabrication, long cycle time of fabrication, high cost of redesign, initial high market prices, rapid market price erosion, high cost of poor quality and rapid obsolescence have meant that short design times, first time design success and high quality have been essentials for survival. Simulation has been a key enabler for success.

The electronic design methodology is highly integrated and automated. At the earliest design phase the systems functionality is described in a very high level behavioural language (e.g. VHDL) where functional blocks and their key parameters are specified. VHDL was developed as a standard by the US Department of Defence in the 1980's in order to be able to comprehend and integrate complex systems; VHDL allowed behaviour to be comprehended more easily than through the complex detailed manuals typical at that time. Tools were quickly developed to simulate the high level behavioural descriptions and synthesise the high level behaviour into hardware specifications for implementation. Libraries of model sets are available to represent different possible hardware types and their associated performance variations. To reduce the overheads and cycle time in producing new designs, standard cell libraries are established where well characterised components which have been fully verified are stored for re-use.

Electronic systems are highly simulated before the expensive tools used to fabricate them are ordered. The simulation testing includes the operational code, has a high level of fault coverage (i.e. high ratio of faults that will be detected by simulation against the total number of possible faults) and includes the likely variations in performance due to uncertainty in the fabrication processes and likely ranges in operating and environmental conditions (Tuohy et al, 1987). The robustness of the design may be quantified using a 'six-sigma' capability index (Pyzdek, 2003). Robustness is defined here as the ability of the system to perform correctly across the range of future uses and future environments that may occur during its lifetime. The six-sigma quality methods used by the electronics manufacturers are imposed on the suppliers of equipment and materials used in the fabrication and testing phases.

Test code is generated from the simulation software with high fault coverage and then used to evaluate the system once built using automated test equipment.

The test flow often includes specific tests designed to weed out subtle or latent defects which would become early-life failures, tests may include stressing the system in a controlled manner (typically beyond specification limits) for short periods and / or measuring background ‘quiescent’ power consumption with the chip in defined modes.

The operation control code developed in the simulation is used as the actual operation code and embedded in the system. The operation code often includes a Built In Self-Test (BIST) function allowing automatic detection of system malfunction when in operation.

Throughout the design and test processes possible failure modes are analysed and assigned a risk level based on likelihood of occurrence, probability of detection and severity of impact (known as failure mode effects analysis or FMEA). Actions are then taken to pro-actively ensure the risk levels are managed i.e. reduced or eliminated so that they should not occur in practice. FMEA’s from one project form the starting point of the FMEA of the next ensuring that learning is accumulated and knowledge transferred.

Where issues do occur then a rigorous 8 step methodology is used to problem solve (known as 8-D). This involves problem root cause and fix identification but also looks at the systemic reasons that allowed the problem to occur (i.e. why not anticipated and avoided through the FMEA process) and ensures that the processes are improved and the FMEA updated to ensure that there can be no recurrence in the current or in future projects.

The electronics systems realisation process initially benefited from a high level of vertical integration in the industry. However recently electronics has become fragmented with the move to low cost sub-contractors. Strong processes have enabled this fragmentation to be achieved successfully.

Recent developments in the buildings industry and the associated legislation are moving towards a more automated and integrated approach. The recognition of building simulation in recent legislation leading to more widespread adoption as well as the ongoing development and increasing adoption of the Building Information Management (BIM) methodology (including adoption by the US Army (Succor, 2009)) are steps in this direction. This more integrated and automated approach then provides a platform for the possible adoption of appropriate elements of the process used in electronics.

Some key definitions from electronics industry process:

VHDL: High level design language allowing a design to be described based on behavioural description of component parts.

Standard Cell Library: Library of previously validated designs and component parts with associated documentation including risk analysis, limitations etc.

Six Sigma: A Quality Process which aims to achieve less than 3.4 defects per million, applied across the project including contractors and suppliers.

Robustness: The capability of a design to function correctly over all likely future environmental and operating conditions.

FMEA: Fail Mode Effect Analysis; an analysis based on historical projects and any new features of this project; captures potential risks and identifies countermeasures to be built into the project plan.

Test Coverage: A measure of test or simulation quality; the percentage of possible faults that are tested for in the simulation testing or in the commissioning testing.

BIST: Built in Self-Test; tests for detection of errors in operation, built into the operating software.

Stress Tests: Test that go beyond normal specifications in order to identify areas of weakness.

Quiescent Tests: Tests which put a system into a defined mode and check for any un-intended energy use which would indicate a fault.

8-D: An 8 step problem solving methodology for dealing with issues and ensuring they are correctly addressed and don't re-occur.

Quality Reporting: Public domain ranking of companies performance in league tables for criteria including quality, defect rates, reliability, energy performance, on-time delivery etc.

These key elements of the electronics industry process include the modular approach and risk management elements expressed to a limited extent in the

Control Mapping and FMEA methods explored in chapter 6. The extent to which further processes from electronics could be useful in shaping future buildings industry process is explored further here.

## 8.2 Relating the gaps between intended and actual building performance to building industry process.

Here the issues highlighted in the literature and in the building evaluations of the previous two chapters (chapters 6 and 7) are related to stages of the buildings industry process. This step will then allow processes from electronics to be mapped against these issues and considered as potential solutions.

The concept, design, construction, commission and operation process as currently applied has a number of issues which can result in the performance of the building being poorer than expected in terms of either comfort or energy use.

The participants in different stages of the process are not consistent and there are contractual and financial milestones in the project which act to partition the project and act against synergy throughout. These contractual and financial milestones also act to put great pressure on the later process steps so that often commissioning is carried out in an extremely stressful environment in the face of financial penalty clauses if project timelines are not achieved. There is no Quality Process established and contracted into by the project participants.

Concept design is carried out using previous experience, gut feel, paper models and simplified calculations. Simulation based virtual prototyping is not yet in general use due in some part to the speed and complexity of the available simulation tools. Each project is largely a start from scratch exercise.

Detailed designs of the construction and plant systems are often carried out making static assumptions about occupant behaviour, operations and climate that may not reflect the range of conditions that will be prevalent over the lifetime of the completed building. The detailed design phase typically does not include design and validation of controls use by occupants or the operation code for the BEMs system where this is to be installed. Simulation, where carried out is not applied consistently and the extent to which the building design is exercised in simulation is not quantified.

Errors occurring during the construction and system installation phases are common, possibly arising due to poor understanding, lack of detailed specifications or lack of a quality system.

Generally components are installed and tested to a standard set of the manufacturer’s routines which may not well represent their intended operation in the specific building.

The commissioning phase of the project is often the last step before a major financial milestone and will often be attempted in a compressed timescale in order to recover slips elsewhere in the schedule. The controls engineer may only receive simplistic conceptual design description of the required operation and translates this in to operational BEMs code based on best judgement. Because the controls are based on the conceptual rather than detailed design these can be too coarse and simplistic for actual operation leading to step function changes in conditions and discomfort. The commissioning process typically exercises the controls and confirms that sensors, set-points and actuators are connected and operational but does not normally fully exercise building responses (time constants, weather compensation etc.), integrated control strategy or fault conditions. The commissioning testing quality and coverage is not quantified and often faults are not found.

The commissioning phase often provides the person responsible for the operation of the building with a thick manual and access to a number of BEMs screens on which set-points may be adjusted but not necessarily a good understanding of the operational strategy, current energy performance or design targets.

Seasonal commissioning is now a specified requirement for non-domestic buildings (CIBSE, 2006) however the process to be used, especially for naturally ventilated or hybrid buildings, is not specified in detail and this often leads to a seasonal repeat of the basic exercise of the controls looking for any simple faults which have occurred plus a tweaking of the control set-points based on the feedback from the building occupants via the building operator without comprehending the effect this will have on other seasons etc.

In the operational phase BEMs screens are often only visited in the case of serious complaints or equipment malfunctions. The energy used is often only monitored if at all through the financial billing from the utilities which are often based on estimated rather than actual energy use.

The end result of the current process is that it is common for buildings to have significantly poorer energy and comfort performance than planned.

## 8.3 Potential for approaches from electronics to improve the buildings industry process?

The approach to quality and validation in the electronic industry appears much more rigorous than is current in the buildings industry, it is possible to propose some improvements which may reduce occurrence of the issues identified in the previous section. It is suggested that the improvements could be implemented within a BIM framework.

Concept design:

Selecting of the right design concept for a sustainable building requires consideration of many factors such as building form, building systems, future climates, occupant perceptions, comfort and behaviours, risks, costs, legislation etc. Decisions at the concept design stage can have the largest impact on actual building performance.

In an ideal world there would be realistic and real time virtual prototyping to inform decisions and give instant accurate feedback on views, energy performance, costs, occupant perceptions and sustainability across a realistic range of future building uses, climates, and energy supply scenarios. This virtual prototyping would quickly capture sketches and ideas in the real time and provide an assessment of the impact of different approaches.

The electronics methods that would potentially contribute at this stage would be the availability of a library of standard cells that have been validated and have associated performance characteristics informed by real performance data. These could be specified using a high level language that would identify the cell function and also the defining parameters (e.g. activity type, system types and dimensions), the standard cells could then be synthesised into specific implementations and contexts with pre-defined worst-case parameter sets representing expected variations in construction, use and climates etc. allowing the assessment of building performance and robustness using six-sigma type quality analysis. The standard cells would have FMEAs based on previous history that would form the basis of a risk assessment and mitigation plan. At the concept design stage these standard cells could be selected from libraries, customised by their defining parameters and combined with other cells to quickly form the prototype building. The prototype building could then be repeatedly manipulated and simulated to give rapid feedback on performance of options.

There are a number of current developments in building simulation that are aligned with this approach and could support its adoption.

The BIM approach and also the linking of tools such as Revit or Sketch-up with building energy simulation is providing a more accessible interface, a library of standard cells with associated performance, risk and other datasets could certainly be included within this environment.

Detailed design:

Energy performance simulation in detailed design could, in addition to the areas discussed in the concept design section above, be improved by expansion of scope to include the modelling of systems and controls including building and system specific parameters, fault detection and fault condition responses. Inclusion of controls in the simulation should allow the development of commissioning tests and the operational BEMs control code (including built-in self test functionality) and the validation of the operation of this code for variations in climate and building use including impacts on occupant comfort.

The software used by BEMs manufacturers and controls companies to define their controls is not generally incorporated in the building energy simulation. There have been some recent developments within ENERGY+ (Ellis et al, 2007) but this functionality is not yet fully established.

Simulation should be carried out with a quantified coverage and building performance robustness validated for a stated variation in input parameters. The range of building use parameters and climates over which performance robustness has been verified and therefore the limitations on the building should be clearly communicated to the building realisation team and made clear to the clients.

The possibility of using a capability parameter to describe building robustness was recently explored in the context of naturally ventilated and hybrid building design (Tuohy, 2009, Tuohy et al, 2009). This work describes the incorporation of adaptive comfort, adaptive behaviour and other uncertainties such as internal gains and climates in a simulation method to give a capability parameter based on the six-sigma approach. This six-sigma capability parameter can be used to compare the robustness of different design options during the design phase and also subsequently be used to communicate to the building owner the limitations within which the building will operate successfully and outwith which some mitigation actions will have to be taken (i.e. if a building is not robust for high internal gains then the building owner should understand this and be aware of the need to reduce the gains, re-locate or upgrade the property appropriately).

The FMEA should be used as a reference as simulation may be required to verify that an identified risk will not occur. Similarly when simulation identifies a new problem then 8-D methodology should be used and the FMEA updated for future use.

Construction and system installation:

Greater coverage e.g. systems and controls etc. in the detailed design phase will allow more detailed specifications to be provided for construction and system installation.

The quality system can be extended to the supply chain and form a common language for the team with FMEA review and 8-D used to avoid problems or resolve them when they occur and ensure action is taken to avoid re-occurrence in future in this or in other projects using the same realisation process.

Validation / Commissioning:

The generation of commissioning test code from the detailed design stage which will exercise the buildings systems and controls in various modes and with a defined high coverage of possible faults should be able to identify with a high level of confidence any implementation or design issues. The test code could be run through the BEMS system itself or through a specialised system (possible including the simulation model) interfaced to the BEMS.

In addition to exercising looking for ‘hard’ faults the commissioning could be developed to include stress tests and quiescent power tests which may also identify latent or marginal faults which would have failed in operation.

Seasonal commissioning should be done with reference to the simulation model and any issues identified rectified using the 8-D process which should involve ensuring that adjustments to the code are not made on an ad-hoc basis but only after validating the changes in the model across seasonal climate and other variations and also understanding the root cause and ensuring the knowledge gained is fed back into the design system (using FMEA) and comprehended in future projects.

Operation:

The operational BEMS code should have been validated in the simulation model and include a built-in self-test function (probably involving quiescent power tests to check for unintended loads etc). Where faults occur they should be dealt with using the same quality system as used in the earlier phases and learning fed back into the process.

During operation, energy performance, comfort and customer satisfaction should be monitored against the design targets and expected performance distribution and the information provided in a clear format to the building occupants and maintenance staff.

Ideally the performance against targets, customer satisfaction and failure rates would be publically available so the team who deliver the building are accountable for its performance. (Electronics customers regularly rate suppliers quality and results are published similar to car manufacturers rankings for reliability). The introduction of display energy certificates for public buildings in England is already achieving high media coverage.

### 8.4 Are current building industry initiatives heading in the right direction compared with BIM benchmark industry process?

The highlighted high importance of public scrutiny and reporting of actual performance in the BIM benchmark industries justifies, in the view of the author, this being added to as a key element of the design process model introduced earlier (figure 8.2).

To explore the extent that key elements of the BIM benchmark electronics industry process are already being addressed by current initiatives, a selection of the current buildings industry initiatives, reviewed previously in chapter 2, was mapped against the electronics process using the 6 stages of this revised model as the template. An overview of this mapping is given in table 8.1 and summarized in table 8.2, allowing observations to be made.

Figure 8.2. Simple model of a design flow – with public performance reporting.

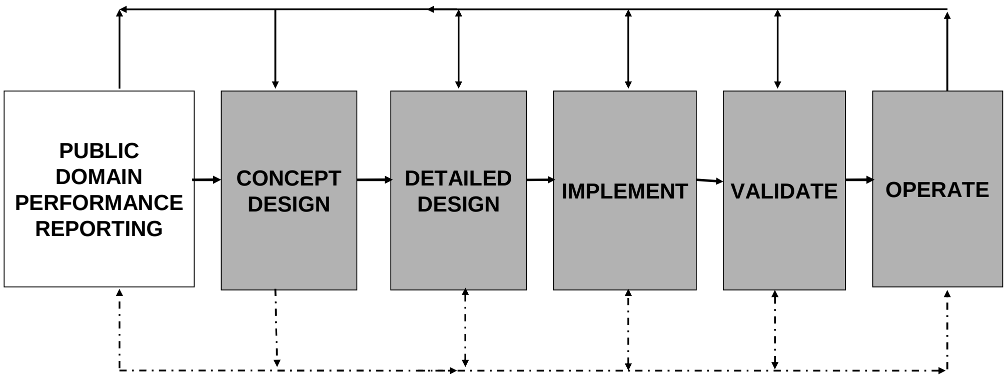


***Table 8.1. Comparison: Buildings initiatives v. BIM benchmark.***

| | **ELECTRONICS (BIM BENCHMARK INDUSTRY)** | **NABERS** | **SOFT LANDINGS** | **UK DISPLAY ENERGY CERTIFICATE (DEC) (PUBLIC BUILDINGS ENGLAND, WALES, N. IRELAND)** | **US ENERGY STAR, [AUSTRALIAN GREENSTAR PERFORMANCE FROM 2013 (T.B.D.)]** | **GREEN BUILDING RATING SCHEMES (BREEAM, LEED, GREEN STAR)** | **EU PASSIVE HOUSE** | **UK BUILDING REGULATION COMPLIANCE AND EPCs (EXCLUDING DEC)** |
|---|---|---|---|---|---|---|---|---|
| **REPORTING OF ACTUAL PERFORMANCE (ENERGY AND USER)** | PUBLIC ACTUAL PERFORMANCE REPORTING, LEAGUE TABLES (ENERGY, USER) | MANDATORY PUBLIC REPORTING (ENERGY) VOLUNTARY (INDOOR ENVIRONMENT) | VOLUNTARY REPORTING ENCOURAGED E.G. UBT, CARBONBUZZ (ENERGY, USER) | YES, MANDATORY PUBLIC REPORTING (ENERGY) | VOLUNTARY PUBLIC REPORTING OF ENERGY STAR PERFORMANCE (TOP 25% FOR ENERGY) | LEED: ANONOMYSED DATA SHARED IN BENCHMARKING REPORTS<br>BREEAM: VOLUNTARY E.G. CARBONBUZZ (ENERGY, USER) | NO, (CERTIFICATION BASED ON PREDICTED ENERGY + AIR TIGHTNESS TEST) | NO, (EPC BASED ON PREDICTED PERFORMANCE ONLY) |
| **CONCEPT DESIGN** | INFORMED BY REAL PERFORMANCE DATA. RE-USE OF VALIDATED MODULES. RISK MANAGEMENT. | ACCESS TO PUBLIC PERFORMANCE DATA , EXPERT REVIEWS, PARTICIPATIVE PROCESS. | EXPERT REVIEWS, PARTICIPATIVE PROCESS | | | BASED ON PREDICTED PERFORMANCE ONLY | BASED ON PREDICTED PERFORMANCE, CERTIFIED COMPONENTS | BASED ON PREDICTED PERFORMANCE , ACCREDITED COMPONENT PERFORMANCE DATA |
| **DETAILED DESIGN** | RE-USE OF VALIDATED MODULES. ROBUST SIMULATION WITH HIGH COVERAGE AND RISK AND ISSUE MANAGEMENT | EXPERT REVIEWS, PARTICIPATIVE PROCESS PROTOCOL FOR DESIGN BASED ON FEEDBACKS | EXPERT REVIEWS, PARTICIPATIVE PROCESS | | | BASED ON COMPLIANCE WITH REGULATORY MINIMUMS | BASED ON COMPLIANCE WITH DESIGN GUIDANCE | BASED ON COMPLIANCE WITH REGULATORY MINIMUMS |
| **IMPLEMENTATION** | QUALITY SYSTEM APPROACH INCLUDING SUPPLY CHAIN | EXPERT REVIEWS, PARTICIPATIVE PROCESS | EXPERT REVIEWS, PARTICIPATIVE PROCESS | | | SOME GUIDANCE DOCUMENTS REFERENCED | SOME GUIDANCE DOCUMENTS REFERENCED. CERTIFIED DESIGNERS. | SOME GUIDANCE DOCUMENTS REFERENCED. |
| **VALIDATION** | ROBUST TESTING WITH HIGH COVERAGE AND RISK AND ISSUE MANAGEMENT | EXPERT REVIEWS, PARTICIPATIVE PROCESS | EXPERT REVIEWS, PARTICIPATIVE PROCESS | | | SEASONAL COMMISIONING AND SUB METERING CREDITS | INDEPENDENT CERTIFICATION PROCESS (BY DESIGN + AT TEST). | BUILDING CONTROL PROCESS |
| **OPERATION** | OPERATION CODE FROM DESIGN AND VALIDATION STAGE. VISIBLE PERFORMANCE. MUST WORK 'OUT OF THE BOX' | EXPERT REVIEWS, PARTICIPATIVE PROCESS, ENERGY AND USER EVALUATIONS AGAINST BENCHMARKS | EXPERT REVIEWS, PARTICIPATIVE PROCESS, ENERGY AND USER EVALUATIONS AGAINST TARGETS. 3 YEAR HANDOVER. | ENERGY EVALUATIONS AGAINST BENCHMARKS | ENERGY EVALUATIONS AGAINST BENCHMARKS | BREEAM: OPTIONAL CREDIT FOR 3YR ENERGY AND USER DATA TO BRE.<br>LEED: COMPULSORY 5YR ENERGY DATA TO USGBC. | GUIDANCE ON USER MANUALS | GUIDANCE ON USER MANUALS |

*Table 8.2. Summary: Buildings initiatives v. BIM benchmark.*

| | REPORTING OF ACTUAL PERFORMANCE | QUALITY SYSTEMS APPROACH TO DESIGN AND BUILD | WORKS FIRST TIME |
|---|---|---|---|
| ELECTRONICS | YES | YES | YES |
| DISPLAY ENERGY CERTIFICATE (DEC) | YES | | |
| NABERS | YES | COMMITMENT AGREEMENT AND PROTOCOL | PROTOCOL AND NABERS ACTUAL PERFORMANCE RATING PROVIDES INCENTIVE |
| SOFT LANDINGS | INTERNAL TO TEAM | CORE PRINCIPLES AND FRAMEWORK | 3 YEAR HANDOVER PROCESS PROVIDES INCENTIVE |
| ENERGY STAR, GREEN STAR Performance. | PERFORMANCE BASED AWARDS | | |
| EU PASSIVE HOUSE | | CERTIFIERS | |
| GREEN BUILDING RATING SCHEMES e.g. BREEAM, LEED, GREEN STAR. | INTERNAL TO RATING ORGANISATION. METERING. | | SEASONAL COMMISSIONING |
| UK BUILDING REGULATIONS | METERING | | COMMISSIONING |

The BIM initiative, RIBA plan of work and CIC work stage processes were not directly included in the comparison as these were viewed as frameworks within which the analysed processes may be incorporated e.g. Green Overlay for RIBA Plan of Work, Government Soft Landings within BIM.

Regarding the reporting of actual performance data, the UK Display Energy Certificate (DEC) stands out as a mandatory public domain operational performance based scheme which reports actual energy performance. The DEC is however only applied to existing public buildings over 1000m$^2$ in England, Wales and Northern Ireland. There has been support for extending the DEC scheme further e.g. non public buildings, but this has not been supported by Government policy so far.

Within the voluntary NABERS scheme there is mandatory public reporting of the energy rating based on actual annual energy use, and voluntary reporting of indoor environmental performance.

Worldwide there are a growing number of voluntary schemes for capturing actual operational performance data. These include Energy Star and 'Green Star Performance'. Energy star awards are based on achieving a top 25% performance compared to a benchmark distribution. CarbonBuzz does not provide ratings but allows both predicted and operational performance data to be submitted. While these initiatives appear to be steps in the right direction they fall short of the full public disclosure and scrutiny of actual performance data that has been a driver in electronic systems. Soft Landings encourages reporting of the energy performance through CarbonBuzz or similar but this is not a requirement.

Regarding a quality systems approach, the Soft Landings process core principles and framework can be viewed as a step in this direction. Soft Landings currently relies more on individual expert or design team inputs and less on the more formal processes of the benchmark industry. The 3 year post occupancy handover period of analyzing, tuning and optimizing building performance (energy and user experience) serves to inform the design team of the causes of gaps between intended and actual performance, and will also act as an incentive for the design process to be improved to avoid issues in this phase.

The NABERS Commitment Agreement and its associated procedures can also be viewed as having similarities with a quality system approach, it mandates the involvement of experts in reviews at critical stages, a specification for the use of simulation for performance predictions, and the communication of assumptions and risks to clients and the project team. The commitment agreement has been informed by previous post occupancy evaluations and particularly focuses on the representation of systems and controls in the design simulations which is recognized to be an area of general weakness. Once construction is complete the NABERS rating is based on the actual performance. The NABERS process gives direct comparison between predicted and actual performance where the Commitment Agreement has been used, and again will act as an incentive to further improve the design process to avoid post delivery problems.

In Passive House the Certified Designer accreditation training and independent Certification processes for Designers, Components and Buildings are intended to address quality issues. However, evidence presented in this thesis indicates that despite these processes, performance gaps will still remain and re-enforces the suggestion that actual performance must be validated if good performance is to be routinely achieved.

The UK building regulations (for both compliance and energy ratings), the Passive House standard, LEED, BREEAM and Green Star ratings are (with the notable exception of the UK DEC described above), based on predicted rather than actual performance. LEED and BREEAM do require mandatory but anonymous reporting of predicted v actual performance to their oversight bodies for purposes of improving their processes and the generation of anonymised reports. Optional credits are gained in BREEAM, LEED and Green Star for specifying sub-metering and engaging a commissioning engineer in the earlier concept and detailed design process steps. The route to process improvement here is less direct than for Soft Landings and NABERS.

With regards to delivery of buildings that work ‘out of the box’ it would appear to need a paradigm shift in the industry for this to happen. Actual performance reporting and the adoption of Soft Landings or NABERS process will provide feedback to improve processes and also a large financial and productivity incentive for companies to get the building to work ’out of the box’ and avoid the potential adverse publicity, difficulties and resources involved in post occupancy remediation, providing an incentive for a ‘works first time’ aspiration to be brought closer to a reality, initially through better design of validation testing and procedures (commissioning) but it remains some way off.

### 8.5 Discussion: a potential future process for the building industry?

Since Government policy aimed at low energy buildings is largely enacted through predicted performance for regulated uses rather than actual building performance, it is to be expected then that industry then will become adept at delivering good predicted performance for regulated uses rather than good actual performance.

If the focus was to be on actual rather than predicted performance then this would necessarily lead to industry developing the processes needed to achieve good performance in practice. Economic benefits would then be available from: reduced energy use, productivity improvements associated with avoiding spending effort on remediation, and increased competitiveness in global markets.

The principle behind the EU EPBD energy labelling scheme was that labelling would reflect actual performance and create a market that drives industry to deliver good actual performance, the adoption of labelling based on predicted regulated energy use misses out large sections of the industry required to deliver the intended results. Resulting performance gaps may undermine the credibility of labelling schemes.

It would then appear to be essential that actual performance becomes the target. There are practical difficulties with this but the DEC and NABERS processes provide examples of how this can be implemented. Performance ranking and accountability mechanisms based on actual performance such as those that exist for products of other industries should be encouraged e.g. government supplier rankings, consumer organisations ratings etc. Esteem awards and recognition of best practice should only be based on actual verified performance.

There are a number of programs that gather post occupancy performance data on a sample basis and use this data to inform process improvements. Examples include EST and TSB evaluations, BREEAM and LEED reporting back of performance data. While these studies will undoubtedly lead to improvements over time there is little evidence (given the large number of historical post occupancy performance studies) that the rate of improvement will be greater than the industry historical trend. More direct accountability plus the motivation provided by potential consequences of public reporting or contractual obligations (e.g. as in Soft Landings or NABERS) would be expected to disrupt this situation and drive the industry more directly to close the gaps.

It would seem reasonable that BIM should focus more on processes that target actual building performance. The recently stated UK Government BIM Task Force policy to incorporate support for the Government Soft Landings (GSL 2012) process within the UK BIM initiative is possibly a step in this direction.

The extent to which industrial engineering approaches such as those highlighted in custom electronics will be adopted, and timeframes for these changes if they were to occur, is uncertain.

The BIM initiative has highlighted other industries as having consistently higher rates of productivity improvement; there would appear to be an opportunity for a strand within BIM research and the BIM initiative to target development of robust modular design approaches leveraging techniques from these benchmark industries aimed at comfortable low energy and low carbon performance in practice. The modular approach with a pre-simulated library of exemplars uniquely described by combinations of determinant parameter levels that forms a basis for the option appraisal method of chapter 3 could be viewed as demonstrating some mechanism that could possibly support this.

Other processes with potential for adoption in the buildings sector include a more formal quality culture embedded across the workforce and supply chain with quality management methods such as FMEA, 8D, robust design, 6 sigma etc. In electronics everyone involved in the delivery of products is trained in quality.

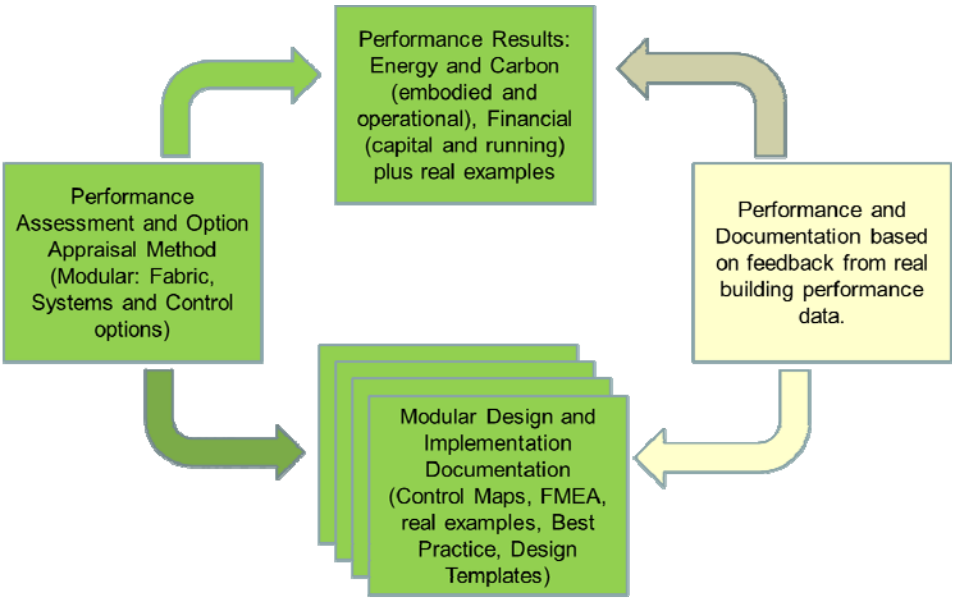
Soft Landings and NABERS have commitments, frameworks, core principles and guidance which support transfer of knowledge and process improvements. These rely largely on inputs from individual experts in contrast to the more prescriptive and automated approaches of the custom electronics industry. The Control Mapping and FMEA method developed here has potential to contribute in this area.

It is probable that a more automated and formal modular and quality systems based approach to design, if it is to evolve, will evolve first driven internal to large organisations, such as Government, which procure large numbers of buildings (the US military has already played a leading role in the BIM initiative), or within larger companies delivering high volumes of buildings (some large companies already have both buildings and industrial engineering skillsets). This modular approach could be supported by customisable design software within the BIM framework.

A recurring problem area appears to be the design, implementation and validation of controls, particularly with respect to new technology systems. The NABERS and Soft Landings processes make efforts in this area while recognising limitations in current design and modelling tools. These limitations in design and modelling tools remain to be addressed. Methods for better incorporating control into concept selection, detailed design, and validation, is the focus of research. The control mapping and FMEA approach is put forward in this thesis as a step in this direction.

It is proposed here that both the Option Appraisal method and the Control Mapping and FMEA methods developed in the research of this thesis could in future work be usefully integrated within the BIM environment as shown in figure 8.3.

***Figure 8.3 A proposed integration in BIM of: a) performance assessment and option appraisal, and b) modular control maps and FMEA. When modular design options are considered (e.g. mechanical ventilation, heat pump etc.) appropriate performance results are generated and also the modular design information for those modules identified (including Control Maps and FMEA) from the BIM repository. The performance calculations and the modular design information should be informed by feedbacks from real example projects.***



Indoor environmental performance and user perceptions of buildings have not been described to the same extent as energy in this discussion, but processes exist that allow this to be similarly addressed (e.g. performance measurement criteria exist within Soft Landings, NABERS etc). Many of the problems if resolved will positively impact on energy, carbon and indoor environment.

## 8.6 Conclusions.

Current policy initiatives aimed at delivery of low carbon buildings are largely based on predicted performance. There are significant disconnects between predicted and actual energy performance so that current policy intent is unlikely to be met.

A comparison with the process of the custom electronics industry, suggested as a BIM benchmark, was used to suggest measures with potential to address these disconnects. These include:

- Establishing accountability for actual building performance.
- Esteem awards and high ratings of buildings only to be awarded based on actual performance.
- Adoption of a modular robust design and implementation process including feedbacks and feed-forwards within a quality systems approach.

DECs, Soft Landings and NABERS are highlighted as the buildings industry initiatives most likely to deliver intended building performance in practice.

It is suggested that if actual performance measurement is targeted then the buildings industry will develop the processes required to deliver good actual performance while maximizing productivity.

The BIM initiative is largely focused on more efficiently supporting current industry processes which are based on predictive methods. It is suggested that BIM should be re-focused on achieving actual building performance. It is also suggested that processes from BIM benchmark industries and in particular the custom electronics industry, merit further investigation.

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# Chapter 9. Conclusion

*The context, overall aim, problem statement, high level objectives, research questions, research methods, and each of the thesis chapters are briefly reviewed.*

*The most significant research outcomes from the work are stated, conclusions summarised and future work proposed to build further on these research outcomes.*

## 9.1 Review.

The overall aim of this thesis is to make a contribution to the realisation of low carbon buildings.

Problems in the realisation of low carbon buildings were identified in two areas: a) Performance assessment and upgrade option appraisal, where legislation such as the EPBD has stimulated a range of Governmental and other requirements, and has also stimulated the market to supply an increasing range of technical options to potentially address these requirements across a wide range of building types, and b) Translating intended performance into performance in practice, as there is much evidence that the intended improvements in performance are not being achieved, particularly due to poor implementation of low carbon systems and controls.

The objectives were set to make contributions in each of these two areas.

In the following sections, the work of each of the thesis chapters is briefly summarised, then the main outcomes from the research are listed, conclusions drawn, and potential future work described.

### 9.1.1 Part A: Performance assessment and upgrade option appraisal.

The work on this topic is contained in chapters 2 to 5 of the thesis.

Chapter 2 (Part A).

Based on the literature review the research question was formulated:

*"Can a low cost simulation based method be developed to support real-time performance assessment and upgrade option appraisal by a range of users in the context of the EPBD?"*

The research approach adopted was to hypothesise that such a method could be developed, then test the hypothesis by formulating a method and assessing its usefulness in a number of test applications.

Chapter 3.

The formulation of the performance assessment and option appraisal method was described.

The proposed method is intended to be replicable for different contexts. While the test application here was for the Scottish domestic building stock, this provides a template for future deployment to other contexts.

In the method formulation for the test applications decisions had to be made *a-priori* on the detailed implementation. These *a-priori* decisions are reflected on in chapter 3 and also reviewed after the test applications (chapter 5).

Chapter 4.

The formulation and application of the method was tested for energy performance rating of existing dwellings based on a simple questionnaire to be filled in by non-experts. The method was compared with the approach taken by the UK Government EPBD implementation method which requires expert energy assessors to visit and survey properties in detail.

A range of questionnaire formats and data collection methods was explored and trade-offs identified between the quality of data inputs, the level of detail of the required data, and the cost of gathering and assuring the data quality.

It was concluded that a simple questionnaire based method could be feasible but would need to be supported with an education framework and a quality assurance process.

Chapter 5.

A more general formulation of the method was investigated for test application to a range of different situations. Applications included policy, strategy and concept design investigations.

In many of the applications the method proved very useful.

Where individual dwelling specifics needed to be represented the level of detailed in the representation of building geometry chosen for this formulation was identified as a limitation.

The future extension of the method was proposed to address these more specific geometric details for individual dwellings, and also to support more detailed representation in dynamic simulation of other features such as low carbon systems and controls.

### 9.1.2 Part B: Translating design intent into performance in practice.

The work on this topic was contained in chapters 2, 6 and 7 of the thesis.

Chapter 2 (Part B).

Based on the second part of the literature review the research question was formulated:

*"Could a modular control mapping and Failure Mode Effects Analysis (FMEA) approach be developed to address the gaps between intended and actual performance for systems and controls in low energy buildings in synergy with current industry initiatives?"*

As with part A of the research, the approach taken was to hypothesise that such a method could be developed, then test the hypothesis by formulating a method and assessing its usefulness in a number of test applications.

The proposed method involved a Modular Control Mapping and Failure Mode Effects Analysis (FMEA) approach leveraging in part processes used in Building Information Modelling (BIM) benchmark industries such as automotive, aerospace and electronics.

Chapter 6.

The proposed Modular Control Mapping and FMEA method was described. It was then applied to the first test case: the BRE Environmental Office.

The method proved very useful in identifying problems with the systems and controls implementation in the test case building, and as a vehicle for communicating these issues, and defining and communicating potential improvements.

The application was in post occupancy mode. Application based on concept and detailed design stage information was also demonstrated using information relating to those stages. This application based on information from different stages allowed disconnects in the overall design and implementation process to be highlighted.

The ability was demonstrated for the method to be evolved to capture knowledge developed through the course of a project for potential use later in the same project or on subsequent projects.

Chapter 7.

The Modular Control Mapping and FMEA method was applied to two domestic buildings intended to be low carbon, a Passive House, and the Glasgow House. These buildings had a range of low carbon systems including solar thermal, heat pump, and mechanical ventilation with heat recovery, and associated controls.

Control maps and FMEAs were constructed based on Passive House concept design information and then used as a framework to investigate the actual buildings as implemented.

The method proved useful when applied to the Passive House in identifying many issues and disconnects. The method was also useful as a vehicle to describe and communicate potential improvements.

The Control Maps and FMEAs for the Passive House Solar Thermal and MVHR components were used to investigate similar components in the Glasgow House. The relevant modules of the Passive House control map and FMEA were again useful in highlighting disconnects and communicating potential improvements.

Overall the proposed method proved useful in addressing the problems which were the cause of disconnects between intended and actual performance.

The potential integration of the method within a design flow was illustrated, in synergy with expert reviews as called for in Soft Landings and NABERS.

### 9.1.3 Discussion

A broader discussion of industry process was provided in chapter 8.

Based on the success of the Modular Control Mapping and FMEA method which in part leveraged techniques from BIM benchmark industries, it appeared that further investigation of techniques from a BIM benchmark industry would be worthwhile.

A number of processes from the electronics industry were identified as potentially useful and candidates for future investigation.

Public availability of performance data was also proposed to be a key driver of the development of BIM benchmark industry processes.

The extent to which the identified processes and public performance data are being addressed by current initiatives was reviewed. It was concluded that significant gaps remain and that further processes from the BIM benchmark industries merit future investigation.

Strategies were illustrated for integrating both the option appraisal method and the modular control mapping and FMEA approach within a future BIM process.

## 9.2 Research Outcomes.

The outcomes from part A of this work are:

- The elaboration and investigation of a low cost, EPBD aligned, simulation based, real-time method for performance assessment and upgrade option appraisal. The method is able to inform decisions for a range of users with various levels of technical knowledge. The method developed addresses gaps in previous work. Technical and user process aspects of the proposed method are covered.

- An example development and deployment process for the proposed method that provides a template for others to follow, and a platform for future research.

- A critical analysis of the performance of the proposed method for a number of test applications. Test applications included: EPC generation based on a simple questionnaire; and more general applications to inform policy, strategy and early stage design decisions.

- The appropriate application of the method is described. Where there are limitations for specific applications these are identified. Future work is detailed that will address these limitations and expand the scope of potential applications.

- The general formulation of the performance assessment and option appraisal method developed and deployed in this work is freely available and being used to support learning, performance assessment and option appraisal in teaching, research and practice.

The outcomes from part B of the work presented in this thesis are:

- The elaboration of a new Modular Control Mapping and FMEA approach. The approach was then deployed on a number of test applications to both non-domestic and domestic buildings.

- The application of the method was demonstrated at post-occupancy stage. The method proved successful in providing a useful template for post occupancy evaluation, facilitated clarification of the intended and as implemented operation, allowed clear communications and transfer of knowledge, and led to identification of numerous potential and actual failure modes so these could be addressed.

- The modular nature and re-usability of the proposed method was demonstrated through subsequent re-application of selected modules to a further project.

- The applicability of the modular control mapping and FMEA method to various levels of the design process was demonstrated. The method was applied based on concept design information, detailed design information, as implemented based on observations and monitoring, and to communicate potential improvements.

- The integration of the modular control mapping and FMEA process in the design flow was elaborated. It was illustrated how the Control Mapping and FMEA process can underpin the expert reviews called for in initiatives such as Soft Landings and NABERS.

- The potential adoption of the method within a BIM process is discussed.

- The Control Maps and FMEAs generated through the test applications are freely available for re-use and form the start of a modular library.

- This re-use will ensure that expert knowledge developed for the test applications is captured in future projects. This will result in the elimination of the fail modes identified. This will also facilitate clearer understanding and communication of controls as intended and implemented.

- The method where adopted will facilitate the capture of expert knowledge and facilitate the elimination of disconnects between design intent and performance in practice.

The outcomes from the review of BIM benchmark industry process and current buildings industry initiatives are:

- Other methods from BIM benchmark industries with potential to contribute to the realisation of low carbon buildings in practice are identified.

- The availability of public performance data is identified as a key driver of the BIM benchmark industries processes.

- Gaps in the current buildings industry initiatives are identified by comparison with a BIM benchmark industry and methods proposed as having potential application and that should be researched further.

- The future integration of the option appraisal and modular control mapping and FMEA methods together within a BIM framework is proposed.

## 9.3 Conclusions

The overall aim of this work was to contribute to the realisation of low carbon buildings. Two problem areas were identified: the need to support performance assessment and option appraisal in design concept, strategy, policy and legislation; and the need to translate design intent into performance in practice.

The current building industry environment with high focus on low carbon performance, challenging legislation, and plethora of new or improved products being applied in combinations, to a broadening spectrum of building types, has strained existing processes.

Problems with availability, capability, quality, and cost of expert inputs, on which the industry has historically depended for advice on more advanced systems, are an increasing issue, leading to the gaps between intended and actual performance highlighted in this thesis.

This thesis put forward the hypothesis that two methods could be developed to usefully address these problem areas. Both of these new methods are intended to provide a vehicle for expert knowledge to be embedded and made available to a range of users.

The performance assessment and upgrade option appraisal method was formulated to address the hypothesis that a low cost simulation based method could be developed to support real-time performance assessment and option appraisal by a range of users in the context of the EPBD.

Expert knowledge is embedded in this method in two ways, firstly in the formulation and pre-simulation of the dynamic simulation models, and secondly in the values used in the calculations which are inferred from user inputs e.g. infiltration rates, low carbon system performance, financial and carbon information etc.

A version of the method was developed and tested and the hypothesis shown to be correct for a range of applications. The method proved useful in education, policy, strategy and early design stage analysis.

Some applications of the method gave insights into limitations, allowing proposals for future work that addresses these limitations to be put forward.

The method elaborated in this thesis is useful in its current form and insights gained through its research and development has provided a basis for future work.

The formulation of the method developed here allows dynamic simulation based data to be made available real time for a range of users (expert and non-expert) to inform decisions in the context of the EPBD. A method for further increasing the use of dynamic simulation has been elaborated that will enable this rich physical representation to better inform decisions in future.

But in practice, decisions at the policy, strategy or early design stage are not sufficient to achieve low carbon performance. These decisions must be translated through industry process into low carbon performance in practice. There is much evidence that current industry processes are not effective in delivery of intended performance in practice, and that there is a need for improved processes. Implementation of low carbon systems and controls was highlighted as an area of weakness.

The Modular Control Mapping and FMEA method was formulated to test the hypothesis that a method could be developed to address the identified gaps between intended and actual performance, with particular focus on low carbon systems and controls.

The method was demonstrated to provide a modular approach and allow knowledge to be captured and transferred within a project and from project to project. The proposed method can fit in synergy with the ‘expert review’ requirements of processes such as Soft Landings and also facilitate translation of system and control information to and from dynamic simulation modelling and optimisation.

The method was successfully implemented for office and domestic buildings with systems intended to be low carbon. The use of the method at different stages of the design process based on concept, detailed design and as-implemented information was demonstrated.

The templates created in these test applications have potential for use in other similar projects and to be available as the start of a modular library. The extended application of the method to other building and system types is a simple next step.

In conclusion, both of the methods put forward in this thesis have been shown to be useful to address current challenges in the buildings industry. The research described here covers the development and test of the proposed methods and provides insights for further research to build on. Some possible future research is described in the next section.

### 9.4 Future work.

The performance assessment and option appraisal method developed in this thesis is being used as it is currently configured. There are however many opportunities for further work.

The method is intended for replication to other situations and contexts e.g. building stocks of different countries, different climates etc. This could be the basis of a future project.

The method could be further developed to address the limitations identified for specific applications as discussed in chapter 5:

- To accept more detailed geometrical factors and other dynamic factors through the use of Response Surface Modelling (RSM) techniques proposed in chapter 5.
- To support modelling of multi-building stocks automatically without the use of supporting spreadsheets.

- To include an educational infrastructure, quality control and feedback mechanism, to support questionnaire (on-line or physical) data entry for non-experts.

The simulation component of the option appraisal method could be expanded to support more detailed simulation modelling than in the current implementation. Low carbon systems and controls performance could be incorporated and calibrated based on actual performance for a sub-set of seed models.

Other opportunities include the assessment of summer overheating and other thermal comfort parameters. The inclusion of robustness analysis against variations in patterns of use and variations in weather would also be possible. These added layers of complexity in the modelling array would be facilitated by the Response Surface Modelling (RSM) methods proposed as a means to overcome the limitations of the current full factorial implementation.

The Modular Control Mapping and FMEA method has been effective in the test cases. Repeated use of the modular control maps and FMEAs generated for the exemplar buildings and their systems will allow direct re-use for other similar buildings and systems at any stage of the design process.

Further work could develop Control Maps and FMEAs for an expanded range of modules e.g. Combined Heat and Power, Ground Source Heat Pumps, Wind Turbines etc. This would have the potential to capture appropriate knowledge and provide a framework to address the gaps between intended and actual performance for these technologies.

The integration of the method with industry processes such as Soft Landings, NABERS, BREEAM, LEED and guidance such as from CIBSE, CIC or RIBA would be a further opportunity for future work leveraging the outcome of this research.

The proposed integrated approach with option appraisal plus a modular library of associated documentation such as design templates, control maps and FMEAs could be developed within a BIM context.

Techniques from BIM benchmark industries with potential to improve buildings industry processes could be further explored. It would appear that there are opportunities, but further work would be required to demonstrate feasibility.

## 9.5 Concluding statement

The overall aim in this work has been to contribute to the realisation of low carbon buildings in practice. Barriers were identified in the decision making process, and in the process of translating decisions into performance in practice. Methods have been hypothesised as potential solutions, and the hypothesis tested by formulating these methods and testing them for a range of applications. The proposed methods have proved to be useful and also to provide a base for future research and development. The adoption of the methods in synergy with building industry current initiatives has been proposed. Other methods from BIM benchmark industries with potential for application have been highlighted.

# Appendix A

## A.1 Prior ESRU work and gaps to be addressed in this thesis

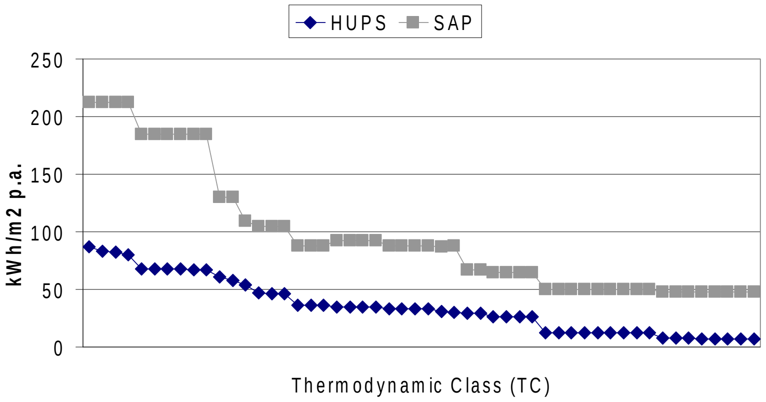
In prior work, Clarke et al (2004) developed and deployed a simulation based method for evaluating the impact of thermal improvements on the space heating performance of existing Scottish dwellings and housing stocks in research funded by the Scottish Government, the method is encapsulated in the Housing Upgrade Planning Support (HUPS) toolset. The approach taken by Clarke et al was to map the entire range of thermal performance possibilities of the Scottish building stock into an array of dynamic simulation models with each one identified as a specific thermodynamic class (TC). Upgrades of dwellings were evaluated by mapping the original unimproved dwelling to the corresponding thermodynamic class (with known simulated thermal performance) then mapping the improved dwelling to a second thermodynamic class (also with known thermal performance), the tool then computes the savings in space heating demand achieved through the upgrade. This approach reduces the complexity of the modelling task compared to the traditional approach which has been to model dwellings by distinct architectural types in combination with all possible thermal upgrades. In the TC mapping approach of Clarke et al the thermal performance of dwellings of the same architectural type (e.g. 1930’s terraced house) with different upgrades applied are represented by different TCs while two different architectural types (e.g. upgraded 1930s terraced house and a 1985 terraced house) with similar thermal properties are represented by the same TC. The main HUPS tool supports space heating demand analysis; further spreadsheet based tools allow simple analysis of renewable energy systems and the impact of energy efficient lights and appliances.

The Housing Upgrade Planning Support (HUPS) method as implemented in the available toolset was reviewed against the requirements for the proposed new method. As would be expected from the timeframe and more limited scope of HUPS, many gaps were identified:

- The three part HUPS method relies on the availability and manual entry of technical data (e.g. thermal mass and thermal mass position, window to floor area ratio etc) and economic data (e.g. capital cost of wall insulation) not readily available to the policy and strategy decision makers or most building professionals.
- Thermal upgrades are evaluated in the form of packages where all building thermal elements are upgraded together from one standard to another e.g. 1983 building regulations to 2002 building regulations. Intermediate levels of upgrade between the pre-set values are not supported. Upgrade of individual fabric elements is not supported e.g. window replacement, loft insulation upgrade etc.
- Fixed values are assumed for space heating per unit floor area irrespective of geometrical factors such as: number of storeys (wall to floor/ceiling ratio), form (detached, terraced, top/mid/ground flat etc which affects heat loss surface area), ceiling height (wall and window heat loss areas), surface to volume ratio, thermal bridges, orientations and shading (solar gains).
- The range of thermal upgrade options is limited to 2002 best practice; does not include the latest best practice upgrade standards (e.g. 2007, 2010 building regulations, EU Passive House etc.).
- Simulation input assumptions and outputs in HUPS (occupancy profiles, temperature set-points, ventilation rates, lights and appliance usage etc) do not align with the data underpinning the UK Governments SAP or EU Passive House PHPP which have both been aligned with significant survey data (up to 60% lower heating energy demand in HUPS than SAP, up to 80% lower than PHPP, figure A.1).
- Scope does not directly include:
    - Full range of space heating: types, secondary heating, fuels, controls.
    - Hot water: demands, systems and fuels.
    - Full range of ventilation options.
    - Full range of renewable energy options.
- The requirement for specialist input data and some of the other factors highlighted above have so far restricted use of the HUPS method to the development team.

The HUPS tool did however provided a significant step forward in directly linking the capabilities of dynamic simulation within a tool for use in policy formulation and also in the mapping of architectural types into an array of thermodynamic classes of similar thermal properties.

Figure A.1: HUPS v. SAP estimation of space heating energy demands.



## A.2 The work in this thesis

The research work described in this thesis was carried out subsequent to the work described in 3.5.1 and independently by the author. The Scottish Governments EPBD implementation group provided user requirements, perspectives and feedbacks in response to questions and propositions from the author. Some support was provided from ESRU software experts in Java and C coding of the user interfaces, this was to the detailed specifications of the author with appearance and underlying operations, logic and equations being specified by the author ahead of the software coding task. (Evidence for the above can be provided if required).

# Appendix B: Manual for the general implementation of the performance assessment and upgrade option appraisal method.

## HEM detailed description: Part 1 - inputs and outputs.

### Summary

HEM is a flexible approach to mapping the possible building carbon and energy performance universe in terms of a matrix of simulation models. Each individual dwelling is then described by a specific combination of parameters which allows a discrete model to be identified which is then used to represent the dwellings behaviour. The matrix of models can be simulated for a range of different contexts e.g. climate change, changed occupancy patterns etc. to allow building performance to be established for these circumstances.

The case used here to illustrate the methodology is the 'Scottish Dwellings' project. Other projects exist or are in development and follow the same structure but have different parameter levels or different contexts (climates, behaviours, costs) appropriate to the specific target application.

The level at which dynamic simulation is applied also depends on the specific application. The 'Scottish Dwellings' application described here has pre-simulated results embedded as a data table in the tool and applies the appropriate system and context calculations to provide instant energy, carbon and cost results.

Other projects have included pre-simulated detailed modelling of system performance or are configured to allow the user to run ESP-r dynamic simulation software directly through the interface – these are not described in detail here.

### Part 1 Contents:

Note: The detailed calculations and the data tables used in the calculations are described in Part 2 of the HEM detailed description: Part 2 – Calculations and Tables. In this version of the document this is appended directly after Part1.

## 1. Primary input parameters (Fabric, System and Context Determinants)

The input parameters are in 3 groups; ‘fabric determinants’, ‘system determinants’ and ‘context determinants’. The fabric determinants are used to select the appropriate thermal simulation models, the system determinants are used to select the appropriate system calculations, the context determinants are used to set the background for the thermal and system performance assessment and the cost calculations. Each category is described in more detail below.

### 1.1 Fabric input parameters and associated displayed outputs

The dwellings fabric parameters are used to select the appropriate model within the array. The heating (and cooling) energy demand of this model then represents the dwellings thermal performance. The parameters and levels that can be selected are described below as well as the associated tool output parameters:

**Insulation**

| | |
|---|---|
| **poor (pre-83)** | Insulation standards applied representing building standards prior to the 1981 Scottish building regulations. |
| **standard (83-02)** | Insulation standards applied representing building standards defined by the 1981 Scottish building regulations. |
| **medium (03-07)** | Insulation standards applied representing building standards defined by the 2002 Scottish building regulations. |
| **good (post07)** | Insulation standards applied representing building standards defined by the 2007 Scottish building regulations. |
| **super (post07)** | Insulation standards applied representing building standards defined by the AECB ‘Gold’ and ‘Passivhaus’ guidelines. |
| Outputs: | The insulation value selected is displayed in the ‘Determinant levels’ ‘Insulation’ display box.<br>The **‘Glz U’**, **‘Roof U’**, **‘Wall U’**, and **‘Floor U’** display boxes in the detailed inputs columns give the U-values in W/m2K for the Insulation selection made**.** |

**Air-changes**

| | |
|---|---|
| **poor** | This represents the value of air-changes that would be expected in a property with single glazing without draught proofing. If ‘poor’ is selected then an air change rate of 1.5ac/h is used. |
| **standard** | This represents the value of air-changes that would be expected in a property with good double or draught proofed single glazing.If ‘standard’ is selected then an air change rate of 0.85ac/h is used. |

| | |
|---|---|
| **tight** | This represents the value of air-changes that would be expected in a property built to 2007 details or where extensive draught proofing has been carried out (glazing, doors, loft, floor, service openings etc). If ‘tight’ is selected then an air change rate of 0.6ac/h is used. |
| Outputs: | The Air change value selected is displayed in the ‘Determinant levels’ ‘Air changes’ display box. |

## Capacity

| | |
|---|---|
| **high** | This represents a high thermal mass building where the capacity is available to interact with the occupied space. Note for this project there is an assumption that all dwellings with ‘poor’ insulation have ‘high’ thermal mass. |
| **low** | This represents a low thermal mass building or one where the thermal mass is not available to interact with the occupied space. Note for this project there is an assumption that all dwellings that |
| Outputs: | The capacity value selected is displayed in the ‘Determinant levels’ ‘Capacity’ display box. |

## Capacity position

| | |
|---|---|
| **Inside** | In this project the thermal capacity that is considered is always that available to interact with the occupied space, i.e. ‘Inside’ is always selected. |
| Outputs: | The Capacity position value selected is displayed in the ‘Determinant levels’ ‘Cap posn’ display box. |

## Window size

| | |
|---|---|
| **Standard** | In this project the window size is fixed at 17.5% of the total floor area. |
| Outputs: | The Window size value selected is displayed in the ‘Determinant levels’ ‘Window size’ display box. |

## Exposure

| | |
|---|---|
| **detached** | Represents a detached dwelling where all 4 sides are exposed to the external environment. |
| **semi-detached** | Represents a semi-detached or end terrace dwelling where 3 sides are exposed to the external environment. |

| | |
|---|---|
| **mid-terrace** | Represents a mid terrace dwelling where 2 sides are exposed to the external environment. |
| **flat(g)** | Represents a ground floor flat where 3 sides are exposed to the external environment but the roof is not exposed. |
| **flat(t)** | Represents top floor flat where 3 sides are exposed to the external environment but the floor is not exposed. |
| **flat(m)** | Represents a mid floor flat where 3 sides are exposed to the external environment but the roof and floor are not exposed. |
| Outputs: | The Exposure value selected is displayed in the ‘Determinant levels’ ‘Exposure’ display box.<br>The number of external walls is also displayed in the ‘Detailed inputs’ ‘Ext walls’ display box. |

### Shape

| | |
|---|---|
| **1-storey** | Represents a single storey dwelling |
| **2-storey** | Represents a two storey dwelling. |
| Outputs: | The Shape value selected is displayed in the ‘Determinant levels’ ‘Shape’ display box. |

The fabric determinants allow the heating energy to be determined based on the appropriate model (or thermodynamic class, TC) by reading the appropriate pre-simulated heating energy demand value and applying the appropriate calculations. The selected model id number is displayed in the ‘Determinant levels’ ‘TC ID’ display box.

## 1.2 System input parameters and associated displayed outputs

The dwellings system determinants are used to select the appropriate system calculations and parameter values. The system input options are described below:

### Hsys Fuel

| | |
|---|---|
| **main gas** | This selects mains gas as the heating fuel. |
| **electricity** | This selects grid electricity as the main heating fuel. |
| **wood / bio** | This selects wood or bio-mass ass the main heating fuel. |
| **lpg / bt gas** | This selects LPG or other bottled gas as the main heating fuel. |
| **oil** | This selects oil as the main heating fuel. |

| | |
|---|---|
| **coal / sf** | This selects coal or other processed solid fuel (smokeless coal etc.) as the main heating fuel. |
| Outputs: | The Fuel selected is displayed in the 'Determinant levels' display boxes. |

## Hsys Type

### Hsys Type (if main gas, lpg / bt gas, oil or wood / bio Hsys Fuel selected)

| | |
|---|---|
| **fires** | Individual room heaters |
| **boiler l.eff** | Low efficiency boiler |
| **boiler m.eff** | Medium efficiency boiler |
| **boiler h.eff** | High efficiency non-condensing boiler |
| **boiler cond** | Condensing boiler |
| **u CHP** | Stirling engine type individual dwelling CHP<br>Not currently an allowed option for oil or wood / bio Hsys Fuel |
| **com CHP** | Reciprocating type community CHP system. |

### Hsys Type (if 'electricity' Hsys Fuel selected)

| | |
|---|---|
| **fires** | Individual room heaters |
| **storage** | Individual storage type heaters |
| **ashp** | Air source heat pump feeding wet heating system |
| **gshp** | Ground source heat pump feeding wet heating system |
| **boiler h.eff** | High efficiency boiler direct heating wet radiator system |
| Outputs: | The heating system type selected is displayed in the appropriate 'Determinant levels' display box.<br>The heat source efficiency is also displayed in the 'Heff %' 'Detailed inputs' display box. A second efficiency value for the complete space heating system 'Heff Adj %' takes account of the 'Controls' selection. |

## HWsys type

| | |
|---|---|
| **main tank** | The main space heating source also heats the hot water in a storage tank system. |

| | |
|---|---|
| **main combi** | The main space heating source also heats the hot water in an instant heat ‘combi’ system. |
| **elec immer** | A separate electric immersion heater is used to heat the hot water in a storage tank system. |
| **inst gas** | A separate gas heater is used to heat the hot water in an instant heat system. |
| **inst elec** | A separate electric heater is used to heat the hot water in an instant heat system. |
| Outputs: | The hot water heating system type selected is displayed in the appropriate ‘Determinant levels’ display box.<br>The hot water heat source efficiency is also displayed in the ‘Hw Eff Adj %’ ‘Detailed inputs’ display box. Note: this value includes any adjustment for the water heating efficiency based on the Controls’ selection. |

## Controls

| | |
|---|---|
| **standard** | This selection indicates that the controls are typical for the associated Hsys type selection. |
| **advanced** | This selection indicates that the controls have been upgraded to the best practice controls for the Hsys type selection. |
| Outputs: | The Controls selected is displayed in the appropriate ‘Determinant levels’ display box.<br>The ‘Heff Adj %’ and the ‘Hw Eff Adj %’ ‘Detailed inputs’ display values include the control adjustments. |

## Lights

| | |
|---|---|
| **100% lel** | This selection indicates that all of the light is provided by CFL lighting. |
| **0% lel** | This selection indicates that all of the lighting is provided with incandescent light bulbs. |
| Outputs: | The selection is displayed in the appropriate ‘Determinant levels’ display box. |

## Vent / Cool

| | |
|---|---|
| **nat / wet ext** | This selection indicates that there is no centralised ventilation system and that the primary ventilation is by natural means i.e. trickle vents, window opening and infiltration. In addition there is intermittent extract by local fans from the bathroom and kitchen areas. |

| | |
|---|---|
| **mvhr std** | This selection indicates a whole dwelling mechanical ventilation system with heat recovery. In this case the system has standard performance of 66% heat recovery and 2w/l/s specific fan power. |
| **mvhr h.eff** | This selection indicates a whole dwelling mechanical ventilation system with heat recovery. In this case the system has good performance of 85% heat recovery and 1w/l/s specific fan power. |
| **mvhr super** | This selection indicates a whole dwelling mechanical ventilation system with heat recovery. In this case the system has super performance of 88% heat recovery and 0.6w/l/s specific fan power. This option is only allowed together with 'tight' Air change selection and assumes a very low level of infiltration. |
| **Air-cond** | This selection indicates that comfort cooling is installed. |
| Outputs: | The selection is displayed in the appropriate 'Determinant levels' display box. |

## Renewables

| | |
|---|---|
| **Sol 4m2 FP** | Solar hot water heating with a 4m2 flat plate system |
| **Sol 4m2 ET** | Solar hot water heating with a 4m2 evac tube system |
| **PV 8m2 mon** | PV generation with 8m2 mono-xtal panels |
| **PV 8m2 poly** | PV generation with 8m2 poly-xtal panels |
| **PV 8m2 amor** | PV generation with 8m2 amorphous panels |
| **Sol + PV** | Solar hot water heating (Sol 4m2 FP) plus PV generation with 8m2 mono-xtal panels |
| **WT 2m** | Wind turbine with 2m diameter, tall mast and 4.4m/s local wind speed (rural UK only) |
| **WT 3m** | Wind turbine with 3m diameter, tall mast and 4.4m/s local wind speed (rural UK only) |
| **Sol + WT** | Solar hot water heating (Sol 4m2 FP) plus wind turbine with 2m diameter, tall mast and 4.4m/s local wind speed (rural UK only) |
| Outputs: | The selection is displayed in the appropriate 'Determinant levels' display box.<br>The local wind speed is also displayed in the 'More details' 'Wind speed' display box. |

### 1.3 Context input parameters and associated displayed outputs

The context determinants are used to select the appropriate context calculations and parameter values. The context input options are described below:

### Climate

| | |
|---|---|
| **UK std** | This selection gives a climate context similar to that used in the Governments SAP methodology. Note: this is the only option available in the current public release version. |
| **Sco std** | This selection gives a standard Scottish climate. Note: this option not available in the current public release version. |
| **London** | This selection gives a standard London climate. Note: this option not available in the current public release version. |
| **Paris** | This selection gives a standard Paris climate. Note: this option not available in the current public release version. |
| Outputs: | The selection is displayed in the appropriate ‘Determinant levels’ display box. |

### HT demand

| | |
|---|---|
| **Scot std** | This selection gives an averaged UK heating profile similar to that used in the Governments SAP methodology. Note: this is the only option available in the current public release version. |
| **Frugal** | This selection gives a reduced heating profile and could represent occupant behaviour in the case of very high fuel prices etc. Note: this option not available in the current public release version. |
| **Profligate** | This selection gives an increased heating profile (constant 23oC) and could represent occupant behaviour in the case of very low fuel prices etc. Note: this option not available in the current public release version. |
| Outputs: | The selection is displayed in the appropriate ‘Determinant levels’ display box. |

### HW demand

| | |
|---|---|
| **Scot std** | This selection gives an averaged UK hot water use profile similar to that used in the Governments SAP methodology. Note: this is the only option available in the current public release version. |
| **Frugal** | This selection gives a reduced hot water use profile and could represent occupant behaviour in the case of very high fuel prices |

| | |
|---|---|
| | or the use of low water use fittings and appliances etc. Note: this option not available in the current public release version. |
| **Profligate** | This selection gives an increased hot water demand profile and could represent occupant behaviour in the case of very low fuel prices etc. Note: this option not available in the current public release version. |
| Outputs: | The selection is displayed in the appropriate 'Determinant levels' display box. |

## Appliances

| | |
|---|---|
| **standard** | This selection gives an averaged UK appliances use profile similar to that used in the Governments SAP methodology. Note: this is the only option available in the current public release version. |
| **Frugal** | This selection gives a reduced appliance use profile and could represent occupant behaviour in the case of very high fuel prices etc. Note: this option not available in the current public release version. |
| **Profligate** | This selection gives an increased appliance use profile and could represent occupant behaviour in the case of very low fuel prices etc. Note: this option not available in the current public release version. |
| Outputs: | The selection is displayed in the appropriate 'Determinant levels' display box. |

## Grid Intensity

| | |
|---|---|
| **UK std** | This selection gives an averaged UK CO2 emissions factor profile by fuel type similar to that used in the Governments SAP methodology. |
| **low CO2 el** | This selection gives a reduced CO2 emissions factor for the electric grid - consistent with a much higher use of renewable and nuclear generation than the current UK standard assumptions. |
| **high CO2 el** | This selection gives an increased CO2 emissions factor for the electric grid - consistent with a much lower use of renewable and nuclear generation than the current UK standard assumptions. |
| Outputs: | The selection is displayed in the appropriate 'Determinant levels' display box. |

## Tariff £

| | |
|---|---|
| **standard** | This selection gives a fuel unit cost and standing charge similar to that used in the Governments SAP methodology. |
| **2Xstandard** | This selection gives unit cost and standing charge 2X standard to represent possible fuel price increases. |
| Outputs: | The selection is displayed in the appropriate ‘Determinant levels’ display box. |

**Capital £**

| | |
|---|---|
| **standard** | This selection gives capital costs for upgrade of fabric and systems based on current costs. |
| **0.5Xstandard** | This selection gives capital costs of 0.5X standard to represent possible price reduction due to increased volumes in future. |
| Outputs: | The selection is displayed in the appropriate ‘Determinant levels’ display box. |

## 2. Secondary inputs (Categories list, Fabric Slider, System slider, More detailed inputs)

### 2.1 Categories list and sliders

The primary input parameters are used in the calculations as described above in section 1 but there are other ways of selecting these input parameters rather than setting each directly.

The **‘Categories list’** can be used to set the fabric and system parameters to those pre-determined for a specific dwelling or dwelling type e.g. selection of ‘Detached-pre 1981 – reg boiler l.eff’ sets the fabric determinants to ‘poor’ insulation, ‘poor’ air changes, ‘detached’ exposure, ‘main gas’ fuel, ‘boiler l.eff’ heating system etc. The categories list can be customised to meet the requirements of a specific project. New categories can be created using the **‘Save new category’** option from the ‘File’ pull down menu at the top of the tool, the user is asked to supply the name for the new category which will then appear at the end of the categories list.

The **‘Fabric slider’** and **‘System slider’** also allow the indirect selection of determinants. In this case the sliders position represents the incremental level of CO2 performance.

Where the fabric slider position is to the left hand side then the fabric has high associated CO2 emissions (i.e. poor insulation, poor air-changes), where the fabric slider is moved to the right hand side then the fabric has low associated CO2 emissions (i.e. super insulation, tight air-changes). The fabric slider follows the insulation and air-changes selections or if the slider is manually adjusted it forces the insulation and air-change settings to those appropriate to the new slider position. In this way the slider can be used to investigate the impact of fabric improvements.

The system slider operates in a similar fashion. When the slider position is to the left hand side then the heating system has high associated CO2 emissions (i.e. coal, open fires), where the fabric slider is moved to the right hand side then the heating system has low associated CO2 emissions (i.e. wood fired CHP). The slider follows the heating fuel and system type selections or if the slider is manually adjusted it forces the fuel and system settings to those appropriate to the new slider position. In this way the slider can be used to investigate the impact of system improvements.

### 2.2 More detailed inputs

The **‘More detailed input’** button opens up a window which allows entry of a set of inputs allowing greater resolution than those available through the main interface. This window can be customised to meet the needs of each different project. For the Scottish Dwellings project these more detailed inputs are to allow the building form, insulation levels and systems to be specified in more detail. The details are held until the **‘Clear detailed input’** button is selected.

#### Building form

| | |
|---|---|
| **non-sep cons** | This selection indicates a conservatory has been added to a dwelling but not thermally separated by good quality doors, walls and windows, this has the effect of negatively impacting the thermal insulation of the property. |
| **ceiling height** | This selection selects either ‘average’ or ‘high’ ceilings. |
| **floor area** | This box allows the floor area to be entered directly rather than using the default values of 94m2 for a house and 71m2 for a flat. |
| **cavity y/n?** | This box allows the type of wall upgrade to be specified to allow appropriate costs to be allocated, wall cavity fill has a lower cost than internal or external insulation. |
| **solid floor y/n?** | This box allows the type of floor upgrade to be specified to allow appropriate costs to be allocated, suspended wooden floor upgrade has a lower cost than solid floor insulation. |
| **flat roof y/n?** | This box allows the type of roof upgrade to be specified to allow appropriate costs to be allocated, pitched roof upgrade has a lower cost than flat roof insulation. |

#### Insulation

| | |
|---|---|
| **glazing U-value** | This allows a glazing-only upgrade to be selected rather than the package of upgrades available through the main screen categories which include wall, roof and floor upgrades. |
| **roof/loft U-value** | This allows a roof-only upgrade to be selected rather than the package of upgrades available through the main screen categories which include wall, glazing and floor upgrades. |
| **wall U-value** | This allows a wall-only upgrade to be selected rather than the package of upgrades available through the main screen categories which include roof, glazing and floor upgrades. |

| | |
|---|---|
| **floor U-value** | This allows a floor-only upgrade to be selected rather than the package of upgrades available through the main screen categories which include roof, glazing and wall upgrades. |

**System**

| | |
|---|---|
| **Heating eff %** | This allows the heating efficiency to be entered directly rather than accepting the default values from the main inputs. |
| **Sec heat type** | This allows a secondary heating system to be specified which is assumed to supply 10% of the heating demand. If not selected then the main heating system is assumed to deliver all of the heating demand. |
| **wind speed** | This allows a specific value to be entered rather than the default of 4.4m/s. |

| | |
|---|---|
| Outputs: | The selections are displayed in the appropriate ‘Detailed inputs’ display boxes.<br>Where detailed inputs have been used then ‘yes’ is displayed in the ‘Detailed inputs?’ box. |

### 3. Results (Energy, Carbon, Cost, Comparison to base, Ratings)

The ‘Results’ area is at the bottom right hand corner of the tool. The results are given as a comparison between the ‘base’ and the ‘current’ dwellings. The base is set using the **‘Select base’** button and cleared using the **‘Clear base’** button. Note that when a base has been selected then the building form is kept constant for the base and current dwelling (i.e. exposure, shape, ceiling height, floor area) until the base is cleared.

### 3.1 The $CO_2$ rater

The results can also be displayed in the form of an energy certificate, this has been calculated based on the SAP2005 method utilising the ‘Environmental Impact’ (EI) parameter to establish the rating band and score for the base and current dwelling. The rating is based on the EI score which is calculated from the Carbon Emissions rate for Heating, Hot water, Ventilation and Lighting (but excludes Appliance energy use).

| | |
|---|---|
| **CER kgCO2/m2 p.a.** | This value represents the annual carbon emissions in kgCO2 per m2 of floor area including heating, hot water, ventilation and lighting but not appliances. This value is consistent with the CER from SAP 2005. |
| **EI score** | This value the Environmental Impact with a value between 1 and 100, 100 being best. It is calculated from the CER in 2 stages, the first being to apply a factor to eliminate the effect of floor area |

|  |  |
|---|---|
|  | on the CER, then the second is to apply a function relating the adjusted CER to a 1 to 100 EI score. (SAP2005). |
| **Rating** | The ratings have been calculated based on the EI score and the bands defined in SAP2005. |

### 3.2 Energy results

|  |  |
|---|---|
| **Heating kWh/m2 p.a.** | This value represents the fuel used in kWh/m2 per year to satisfy the heating demand. |
| **Hot water kWh/m2 p.a.** | This value represents the fuel used in kWh/m2 per year to satisfy the hot water demand. |
| **Lighting kWh/m2 p.a.** | This value represents the fuel used in kWh/m2 per year to satisfy the lighting demand. |
| **Appliances kWh/m2 p.a.** | This value represents the fuel used in kWh/m2 per year to satisfy the appliances demand. |
| **Vent Cool kWh/m2 p.a.** | This value represents the fuel used in kWh/m2 per year to satisfy the ventilation and cooling demand. |
| **Sol thermal kWh/m2 p.a.** | This value represents the solar thermal contribution in kWh/m2 per year towards the hot water heating demand. |
| **RES el gen kWh/m2 p.a.** | This value represents the electricity generated from renewables (PV or wind turbine) or CHP systems normalised to the dwelling floor area in kWh/m2 per year. |
| **H,HW,L,A elec kWh/m2 p.a.** | This value represents the annual electricity demand in kWh per m2 of floor area including heating, hot water, lighting, ventilation and appliances. |
| **H,HW,L,A other kWh/m2 p.a.** | This value represents the annual non-electricity fuel demand in kWh per m2 of floor area including heating, hot water, lighting, ventilation and appliances. (i.e. the non-electric fuel demand). |

### 3.3 Carbon results

|  |  |
|---|---|
| **H,HW,L,A kgCO2/m2 p.a.** | This value represents the annual carbon emissions in kgCO2 per m2 of floor area including heating, hot water, lighting, ventilation and appliances. |
| **CER kgCO2/m2 p.a.** | This value represents the annual carbon emissions in kgCO2 per m2 of floor area including heating, hot water, ventilation and lighting but not appliances. This value is consistent with the CER from SAP 2005. |

| | |
|---|---|
| **Carbon footprint kgCO2 p.a.** | This value represents the dwellings annual carbon emissions in kgCO2 including heating, hot water lighting, ventilation and appliances. |

### 3.4 Cost results

| | |
|---|---|
| **Running cost £ p.a.** | This value represents the annual running costs for fuel (unit cost plus standing charges) including heating, hot water, lighting, ventilation and appliances. |
| **Capital cost £** | This value represents the capital cost for the upgrades required to change the base dwelling to match the current dwelling including fabric, fuel change and system costs. |
| **Payback (years)** | This value represents the capital cost for the upgrades required to change the base dwelling to match the current dwelling divided by the running cost annual savings. |

# HEM detailed description: Part 2 - calculations and data tables.

## Summary

The software tool consists of an interface, a calculation engine and data tables. The interface is used to pass the input variables to the calculation engine which runs and accesses data held in the tables. The interface, calculation engine and the data-tables are contained in the HEM setup file that can be downloaded from the ESRU or SESG websites.

The data tables hold parameter values such as costs, efficiencies, emission factors etc. and can be edited by the user if required e.g. if fuel or capital upgrade costs need to be updated or if a different default system efficiency is required etc. The data tables are in CSV format.

Among the data tables are the **'categoriesList'** and the **'edem_archive'** CSV files which are updated through the interface when either a new category is created or when an **'archive'** record is written.

The **'edem_archive'** is an important results store for the tool user, the file can be read into excel or another spreadsheet to allow easy manipulation of data and analysis of the results. The edem_archive file records the input parameters, the calculation variables and the energy, carbon and cost results for the selected record along with a user input label to help identify the record.

The categories creation function, along with editing of data tables allows the user to customise an existing HEM project for their own stock.

The calculation engine and the interface are programmed in Visual C++ and cannot be changed by the casual tool user but the opportunity exists for those with appropriate skill levels to develop new code as part of a new HEM project. If you wish to modify the source code and develop your own HEM project then please contact ESRU (paul.tuohy@strath.ac.uk) and we can arrange for the source code to be made available. Ideally we would like the new project code to be fed back to us and made available to other developers but this is not mandatory.

The tool is based on data from an underlying array of ESP-r simulation models which represent the range in thermodynamic performance of the stock being studied and have been simulated for the range of contexts (climates, occupancy patterns, heating set-points, hot water use profiles etc) appropriate to the project. This array of models can be made available as exemplars in ESP-r, the HEM tool identifies the relevant model via its **'TC ID'** number allowing users of ESP-r to access the model to allow more detailed dynamic simulation analysis to be carried out. If you would like access to the ESP-r model array then please contact ESRU (paul.tuohy@strath.ac.uk) and we can arrange for the source code to be made available. Again it is possible to develop your own array of simulation models as part of your own HEM project.

## Part 2 Calculations and data tables - Contents

## 1. Data tables (User, Parameter and System tables)

The data tables that are delivered in the setup are of three broad types; User files, Calculation parameter files and HEM System files. The data tables are designed to make all the key calculation and configuration parameters available to the user rather than being hidden in the code.

### 1.1 User tables

There are two user files which capture the user's results and also any user defined categories. The edem_archive file should be actively managed (i.e. contents cleared except for the headings row at the start of a new project, archive created under a new name at the end of a project etc.). The categoriesList file will allow the user to append a new category to the pre-defined project list or can be used to create a new categories list for a specific project, this file should be actively managed also (archive with version identifier etc). Contact ESRU (paul.tuohy@strath.ac.uk) for guidance.

| | |
|---|---|
| edem_archive | User file for storage of results plus input parameters and calculation variables. |
| categoriesList | Contains the pre-defined or user defined categories and the associated settings for the fabric and systems determinants. |

### 1.2 Parameter tables (system, running costs, carbon emissions, capital costs)

There are seven data tables which capture the system, running cost and carbon emissions parameters used in the calculations. These can be easily modified by the user. Contact ESRU (paul.tuohy@strath.ac.uk) for guidance.

| | |
|---|---|
| hsys_eff | Contains the heating efficiency, electrical generation efficiency and heating efficiency standard controls adjust parameter for each of the main space heating system / fuel combinations. |
| hwsys_param | Contains the storage loss factors, primary loss factors and standard hot water system standard controls adjust parameters for each hot water system type. |
| secondary_heating | Contains the efficiencies for each secondary heating option. |
| shw_param | Contains the renewable system parameters for solar hot water and systems. [not yet avail in 'data' – coming soon.] |
| pv_param | Contains the renewable system parameters for solar PV systems. [not yet avail in 'data' – coming soon.] |
| wt_param | Contains the renewable system parameters for wind turbine systems. [not yet avail in 'data' – coming soon.] |
| chp_param | Contains the renewable system parameters for CHP systems. [not yet avail in public 'data folder' – coming soon.] |
| vent_cool_param | Contains the ventilation and cooling parameters for solar hot water and solar PV systems. [not yet avail in 'data' – tbd.] |

| | |
|---|---|
| carbon | Contains the fuel carbon intensities for each of the ‘grid_intensity’ options. |
| cost | Contains the unit costs per kWh and the standing charges for each of the ‘tarriff £’ options. |

A further eleven data tables capture the capital cost of upgrading the fabric and systems. These can also be easily modified by the user. Contact ESRU (paul.tuohy@strath.ac.uk) for guidance.

| | |
|---|---|
| airt_upgrade | Contains the cost for options upgrading the air-tightness. |
| glz_upgrade | Contains the costs for options upgrading the glazing. |
| floor_upgrade | Contains the costs for options upgrading the floor (separate tables for solid floor and wooden suspended floors). |
| wall_upgrade | Contains the costs for options upgrading the walls (separate tables for cavity walls and non cavity walls). |
| roof_upgrade | Contains the costs for options upgrading the roof (separate tables for flat roof and pitched roofs). |
| controls_upgrade | Contains the costs for options upgrading the controls from standard controls for that system to ‘Advanced’ controls. |
| hfuel_upgrade | Contains the cost of a change in the main heating fuel (includes the provision of storage for wood fuel, lpg, oil etc..) |
| hsys_upgrade | Cost of changing the main heating system. |
| hwsys_upgrade | Cost of changing the hot water heating system. |
| vent_cool_upgrade | Cost of changing the vent_cool system. |
| res_upgrade | Cost of adding or upgrading the renewable energy systems. |

### 1.3 System Tables

The system tables can be modified by an experienced developer but requires detailed understanding of the code operation, contact ESRU (paul.tuohy@strath.ac.uk) for guidance.

Five tables contain information allowing the correct operation of the interface:

| | |
|---|---|
| edem_strings | Details the main interface combo-box drop down menu options. |
| edem_detailed_strings | Details the detailed input combo-box drop down menu options. |
| fab_slider_combo | Gives the synchronisation between main interface combo-box values and the fabric slider position. |

| | |
|---|---|
| fab_tc_id | Gives the fabric TC id for each combination of main parameters. |
| sys_slider_combo | Gives the synchronisation between main interface combo-box values and the system slider position. |

Two tables store the results of the simulations and also document the elemental U-values associated with each of the insulation categories.

| | |
|---|---|
| Hdem | Contains the heating demand parameters for each model (TC) |
| element_ins_std | Details the elemental U-values associated with each insulation category. |

## 2. Calculations

The calculations are documented in this section as a logical description only and provide a snapshot of an evolving tool, the full C++ code for HEM is available on request, contact ESRU (paul.tuohy@strath.ac.uk). The description here is for the ‘Scottish Dwellings’ project but the calculation code can be customised on a project by project basis based on the levels of available information or the levels of analysis that is desired to be carried out. Where additional parameters are to be considered then these can be made available either through the main tool drop down menu’s or the more detailed inputs window. Some reference to additional parameters is made in the descriptions of the calculation logic given below.

The structure of the calculations follows the form: A) Establish Variable Values, B) Carry Out Calculations, C) Set Display Parameters. The variable values are established based on the settings of the interface and the corresponding values read from the data tables. The displayed items are described in detail in Part 1 of this manual ‘Inputs and Outputs’ and not covered here.

### 2.1 Calculations Logical Flow

The following list illustrates the flow of the calculations, the calculations are explained in detail and references provided in the following sections.

2.1.1 Establish Geometry
2.1.2 Establish Lighting Energy Use and Carbon Emissions
2.1.3 Establish Appliance Energy Use and Carbon Emissions
2.1.4 Establish Ventilation and Cooling Energy Use and Carbon Emissions
2.1.5 Establish Occupancy and Hot Water Demand
2.1.6 Establish Heating Energy Demand
2.1.7 Establish Heating Energy Use and Carbon Emissions
2.1.8 Establish Energy from Solar Hot Water System
2.1.9 Establish Hot Water Energy Use and Carbon Emissions
2.1.10 Establish Energy and Carbon Emissions Impact from Local Generation
2.1.11 Establish Totals, Costs, CER, EI and Ratings

### 2.1.1 Establish Geometry

The geometry is established for the dwelling from the floor area and the building form (window size, ceiling height, shape and exposure). Note: this calculated geometry is not used directly in the thermal simulation models which have been pre-defined but is used in the calculations which relate the simulation model performance to the specific geometry of the actual dwelling. This calculated geometry is also used to calculate the upgrade costs etc. More detail is given on the use of the calculated geometry in the subsequent calculation descriptions.

**Geometry part 1: establish variable values:**

| | |
|---|---|
| **property type:** | 'Exposure' determinant value |
| **storeys:** | 'Shape' determinant value |
| **total floor area (TFA):** | Defaults based on property type: det, sd-et, mt: 94m2; flat: 71m2,<br>default replaced when TFA entered directly through detailed inputs. |
| **ceiling height:** | Default 2.5m<br>replaced by value selected through detailed inputs (2.5, 3.5). |
| **flat external walls:** | Default = 3<br>could be replaced with detailed input (1,2,3,4,3.5 etc..) |

**Geometry part 2: calculations:**

**ground floor ext'l area:** ground floor area = total floor area (TFA) / storeys
ground floor external area = 0 if flat(m),flat(t), else = ground floor area
**glz+door area:** glazing area = 0.175*total floor area
could be replaced with more detailed window-size from main combi
door area = 1.85 for flats, 3.7 for mt,det,sdet.
glz+dr area = glazing area+door area
**wall height** wall height = ceiling height*storeys
**volume** volume = wall height *ground floor area
perimeter adjust = 1.15
this accounts for increased non-square wall areas
ground floor perimeter = 4*sqroot{ground floor area} *perimeter adjust
external perimeter factor = 1 if det, 0.75 sdet, 0.5 mt, flat external walls/4 if flat
ground floor external perimeter = ground floor perimeter*external perimeter factor
**external wall area:** external wall area = wall height*ground floor external perimeter - glz+dr area
roof area = ground floor area
**external roof area:** external roof area = 0 for flat(m),flat(g), else = roof area
**total ext'l surface area:** total external surface area = external ground floor area + glz+dr area….
… + external wall area + external roof area

### 2.1.2 Establish Lighting Energy Use and Carbon Emissions

The SAP2005 [1] lighting energy equations have been used in HEM.

**Lights part1: get input variables:**
**LEL** = if(Lights = "100% lel",100, else 0) from system determinant.
**Lights part 2: calculations:**
**L_cons** = 9.3
**L_C1** = 1 – 0.5 * LEL / 100
**L_gratio** = (glazing area / TFA) * 0.9 * 0.75 *0.75 * 0.83
**L_C2** = if L_gratio < 0.095 then 52.2 * (L_gratio)2 – 9.94 * Lgratio + 1.43 else 0.96
**L_energy** = L_cons * TFA * L_C1 * L_C2
**L_energy_m2** = L_energy/TFA
**Lfuel_emm** = Emm_elec
**Lfuel_CO2** = value for Lfuel_emm type and appropriate Grid intensity from the carbon table.
**L_annCO2** = L_fuel * Lfuel_CO2
**Lcarbon_m2** = L_annCO2/TFA

### 2.1.3 Establish Appliance Energy Use and Carbon Emissions

The Appliance Energy Calculations established by the UK Government for the ‘Net Zero Carbon’ Stamp Duty Exemption [2] are used in HEM but with the option to vary this through the ‘Appliances’ context using a scaling factor. The Governments ZC2 parameter represents the CO2 emissions for appliances including cooking. The fuel use and CO2 emissions rate used in the Governments calculations is assumed to be grid electricity with the SAP standard emissions rate of 0.422 kgCO2/kWh. The HEM calculated carbon emissions takes account of the different carbon intensities available through the context parameter inputs.

**Appliance part 1: set variables:**
**AppF** = depends on context appliance determinant, e.g. std = 1, profligate = 1.5
**Appliance part 2: calculations:**
Calculate from standard equation (SDLT SAP2005sectionM, 2008).
**N** = if(TFA<43, 1.46, 2.844*(1-(exp(-0.00039)*TFA*TFA))
**App_carbon_SDLT_m2** = [99.9*(power((TFA*N),0.4714))-3.267*TFA+32.23*N+72.65]/TFA
**App_energy_m2** = App_carbon_m2/0.422
**Appfuel_emm** = Emm_elec
**Appfuel_CO2** = value for Appfuel_emm and appropriate Grid intensity from the carbon table.
**App_carbon_m2** = App_energy_m2*Appfuel_CO2

### 2.1.4 Establish Ventilation and Cooling Energy Use and Carbon Emissions

The ventilation and cooling energy calculations for mechanical systems mainly follow the SAP2005 calculations except in the case of the intermittent extract fans which are excluded from SAP but included here. The cooling energy is at present just a punitive energy – this can be displaced by actual simulation values in future if desired. The performance level for the standard MVHR is the standard set in SAP (66% HR, 2 w/l/s) while the MVHR HiEff system selection represents a system with better performance (85%, 1 w/l/s). The MVHR super assumes that the dwelling has been very well sealed and the best available ventilation system (SAPappendixQ) used (88%, 0.6 w/l/s). The heat recovered by the MVHR systems is calculated as part of the heating demand calculations.

**VentCoolType** system parameter selection: either NatWetExt, MVHR, HeffMVHR, AC.
default value is NatWetEx

**NoExFans** = if NatWetEx then 2 for flat, 3 for not flat (detached, semi, terr), else 0.
**EXEnergy** = if NatWetEx then 18*NoExFans, else 0 (kWh p.a. assumes 50W fan1hr/day)

**MVsfp** = 2 for (MVHR or AC), 0.6 for HeffMVHR, else 0
**MVEnergy** = if (MVHR or HeffMVHR or AC) then sfp*1.22*volume, else 0
(kWh per year from SAP, assumes 0.5ACH energy = sfp*1000*V*8760/3600)
Note: AC assumes same fan power as std MVHR system plus cooling energy.

**ACEnergy** = if AC then 10*TFA, else 0
(10kWh/m2 elec for cooling per m2 - will update later with simulation values)

**Cool_vent_energy** = EXEnergy + MVEnergy + ACEnergy

**Cool_vent_energy_m2** = Cool_vent_energy / TFA
**VentCool_emm** = Emm_elec
**VentCool_CO2** = value for VentCool_emm and appropriate Grid intensity from the carbon table
**Cool_vent_carbon_m2** = Cool_vent_energy_m2*VentCool_CO2

### 2.1.5 Establish Occupancy and Occupant Hot Water Demand

The Occupancy and Occupant Hot Water demands are calculated using SAP2005 calculations. The opportunity is provided to vary the hot water demand using the ‘HWdemand’ context parameter which applies a scaling factor (HWdemF). The hot water demand given here is the requirement at the point of extraction i.e. at the tap or shower head, sections 2.1.8 and 2.1.9 deal with the system losses, solar hot water system contribution, heating system efficiencies and fuel required to deliver the required hot water.

**Hwdemand part 1: get variable values:**
**HWdemF:** based on HWdemand, HWdemF = 1 (std), 1.5 (profligate), 0.67 (frugal)

**Hwdemand part2: calculations:**
**occupancy (OCC):** OCC = 0.035*TFA-0.000038*TFA*TFA
**HWdem:** **HWdem** = ((61*OCC)+92)*0.85*8.76*HWdemF

### 2.1.6 Establish Heating Energy Demand

2.1.6a Heating demand from simulation models (Hdem)

The heating demand comes primarily from the array of simulation models underlying the HEM tool, these provide the annual kWh/m2 values for each discrete combination of fabric determinants. These values are read from the Hdem table and then used in the subsequent calculations. The simulation models for the Scottish Dwellings project are of two basic physical forms representing a single storey and a two storey dwelling. The constructions applied to these basic models are varied based on the fabric determinant values selected. The Scottish Dwellings project models are oriented with the main door and living area glazing facing south but solar gains are limited by a large obstruction representing a three storey building across the street from the dwelling being studied. This approach to orientation and shading gives a somewhat pessimistic view of the solar gains contribution to the heating load but this was deemed to be the most appropriate approach for this project where these parameters are unknown. For other projects it would be possible to add orientation of glazing and / or level of shading to the determinant parameters.

The models for the Scottish Dwellings project were simulated with average UK occupancy and gains patterns and UK climate to give heating demand values similar to those derived from the Governments SAP2005 calculations. The Scottish Dwellings project models have also been simulated for a number of other contexts (climates, occupancy patterns, heating set-points etc) but these results are not yet being made available in the public release version. The current public release version with the heating demands and calculations aligned to SAP2005 allow the EPC ratings to be similarly aligned with the official SAP EPC ratings. For more detail on the simulation models and simulation input parameters contact ESRU (paul.tuohy@strath.ac.uk).

The heating energy demand results from the simulation model are then read from the Hdem table. This Hdem value is then adjusted by factors which allow additional dwelling details to be in some way more closely represented.

A **‘ceiling height’** adjustment is made, the base model has a 2.5m ceiling height, where a 3.5m ceiling height is selected (to represent a traditional Victorian tenement flat say) then the heating demand is multiplied by a scaling factor based on the ratio of heat losses (fabric + ventilation) for the increased ceiling height v. the existing ceiling height. The heat loss calculations used are based on SAP2005 and include thermal bridging.

A similar adjustment could be made to represent different numbers of **‘external walls’** for flats or the presence of bay windows etc. but this has not been enabled for this project.

The effect of a **‘non-separated conservatory’** on the heating demand has been represented in a course way. Where a non-separated conservatory is selected then if the insulation was previously ‘good’ or ‘super’ then it is reduced to ‘standard’, where the dwelling initial insulation level was ‘medium’ or ‘standard’ then it is reduced to ‘poor’.

The possible reduction (in some cases increase!) in heating demand due to a mechanical ventilation heat recovery system **‘MVHR’** is also factored in to the heating demand. The heat recovery saving is represented by the ratio of the heat losses with MVHR (HLfabric + VLtotal)

v. the heat losses without MVHR (HLfabric + VLinf + VLmech) where VLtotal is based on the total natural ventilation rate (ACH) due to infiltration and occupant window opening etc., VLinf is based on the infiltration rate only (ACHINF) and VLmech is based on an 0.5ac/h mechanical ventilation rate and a heat recovery fraction of MVhreff.

| **Air changes** | **ACH** | **ACHINF** |
|---|---|---|
| **"Poor"** | 1.5 | 0.8 |
| **"Standard"** | 0.85 | 0.6 |
| **"Tight"** | 0.6 | 0.4 |
| **"Tight" + "MVHRsuper"** | 0.6 | 0.1 |

```
VLtotal = ACH   * 0.33 *volume;
VLinf   = ACHINF* 0.33 *volume;
HLplusVLtotal = HLfabric_total_adj + VLtotal;
VLmech  = 0.5 * (1- MVhreff) * 0.33 * volume;
VLsaving  = VLtotal - (VLinf + VLmech );
if (MVhreff == 0) MVHRsavingF = 1;
else MVHRsavingF   = (HLplusVLtotal - VLsaving)/HLplusVLtotal;
```

The variation in heating load due to the effect of variation in **'appliances'** and **'lighting'** gains are also factored in at this stage using a utilisation factor to represent the relationship between these gains and the annual heating demands. The standard simulation model assumes 50% of lighting is by CFL and that the appliance use is 'Standard'. Changes in these energy uses are assumed to impact the heating demand with a utilisation factor of 0.5.

### 2.1.6b Heating demand adjusted for detailed fabric upgrade inputs (Hdemm2)

The above section deals with establishing the heating demand for a given set of fabric '**Insulation'** determinant values set through the main screen such as "Poor (pre-1983)", "Standard (83-02)", "Medium (03-07)", "Good (post-07)" and "Super" and '**Air changes'** set to "Poor", "Standard" or "Tight". These heating demands are based on defined fabric packages (walls, glazing, roof, floor) based on the building regulations in the associated time-periods e.g. The "Medium (03-07)" Insulation setting represents wall u-value of 0.3, glazing u-value of 2, roof u-value of 0.16 and floor u-value of 0.25, while the "Super" setting represents wall, roof and floor u-values of 0.13 and glazing u-value of 0.8.

In this way the main tool allows the user to investigate packages of fabric upgrade measures where all building elements are upgraded together. It is possible however to investigate individual element upgrades using the '**more detailed input**' function. If more detailed input is selected then any one or any combination of the available upgrades of individual elements (e.g. glazing) can be applied to any base dwelling and the effect of this upgrade quantified e.g. the impact of adding super glazing with a u-value of 0.8 to a "Poor (pre-1983)" dwelling can be quantified etc.

As the array of thermal models is pre-simulated and the models differentiated by the combined packages of insulation measures the heating demand cannot be extracted directly as in the above section 2.1.6a but is calculated using interpolation between the models.

The interpolation process depends on calculating the fabric heat loss of the improved dwelling using the dwelling geometry and elemental u-values and comparing this to the fabric heat loss for the base building and each of the main insulation improvement 'packages' to find the two models between which the building performance lies and the fraction representing the extent of the improvement between these two models. The heating demand for each of these models is then established and the heating demand for the specific dwelling with the detailed improvements is calculated by interpolating between these points.

### 2.1.7 Establish Heating Energy Use and Carbon Emissions

The heating energy use calculations are based on the '**Heating system'** efficiencies (for primary and secondary heating systems) and adjustments made for control effectiveness. The default is for no secondary heating, where secondary heating is selected then it is assumed it supplies 10% of the space heating load. The situation is more complicated in the case of community CHP systems, the situation for community CHP is given in section 2.1.10 on Local Generation.

The **'Controls'** are configured such that where 'Advanced' controls are selected then the space heating efficiency adjust is 1, while where 'Standard' is selected then the controls adjust parameter is read from the Heating system parameter table and varies by system type.

The secondary heating efficiencies are read from the **'Secondary heating'** table.

The values for the efficiencies and control adjust parameters that are in the tables have been derived from a number of sources including the Scottish House Condition Survey [3], The BRE Domestic Energy Fact File [4], the SEDBUK database [5] etc..

| | |
|---|---|
| **Heating Part 1: get system variable values set:** | |
| **Heff** | Read heating system efficiency (Heff) from Hsys table for matching determinants.<br>If no match then default to the lowest efficiency option for fuel type.<br>If Heff entered directly Heff = entered value until detailed input updated or cleared |
| **Heff_ctl_adj** | Read default control adjustment factor (0 to1) from Hsys table<br>default updated to 1 if control determinant set to 'advanced' |
| **Heff_adj** | = Heff*Heff_ctl_adj (the eff of the heating system including controls adjustment). |
| **Htype_secondary** | default = "none"<br>default updated to new value if detailed input 'secondary heating type' is selected. |
| **Hfract_secondary** | = 0 if Htype_secondary = 'none' else 0.1 (if no detailed input then no secondary). |
| **Hfract_primary** | = 1 if 'none' else 0.9 |
| **Heff_secondary:** | read from Secondary_heat_type table |
| | |
| **Heating Part 2: calculations:** | |
| **Henergy_m2_primary:** | = [(Hfract_primary***Hdemm2**) / Heff_adj] |
| **Henergy_m2_secondary:** | = [(Hfract_secondary***Hdemm2**) / Heff_secondary] |
| **Henergy_primary** | = Henergy_m2_primary*TFA |
| **Henergy_secondary** | = Henergy_m2_secondary*TFA |
| **Henergy_m2:** | = Henergy_m2_primary + Henergy_m2_secondary |
| **Hfuel_emm** | = value for heating system fuel emissions type (Hfuel_emm) from Hsys table. |
| **Hfuel_CO2** | = value of Hfuel_CO2 (kgCO2/kWh) for Hfuel_emm and grid intensity - carbon table |
| **Hfuel_secondary_emm** | = value for sec htg sys fuel emm type (Hfuel_sec_emm) - secondary heating table |
| **Hfuel_secondary_CO2** | = value of Hfuel_CO2 (kgCO2/kWh) for the appropriate fuel_emm and grid intensity |
| **Hcarbon_m2_primary** | = Hfuel_CO2*Henergy_m2_primary |
| **Hcarbon_m2_secondary** | = Hfuel_secondary_CO2*Henergy_m2_secondary |
| **Hcarbon_m2:** | = Hcarbon_m2_primary+Hcarbon_m2_secondary |

### 2.1.8 Establish Hot Water System Losses and Solar Hot Water System contribution

This section builds on the occupancy and occupant hot water demands calculated in 2.1.5 and establishes the system losses and the total hot water heating demand. The contribution made by a solar hot water system is then calculated taking the usage profile for the dwelling into account. The remaining load not supplied by the solar system is then quantified and this is the basis for the calculations of fuel use and carbon emissions described in section 2.1.9. The hot water calculations follow the form of SAP2005 but simplifying assumptions are made in some cases.

First the system losses are quantified based on the system type, the losses considered are the distribution pipework losses (HW_Ldist) , the storage tank losses (HW_Lstore) and the primary (i.e. heating system to storage tank) losses (HW_Lprimary).

**(see section 2.1.5 for Hwdemand calculations part2)**

**Hwdemand part3: system loss calculations:**
**HW sys type** default = HW sys type determinant value, update default if entered in detailed input
**Cyl_ins_type** default = 'no detail', update default if alternative entered in detailed input
**HW_Ldist** = ((61*OCC)+92)*0.15*8.76*HWdemF
**HW_tankvol** = TFA*1.3333
**HW_Vf** = (120/HW_tankvol)1/3
**HW_Lf_store** = value from Hot water system table - depends on HW sys type and Cyl_ins_type
**HW_Lstore** = HW_Lf_store*HW_Vf*HW_tankvol
**HW_Lprimary** = value from Hot water Heating system table - depends on HW sys type

Then the contribution of the solar hot water system is calculated and adjusted based on the load for the dwelling. The area and contribution of the solar hot water systems assumes a typical system of either a flat panel or evacuated tube with a gross area of 4m2, south facing at 45degrees in typical Scottish conditions. A further report on the background to the renewable and low carbon technologies in HEM is in preparation and will be added as an appendix to this document.

The solar system calculations are given logically in the excel sheet below. The TFA and the Hot Water demand Factor are input parameters from the interface. The calculations are of a form given in both the SAP2005 and the CIBSE Solar Heating Design and Installation Guide (2007). The system parameter details used in the calculations are read from the SHW_param table and can be modified by the user. The parameters in the SHW_param table are:

| | |
|---|---|
| Type | Collector type – selectable through renewable system input box. |
| Ap | The gross roof area required for the panel (default = 4m2). |
| Apratio | The ratio of absorber area to gross roof area. |
| Eff0 | The zero loss efficiency. (depends on collector type) |
| a1 | Linear heat loss co-efficient (depends on collector type) |
| S | Solar radiation available (default 885kWh p.a. – typical Scotland) |
| Zpanel | The shading factor (default 1 = no shading of panel) |
| Vseff | Effective storage volume (default 100 litres) |

| system | Ap | Apratio | Eff0 | a1 | S | Zpanel | Vseff |
|---|---|---|---|---|---|---|---|
| flat_plate | 4 | 1 | 1 | 3 | 885 | 1 | 100 |
| evac_tube | 4 | 1 | 1 | 2 | 885 | 1 | 100 |

The collector performance parameter values currently in the data table are those given in the 'best' columns of the example calculation sheet below as it is assumed that any future upgrade would follow the current best practice. These defaults give the following values for the hot water demand satisfied by solar in kWh per annum.

| | TFA, Vseff | FlatPlate | EvacTube |
|---|---|---|---|
| FLAT | 71/100 | 1070 | 1129 |
| HOUSE | 94/100 | 1160 | 1218 |

It should be noted that where there is a significantly larger demand for hot water due to either larger dwellings than the default or a higher hot water usage profile then a larger panel (say 6m) would be of benefit as well as an increased solar hot water storage volume.

Detailed design guidance is given in the CIBSE Solar Heating document mentioned above.

|  |  | FlatPlate | EvacTube | FlatPlate | EvacTube |  |  |
|---|---|---|---|---|---|---|---|
|  |  | typ | typ | best | best |  |  |
|  | TFA | 71 | 71 | 71 | 71 | m2 | total floor area (TFA) |
|  | occ | 2.3 | 2.3 | 2.3 | 2.3 | persons | occupancy (SAP calc) |
| H1a | Ap | 4 | 4 | 4 | 4 | m2 | Gross area of panel |
|  | Apratio | 0.9 | 0.72 | 0.9 | 0.8 |  | Aperture fraction, CIBSE typical = SAP H1 default = 0.9, 0.72 fp/et |
| H1 | Aap | 3.6 | 2.88 | 3.6 | 3.2 | m2 | Aperture area table H1, 0.9 for flat plate (glazed), 0.72 for evac tube |
| H2 | Eff0 | 0.79 | 0.72 | 0.83 | 0.85 | num | Zero loss efficiency factor table H1, 0.75 for flat plate, 0.6 for evac tube, CIBSE typ 0.79, 0.72 , best 0.83,0.85 (efficiency measured at zero heat loss i.e. where Tcollectorav = Tamb note the Tcollector for heating is higher and |
| H3 | a1 | 4.5 | 2 | 3 | 1.2 | W/m2K | Linear heat loss co-eff from H1, 6 for flat plate, 3 for evac tube = CIBSE poor, CIBSE average = 4.5, 2, best 3,1.2 for fp/et resp. |
| H4 | a1/Eff0 | 5.696203 | 2.777778 | 3.614458 | 1.411765 |  | Collector ratio a1/Eff0 |
| H5 | S | 885 | 885 | 885 | 885 | kWh/m2 pa | Solar rad (S 45deg) 1023 from SAP table H2, 885 for Scotland from CIBSE |
| H6 | Zpanel | 1 | 1 | 1 | 1 | num | overshading factor (1 = none or very little) from table H3 |
| H7=H1*H2*H5*H6 | Esa | 2516.94 | 1835.136 | 2644.38 | 2407.2 | kWh pa | Solar energy available. |
| HwDemF |  | 1 | 1 | 1 | 1 |  | Demand factor, 0.67, 1, 1.5 |
| [39]+[40] | Load | 2031.444 | 2031.444 | 2031.444 | 2031.444 | kWh pa | energy content of occupant used water plus distribution losses = 2473 for 100m2 house, 2032 for 71m2 flat, calc from TFA, occ |
| H8 | ESa/Load | 1.238991 | 0.903365 | 1.301725 | 1.18497 | ratio |  |
| H9 | Uf | 0.553854 | 0.669442 | 0.536158 | 0.569971 | num | utilisation factor = if H8>0, 1-EXP(-1/H8) else 0 |
| H10 | CPf | 0.695797 | 0.780185 | 0.754947 | 0.823196 | num | collector performance factor, calculate based on H4 >0.8 High, 0.7 to 0.8 average, below 0.7 poor. (CIBSE) |
| H11 | Vseff | 100 | 100 | 100 | 100 | litres | effective solar volume (user enter) for house and flat use 100 and 80. |
| H14 | Vdaily | 95.33605 | 95.33605 | 95.33605 | 95.33605 | litres | daily hot water requirement (depends on HwDemF) |
|  | Vseff/Vd | 1.048921 | 1.048921 | 1.048921 | 1.048921 |  | > 0.8 'good' CIBSE |
|  | SSVfcalc | 1.009552 | 1.009552 | 1.009552 | 1.009552 |  | solar storage volume factor calc |
| H16 | SSVf | 1 | 1 | 1 | 1 | num | solar storage volume factor |
| **H17** | **Qs** | **970** | **958** | **1070** | **1129** | kWh pa | **solar input to meet DHW demand** |
|  | Solar fraction | 0.48 | 0.47 | 0.53 | 0.56 |  | 40% to 50% normal design parameters - typical between 35% and 60% CIBSE |
|  |  | **184** | **182** | **203** | **215** | kgCO2 pa |  |

### 2.1.9 Establish Hot Water Energy Use and Carbon Emissions

The hot water resultant demand is then met through a hot water heating system including a heat source with appropriate efficiency and controls represented by a controls factor both the efficiency used and the controls factor are given in the HWsys_parameters table. The carbon emissions are then calculated based on the appropriate emissions factors for the fuel type and grid intensity.

**Hot water supply Part1: get input variables:**
**HWeff** = value from Hot water Heating system table - depends on HW heating type
(HW heating type set by determinant or detailed inputs)
**HWsys_ctl_adj** = default value from Hwsys_type table
default updated from Hwsys_type table if HW heating type updated
or from Ctrl type table if detailed input used to specify Hwsys_control_type

**Hot water supply part2: Calculation:**
**HW_output** = **HWdem** + HW_Ldist + HW_Lstore + HW_Lprimary – **SHW_input**
**HWeff_adj** = HWeff*HWsys_ctl_adj
**HW_energy** = HW_output * 100 / Hweff_adj
**HW_energy_m2** = HW_energy / TFA
**HWfuel_emm** = value from Hot water Heating system table - depends on HW heating type
**HWfuel_CO2** = value for HWfuel_emm type and appropriate Grid intensity from the carbon table.
**HWcarbon_m2** = HW_energy_m2 * HWfuel_CO2

### 2.1.10 Establish Energy and Carbon Emissions Impact from Local Generation

### 2.1.10a Photovoltaic systems.

The Scottish Dwellings project allows the option of an 8m2 PV system and has 3 options for PV type with associated values for kWh/m2 p.a. of AC electrical generation. The generation assumed for the Scottish context is set at 650 kWh per kWp installed based on the BERR monitoring studies [ ] and the CIBSE solar availability maps [ ]. The table below gives the details for each of the system selections as currently set in the **PV_Parameters** CSV table, the table values can be adjusted by the user.

| PV System type | Area (m2) | AC kWh/m2 p.a. |
|---|---|---|
| Mono-chrystalline | 8 | 82 |
| Poly-chrystalline | 8 | 64 |
| Amorphous | 8 | 28 |

### 2.1.10b Domestic wind turbine systems.

The Scottish Dwellings project allows the option of a 2m diameter Domestic wind turbine or a 3m diameter wind turbine. The default condition is that the turbine is sited in a location with a consistent wind speed average of 4.4m/s. The tool allows the local wind speed to be adjusted by selecting ‘more detailed input’. The local wind speed here must represent the actual wind speed at the turbine and take into account the mast height above the ridge of the roof and the local sheltering as well as the local climate parameters. The tool is configured such that wind speeds less than 4.4m/s do not give any wind turbine output as at these low wind speeds the cut-in speed of the turbine has an increased effect and the turbine output becomes highly uncertain. The background calculations in the tool have been aligned with the latest version of SAP2005 Appendix M which is itself based on monitoring studies and the GreenSpec, BWEA and Danish Wind Energy Data. The table below shows the calculation outline. The parameters are user configurable through the **WT_parameters** CSV table.

Annual output = 8760*CPoa*A*PA*G*IE (SAP2005apM)
[ ref Annual output = 8760*CPoa*A*PA*G (GreenSpec)]

| Parameter | Description | Scenario1 | Scenario2 |
|---|---|---|---|
| Ann hrs | Inc. leap year. | 8766 | 8766 |
| Cpoa | Betz law 0.63 max, typ 0.26, upper 0.35? | 0.26 | 0.26 |
| d | Diameter | 2 | 3 |
| A | Swept area = pi*d2/4 | 3.1 | 7.1 |
| S-ave | Ave local wind speed, 5m/s*corrF for SAP. 4.4m/s in SAP only met for rural with mast height > 2m above ridge of roof. | 4.4 | 4.4 |
| PA | Power available = 0.6125*S^3 | 52.2 | 52.2 |
| G | Generator eff | 0.9 | 0.9 |
| Ave Watts | | 38 | 86 |
| S-corr | Wind speed variation factor | 1.9 | 1.9 |
| IE | Invertor efficiency | 0.85 | 0.85 |
| Cpoa*G*IE | Efficiency factor = 0.24 for SAP2005 | 0.20 | 0.20 |
| **WT kWh pa** | | **543** | **1222** |

### 2.1.10c CHP Systems.

The Scottish Dwellings project allows the option both single dwelling micro-CHP (uCHP) systems or larger scale community CHP systems of a range of different fuel types. The heating and electrical generation system efficiencies are stored in the Hsys_parameter CSV file and are modifiable by the user.

The micro-CHP systems are assumed to provide all of the primary heating system demand and the default parameters have been set based on a Stirling engine type system.

The community CHP systems are assumed to supply 70% of the primary heating load plus hot water load with the remainder being serviced using high efficiency boilers of 85% efficiency.

The hot water system is set to ‘main tank’ for both uCHP and community CHP as the hot water load is assumed to be serviced by the main system in this case.

For both the uCHP and community CHP the efficiencies have been set at current best practice levels based on the assumption that upgrades where applied will follow best practice.

### 2.1.11 Establish Totals, Costs, CER, EI and Ratings

The output parameters are described in the outputs section in Part 1 of the manual. The calculations are based on the values in the CSV tables which are user modifiable.

The running costs (**'cost_table'**) and standing charges (**'cost table'**), the carbon emission factors (**'carbon table'**) are all set at the standard SAP2005 values for the 'Standard' context but alternate values are also included in these tables for use when non- standard contexts are selected such as '2x tarriff' or 'High CO2 grid' etc.

The upgrade costs are based on the changes in the elemental U-values and the selections for wall, floor and roof type and these costs are detailed in the relevant **'upgrade'** tables.

The CER, EI and Ratings calculations follow the UK Governments standards set in SAP2005 however the user must be clear that this tool is not an accredited EPC tool and cannot currently be used to issue certificates. (The current standards require precise physical measurements rather than the inferred building form used in HEM).

### 3. Further HEM Functionality (ESP-r link, Multi-dwelling, File to File, Non-domestic)

HEM has further functionality either developed or in development not yet part of the public release version. This includes the ability to run in Multi-dwelling mode where a file is created which profiles a stock and then the file is run for progressive upgrade scenarios. Another feature is the ability to select a model and make modifications and run the model simulation in ESP-r through the HEM interface. A non domestic version is also in development.

If you would like further information on these functions or other topics then please contact ESRU (paul.tuohy@strath.ac.uk).

# Appendix C

Example FMEA form used for full FMEA analysis.

lean six sigma academy

## Failure Modes Effects Analysis

Process or Product Name:

Process Owner:

Prepared by:

FMEA Date (Orig):

Page: of

Rev.

| Key Process Step or Input | Potential Failure Mode | Potential Failure Effects | SEV | Potential Causes | OCC | Current Controls | DET | RPN | Actions Recommended | Resp. | Actions Taken | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| What is the Process Step or Input? | In what ways can the Process Step or Input fail? | What is the impact on the Key Output Variables once it fails (customer or internal requirements)? | How **Severe** is the effect to the customer? | What causes the Key Input to go wrong? | How **often** does cause or FM **occur?** | What are the existing **controls** and procedures that prevent either the Cause or the Failure Mode? | How well can you **detect** the Cause or the Failure Mode? | | What are the actions for reducing the occurrence of the cause, or improving detection? | Who is Responsible for the recommended action? | Note the actions taken. Include dates of completion. | | | | |
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