University of Strathclyde

Department of Mechanical & Aerospace Engineering

Inverse Dynamics based Energy Assessment and Simulation

Gavin Bruce Murphy B.Sc., M.A., M.Sc.

A thesis presented in fulfilment of the requirements

for the degree of Doctor of Philosophy

2012

COPYRIGHT DECLARATION

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: _____ Date: _____

Abstract

The Standard Assessment Procedure (SAP) is the UK Government's approved methodology for assessing the energy ratings of dwellings. SAP is a calculation method based upon empirical relations from measured data. A yearly calculation was used in SAP until the release of SAP 2009, which employs monthly calculations. SAP has moved from using a large time step with a coarse time resolution to a smaller time step with a medium time resolution.

Rising CO_2 emissions from dwellings advocate that properties designed in a sustainable method will become commonplace in the future. In tandem with enhanced sustainability, dwellings will increasingly be designed with implementations of renewable energy generation. The modelling of renewables in SAP has been highlighted as an area where SAP could benefit from additional research. Modelling future complex dwellings and systems will require an advanced calculation method which is capable of more detailed modelling and simulation; with a smaller time step which is measured in minutes and not months, producing results allowing more detailed analysis of energy performance. Dynamic Simulation Methods (DSMs) already exist which can operate at a very small time step. However with DSMs it is very difficult to make a comparison with SAP as the temperatures used in SAP are not well understood. To calculate energy consumption the SAP methodology guarantees that a standard occupancy temperature profile is met perfectly. A dynamic method which also guarantees the SAP standard occupancy temperature profile is required. This is difficult in complex DSMs as their control algorithms are often inadequate to optimise the heating system to guarantee that a temperature is met perfectly.

The contribution to knowledge detailed in this thesis is the development of a novel SAP compliant advanced dynamic calculation method (IDEAS)

which guarantees that the SAP standard occupancy temperature profile is perfectly tracked and is also calibrated with SAP. The Inverse Dynamics based Energy Assessment and Simulation (IDEAS) method employs the perfect inverse control law RIDE to guarantee that the SAP standard occupancy temperature profile is met. IDEAS produces SAP compliant results and allows confident (i.e. calibrated in SAP) predictions to be made regarding the impact of novel heating and renewable energy systems. Researched in depth are the temperatures used in SAP, leading to analysis of the implications of tracking air temperature and various comfort temperatures. A focused evaluation of the treatment of renewables in SAP and DSMs is also presented, leading to suggestions which were implemented into the SAP framework. The role of real life monitoring in the energy assessment process is highlighted with monitored studies conducted. Also in this thesis case studies applying IDEAS to buildings with renewable heating systems are described.

The IDEAS method employs SAP as an exemplar steady state calculation to highlight the successful use and calibration of a new advanced Inverse Dynamics based symbolic method. The philosophy, research and equations derived in IDEAS are presented in this thesis demonstrating their use in Microsoft Excel and Matlab / Simulink environments. The IDEAS methodology is transparent and portable. IDEAS can be applied to other methodologies, such as those employed by PHPP and SBEM (by carrying out a calibration process), and also to different simulation environments such as ESP-r and ESL (by adopting the IDEAS equations in those methods). The contribution to knowledge of IDEAS is demonstrated in this thesis by the development of the method and the use of SAP as a comparator. The IDEAS method has many uses outwith SAP which are highlighted in the cases studies and future work sections of this body of work.

Acknowledgements

Table of Contents

Figures and Tables

Figures

Tables

Definitions, Acronyms, and Abbreviations

NAME	DESCRIPTION
BRE	Building Research Establishment
BREDEM	Building Research Establishment Domestic Energy Model
CO_2	Carbon Dioxide
COP	UNFCCC - Conference of the Parties
CSH	Code for Sustainable Homes
DEA	Domestic Energy Assessor
DSMs	Dynamic Simulation Methods
EPBD	European Performance of Buildings Directive
EPC	Energy Performance Certificate
ESRU	Energy Systems Research Unit
EST	Energy Saving Trust
EU	European Union
IDEAS	Inverse Dynamics based Energy Assessment and Simulation
ID	Inverse Dynamics
IEA	International Energy Agency
LCBP	Low Carbon Buildings Program
LZCT	Low and Zero Carbon Technologies
MIT	Mean Internal Temperature

MMC	Modern Methods of Construction
OPEC	Organization of the Petroleum Exporting Countries
PV	Photovoltaics
RET	Renewable Energy Technologies
RICS	The Royal Institution of Chartered Surveyors
RIDE	Robust Inverse Dynamic Estimation
RdSAP	Reduced Data Standard Assessment Procedure
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
SCHRI	Scottish Community and Households Renewable Householder Initiative
SDHW	Solar Domestic Hot Water
STC	Standard Test Case
TESS	Thermal Energy Systems Specialists
UNFCCC	UN Framework Convention on Climate Change
UOS	University of Strathclyde
UK	United Kingdom of Great Britain and Northern Ireland
U-Value	A standard used to determine how well the fabric used in the built environment will conduct heat

Nomenclature

A_F = Area (floor) (m²)

A_{FT} = Area (furniture & internal mass) (m²)

A_R = Area (roof) (m²)

A_S = Area (structure) (m²)

A_W = Area (windows) (m²)

C_A = Specific Heat Capacity (air) (J/kg.K)

C_{FT} = Specific Heat Capacity (furniture and internal mass)

(J/kg.K)

C_S = Specific Heat Capacity (structure) (J/kg.K)

hi = Convective Heat Transfer Coefficient Internal (W/m²K)

he = Convective Heat Transfer Coefficient External (W/m²K)

$kWall$ = Thermal Conductivity of Wall (W/m.K)

M_A = Mass (air) (Kg)

M_{FT} = Mass (furniture and internal mass) (Kg)

M_S = Mass (structure, used in 3rd order model) (Kg)

M_{SI} = Mass (internal structure, used in 4th order model) (Kg)

M_{SE} = Mass (external structure, used in 4th order model) (Kg)

$\dot{M}_V$ = Air Mass Flow Rate (Kg/s)

P_Z = Density (material Z) (kg/m^3)

$\dot{Q}_R$ = Heat Transfer through Roof (W)

$\dot{Q}_W$ = Heat Transfer through Windows (W)

$\dot{Q}_F$ = Heat Transfer through Floor (W)

$\dot{Q}_V$ = Heat Transfer through Ventilation (W)

$\dot{Q}_{FREE}$ = Heat Transfer from Free Heats (W)

$\dot{Q}_H$ = Heat Transfer from Heating (W)

U_F = U-Value (floor) (W/m^{2}K)

U_{FT} = U-Value (furniture & internal mass) (W/m^{2}K)

U_R = U-Value (roof) (W/m^{2}K)

U_S = U-Value (structure, used in 3rd order model) (W/m^{2}K)

U_{SAP} = U-Value (structure from SAP, used in 4th order model)

(W/m^{2}K)

U_W = U-Value (windows) (W/m^{2}K)

T = Internal Temperature (K)

T_o = Outside Temperature (K)

T_S =   Structure Temperature, 3rd order model (K)

T_{SI} =   Internal Structure Temperature, 4th order model (K)

T_{SE} =   External Temperature, 4th order model (K)

t =   time (seconds)

$tWall$ =   Thickness of Wall (m)

V_A =   Volume (air) (m³)

CHAPTER ONE

1   ASSESSING THE ENERGY PERFORMANCE OF DWELLINGS

1.1   Introduction

The contribution of the built environment to the production of carbon emissions and the use of energy is vast. It has been stated that the built environment accounts for as much as 50% of the energy requirement of the United Kingdom (Clarke et al., 2008). The construction sector similarly accounts for 40% of resource consumption in the European Union (European Construction Technology Platform, 2005). The domestic sector in the United Kingdom is responsible for 27% of all UK carbon emissions (Yao and Steemers, 2005).

The drive to reduce energy used by dwellings, and to achieve a zero carbon home, highlights that the method of assessing the energy performance of dwellings is of the utmost importance. In the UK the methodology of energy performance assessment is BRE's Standard Assessment Procedure (SAP). Reduced SAP (RdSAP) is utilised for the modelling of existing domestic properties. To reduce the CO_2 emissions and increase the energy efficiency of dwellings a series of rapidly emerging technologies will be employed. Renewable energy technologies and Modern Methods of Construction (MMC) will have an increasingly large role to play. The methodology used to assess homes constructed, and refurbished, in the future must be up to the task.

1.2   Progression of Design Standards in Dwellings (1919 - 2011)

The built environment has changed dramatically over the past 100 years, especially since the 1970s. A combination of enhanced building regulations, retrofitting and improved technology and materials has forever altered the way in which dwellings are now built. Determining the age of a dwelling is a key factor in assessing which materials would most likely have been used in a dwelling's construction and hence what levels of insulation and CO_2 emissions would be commonplace of that time. SAP determines that existing dwellings

are placed into 1 of 11 age bands, through RdSAP table S1.   Different age bandings are given for Scotland, England & Wales and Northern Ireland.   In Scotland, the earliest age band is Pre 1919; the most recent is 2008 onwards.

Table 1.1 : SAP Table S1 – Age Bands

Age Band	Years of Construction		
	Scotland	England and Wales	Northern Ireland
A	before 1919	before 1900	before 1919
B	1919-1929	1900-1929	1919-1929
C	1930-1949	1930-1949	1930-1949
D	1950-1964	1950-1966	1950-1973
E	1965-1975	1967-1975	1974-1977
F	1976-1983	1976-1982	1978-1985
G	1984-1991	1983-1990	1986-1991
H	1992-1998	1991-1995	1992-1999
I	1999-2002	1996-2002	2000-2006
J	2003-2007	2003-2006	(not applicable)
K	2008 onwards	2007 onwards	2007 onwards

Dwellings from the Pre 1919 era, such as those in figure 1.1, were built in great numbers in heavily industrialised areas of Scotland such as Dundee and Glasgow.   Referred to as tenement blocks, the properties were characterised by solid stone construction with small-paned sash windows.   When first built, properties such as these would each have been houses of multiple-occupancy and relied almost exclusively upon coal as a heat source.   The original chimneys can still be seen (in figure 1.1), as can the retrofitting of gas into each property and double glazing into some.

Figure 1.1- Example of Pre-1900 property. DD4 6QR, Dundee

Source: © G.B.MURPHY www.flickr.com/murphygb

The 1919-1929 SAP age band describes properties that in many cases are very similar to those in the previous age band of Pre-1919. The major difference is that properties built between the years of 1919 – 1929 should have benefited from a damp proof course to prevent dampness rising into the structure.

In the 1930 - 1949 age band a marked difference in dwelling styles and construction methods is apparent. Many semi-detached properties were built in this era and brick became the material of choice for construction. Additionally, brick cavity walls started to become more commonplace and provided these dwellings with improved insulation.

The 1950–1964 age band saw the continuing trend for semi detached properties but city councils also decided to construct high rise dwellings. 1956 also saw the passing of the Clean Air Act which coincided with the move from solid based fuels such as coal to fuels which did not require a traditional chimney, such as gas. The Clean Air Act (1956) was passed primarily due to the London Smog of 1952 which directly contributed to over 4,000 deaths (Giussani,

1994). The Clean Air Act (1956) promoted the use of smokeless fuels in urban areas and banned the production of black smoke from both industry and dwellings. It was an act to "make provision for abating the pollution of the air" (Office of Public Sector Information, 1956), which was a significant factor in the improvement of air quality and in the eventual replacement of coal as the main heating fuel used in the UK.

Figure 1.2 - Example of high rise flats. Red Road Flats, Glasgow

Source: © G.B.MURPHY www.flickr.com/murphygb

The 1965 – 1975 age band highlights that semi-detached and terraced council properties became more commonplace. During the 1960's there was a drive for high rise buildings to help alleviate overcrowding in areas such as Glasgow. However, towards the end of this period satisfaction in high-rise dwellings had started to wane. The tallest high rise flats created in Scotland can still be seen in Glasgow, The Red Road Flats; figure 1.2. At the time of their construction (1964-1969), they were the largest flats in Europe. At time of build,

these were sought after dwellings as the population of Glasgow seized on the chance to escape the squalor of the city. Due to poor planning and lack of amenities, they were soon deemed to be crime ridden failures. They are all due for removal before 2015. During this time brick cavity walls were still the material of choice and a small amount of insulation (Insulation of 12mm at joists level) in roof spaces became mandatory.

1976 – 1983 saw a change in the construction of dwellings which was driven by security of energy supply and rising energy costs to a certain extent. In this period, the price of oil was raised 400% due, primarily, to the actions of OPEC (Organization of the Petroleum Exporting Countries) and the Iran Iraq war (1980-1988). A simple to use, but robust and accurate, model to predict the energy use of dwellings in the UK was required. The model which was to become known as BREDEM 1, the precursor to SAP, was created at this time (Shorrock and Anderson, 1995). Concrete block cavity walls became the norm over brick. Following on from this the next SAP age band (1984 - 1991) continued to make cost effectiveness a focal point.

The commencement of the 1992-1998 age band coincides with the development of the Standard Assessment Procedure (SAP) by BRE, based upon BREDEM for the UK government. In 1992, the Earth Summit was held in Rio de Janeiro with Sustainable Development becoming a major international focus. Developments such as this encouraged the drivers for change for the built environment in this era. Cost effectiveness and limitation of CO_2 emissions became the priorities. In 1995, the SAP calculation was made compulsory in buildings regulations in the UK.

The 1992-1998 age band had further impetus added to it by the ratification of the Kyoto Treaty in 1997 by the UK government. The UK government agreed to reduce overall greenhouse gas emissions by 12.5% from

1990 levels by 2008-2012. This focus was continued throughout 1999-2002 where limitation of CO_2 emissions and sustainability of buildings became a refocused priority. Further methods to assist the conservation of heat and energy in a dwelling were introduced during this period, such as the requirement for insulation of ground floors.

In the 2003-2007 age band the best practices of the prior age bands were enhanced by further increasing the insulation levels of floors, walls and roofs. The current and final RdSAP age band is 2008 onwards in which there was a further increase in the insulation levels of its predecessor. Figure 1.3 shows a typical new build property at time of writing.

Figure 1.3 Example of new dwellings, sitting in the shadow of past housing mishaps.

Hilltown, Dundee. Source: © G.B.MURPHY www.flickr.com/murphygb

Technology in the built environment has therefore steadily improved whilst also improving the building materials, methods of construction and levels of insulation utilised as standard. Major developments and improvements have dramatically changed the standard dwelling constructed

today in comparison with a pre-1919 constructed dwelling. Table 1.2 details a comparison of the main differences between properties constructed in these two different eras. The improvement (especially on the methods and materials employed and standard insulation levels) is staggering in many respects. Building Regulations will continue to adapt to improve the housing stock of the UK.

Table 1.2 - Comparison in standard dwellings between Pre-1900 dwellings and dwellings commonplace today

Typical Pre-1919 Dwelling	Typical 2008 Onwards Dwelling
Detached houses but more terraced houses and flats in mid to late Victorian period	Detached or linked predominate with increase in private flats
Suspended Timber Floor Construction	Solid Concrete Floor Construction Insulated (100mm)
Solid load bearing walls (mostly stone 600mm)	Brick: Concrete Block insulated cavity walls (300mm)
Un-Insulated pitched roof	Insulated pitched roof (250mm)
Coal Fire Heating	Gas Heating
SAP rating of 20	SAP rating of 80

Concepts employed in the built environment today are starting to rely heavily on MMC, which employs many new building techniques. An example of MMC includes the production of large sections of a new dwelling off site, which is then simply assembled where and when required. Future dwellings will be designed to be carbon neutral and to use integrated renewables.

As highlighted previously, in 1992 the United Nations held its first conference on environment and development in Rio de Janeiro. This conference is commonly referred to as the Earth Summit. The major output of this conference was the installation of the United Nations Framework Convention

on Climate Change (UNFCCC). The UNFCCC set non mandatory targets with regards to reductions of greenhouse gas emissions and was signed by 154 nations. The UNFCCC set a number of 'Conference of the Parties'(COP) follow up meetings, with the first being the COP-1 Berlin mandate with COP meetings occurring regularly since. However, the most well-known UNFCCC conference is COP-3, the Kyoto Protocol on Climate Change. The Kyoto Protocol is commonly referred to as 'The Kyoto Treaty' and is now more famous than the UNFCCC itself, the first commitments under it are due to expire in 2012. The Kyoto Protocol was ratified by most industrialised nations whom agreed to the legally binding reduction of Greenhouse Gas emissions. European Union countries agreed to reduce Greenhouse Gas emissions by 8% of 1990 levels. The USA and Australia did not commit to the targets of the Kyoto Treaty.

Realising the importance of the built environment to the reduction of Greenhouse Gases, the EU Energy Performance of Buildings Directive (EPBD) was published in 2002. The EPBD sets protocols for the monitoring of the efficiencies of new dwellings and other buildings and is a legal requirement for all EU nations which was implemented from January 2009.

In 2003 the UK Energy White Paper was released, which envisaged a UK built environment energy system in 2020 as follows:

"New homes will be designed to need very little energy and will perhaps even achieve zero carbon emissions. The existing building stock will increasingly adopt energy efficiency measures. Many buildings will have the capacity at least to reduce their demand on the grid, for example by using solar heating systems to provide some of their water heating needs, if not to generate electricity to sell back into the local network." (DTI, 2003)

The UNFCCC with the Kyoto and Copenhagen COP Amendments, the EU Performance of Buildings Directive and the various UK Energy White

Papers point in one direction – that of the advancement of construction methods and the integration of renewable energy and energy efficient technologies in the dwellings. Therefore SAP must be able to adapt to rapidly assess the modelling of emerging technologies accurately.

The United Kingdom has some of the oldest housing stock in the western world (DTI, 2003) due to the high number of properties still in existence from 100 or more years ago. As has been highlighted, properties of this period were built with no insulation and comparatively (by today's energy efficient standards) poor materials. The existence of a vast number of older dwellings suggests that a great focus should be placed on the fabric improvement of older properties before any notion of retrofitting of renewables is considered.

1.3   Importance of Renewables in Dwellings

Dwellings are one of the largest areas where renewable energy will play an ever-increasing role in the near future. Each dwelling can contribute extensively in terms of both energy consumption and carbon emissions.

The focus of this body of research is the assessment of the energy performance of dwellings utilising BRE's Standard Assessment Procedure (SAP). A series of propositions are presented stating where SAP could be updated. Areas which can improve the energy performance of dwellings such as the use of renewable technologies will be researched to assess the benefit which SAP provides for these new technologies.

The use of renewables in the built environment is an area which has drawn significant attention in the UK due to schemes such as the move towards zero carbon new build dwellings by 2016 in some areas of the UK. In April 2007, the Code for Sustainable Homes (CSH) (Gaze, 2009) replaced EcoHomes for the assessment of new build domestic properties in England. The CSH is the mechanism for companies to deliver zero carbon homes in all areas of the

UK with the exception of Scotland. BRE manages the CSH and is licensed to provide CSH assessor training and accreditation services. CSH is based on EcoHomes which provides a rating system used in converted, new and existing dwellings. The CSH has been adopted by Wales, England and Northern Ireland.

Table 1. 3 - Timetable for implementation of the CSH

Mandatory CSH LEVEL	Date of Introduction (Private Sector)
Assessment Mandatory	2008
Level 3	2010
Level 4	2013
Level 6	2016

Table 1.3 details the timetable for the implementation of the CSH for all new dwellings in England. Scotland is following the Sullivan Recommendations (The Scottish Government, 2007). The Sullivan Report made 56 recommendations to the Scottish Government such as:

- "staged increases in energy standards in 2010 and 2013 to substantially reduce carbon emissions from new buildings;

- the aim of net zero carbon emissions for space heating, hot water, lighting and ventilation within the next 10 years, if practical;

- the ambition of total-life zero carbon buildings by 2030;

- Consideration of zero fees for building warrant applications where new buildings are to be significantly above the current energy standards." (The Scottish Government, 2007)

In England, assessment for properties is mandatory with a staged

increase of CSH level requirements until 2016 when all new dwellings in England will have to meet CSH level 6. CSH level 6 states that all new dwellings will be carbon neutral and will therefore require the use of renewable energy and energy efficient technologies to replace all energy used from the national grid.

The phenomenon of integrating renewables into the built environment is not an isolated UK event. An example of a major oil producing nation moving towards renewables in the built environment is highlighted by the Masdar initiative, owned by the Government of the Emirate of Abu Dhabi. Masdar will be the world's first zero carbon and zero waste city, reliant upon renewable energy from the outset: The Masdar Initiative City will be entirely carbon neutral and act as a hub for sustainable and new energy technologies. (Masdar Initiative, 2011)

The SAP energy performance of dwellings methodology must be able to accurately record the benefit given to dwellings by the incorporation of renewables. A focus of this thesis is a comparison of SAP and Dynamic Simulation Methods (DSMs) to measure the performance of solar renewables calculated by both methods. The differences between SAP and DSM calculated results for solar renewables can then be assessed; this will lead to suggestions where the treatment of renewables in SAP could be strengthened.

1.4 The Building Research Establishment

BRE was initially founded in 1921 as part of the British Civil Service and remained part of UK Government until privatisation in 1997. Today BRE employs in the region of 600 employees throughout the UK and remains the pre-eminent centre for research in the built environment of the United Kingdom. BRE created, maintains and updates SAP and RdSAP. BRE is part of the BRE Group and are owned by BRE Trust, a registered charity. The

University of Strathclyde is, amongst others, a member of the BRE Trust.

1.5   Introduction to Energy Ratings of Dwellings Methods

1.5.1   SAP (Standard Assessment Procedure)

SAP was initially created in 1993 with the most recent available version being SAP 2009 (BRE, 2011). SAP is a means of assessing a building's energy efficiency and carbon emissions. For domestic new builds and conversions full SAP is also used for assessment whilst current dwellings can use RdSAP or SAP. SAP is used to demonstrate compliance under the Section 6 (Scotland), Part L (England and Wales) and Part F (Northern Ireland) building regulations. SAP is also the UK Government's approved National Calculation Methodology (NCM) for the assessment of dwellings under the European Directive on the Energy Performance of Buildings (EPBD). Whenever a UK dwelling is constructed, sold or rented, the SAP methodology must be employed to calculate ratings for Energy Efficiency and Environmental Impact. SAP ratings are measured on a scale of 1-100; the higher the number the lower running costs of that dwelling. SAP is based on BREDEM (Building Research Establishment Domestic Energy Model). BREDEM 12 and BREDEM 8 have been described in depth (Anderson et al., 2001a, Anderson et al., 2001b).

SAP ratings are based upon a notional centre of the UK – approximately Sheffield. This is taken as a representative location for the UK as a whole. Mean temperatures and levels of solar irradiance are derived from this. Figure 1.4 highlights the annual solar irradiation across the British Isles. Significant demarcation between the solar irradiation experienced throughout the UK can be seen from Figure 1.4
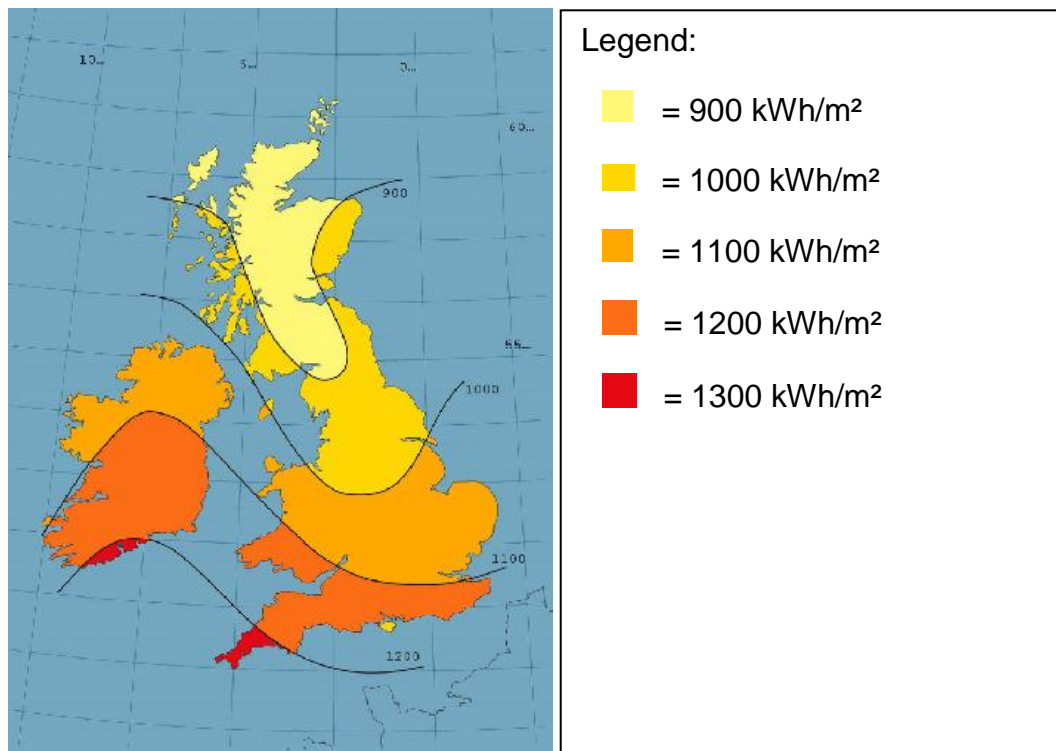
Figure 1. 4 - Annual Solar Irradiation (kWh/m²) in the UK; 'shows the total average solar radiation on one square meter surface, inclined at 30 degrees to the horizontal'.

Adapted from source: Solar Trade Association www.solar-trade.org.uk

SAP derives solar irradiation figures from the Sheffield weather location and applies this throughout the UK. The SAP methodology therefore provides a rating for properties based upon the Sheffield, England climate location regardless of where they are physically situated in the UK. This fact is not made clear in the SAP documentation.

A detailed study comparing the affect of differing UK weather profiles will be conducted to assess the SAP system of benchmarking all UK dwellings against one weather location.

1.5.2 RdSAP (Reduced Data Standard Assessment Procedure)

RdSAP is required for the creation of Energy Performance Certificates (EPCs) for existing domestic properties, and makes assumptions for items such as U-Values and insulation levels based primarily upon the age banding of a

property. Appendix S of SAP is RdSAP.

U-Values are a standard used to determine how well the fabric used in the built environment will conduct heat (Anderson, 2006). Therefore, a U-Value is a measure to demonstrate how well a material will allow heat to pass through it. For example a single glazed window will have a higher U-Value than a double glazed window. In an average property, different U-Values will be assigned to different sections of a building – an external door, double glazed window and cavity wall will each have differing U-Value properties. The lower the U-value, the more difficult it will be for heat to pass through it. RdSAP makes assumptions for the U-Values of a dwelling based upon factors such as the build year. Buildings standards matching the build date of a dwelling determine the U-Values of materials and insulation of that dwelling.

RdSAP differs from SAP primarily on the numbers of input parameters which are required to be entered by the assessor. For an EPC to be created utilising the RdSAP methodology, approximately 60 data input parameters are required to be entered. To create an EPC utilising the full SAP methodology over a hundred input parameters would be required.

By reducing the number of input parameters required to be entered, RdSAP does not offer a devalued assessment of a building in comparison to SAP. As there are fewer data input parameters to be recorded in RdSAP, scope for human data entry errors are accordingly also reduced (Hitchin, 2010). Hence, the SAP result and subsequent EPCs produced using RdSAP should have a similar degree of accuracy as those produced by SAP.

1.6 Research objectives and Thesis outline

1.6.1 Aims

An evaluation will be made of the benefit SAP gives for solar renewable implementations. From this it will be possible to state areas where SAP could

learn from dynamic simulation. A new SAP compliant advanced dynamic simulation method which can be used in the energy modelling of dwellings is presented in this thesis. The new SAP compliant advanced calculation method will hence forth be known as IDEAS (Inverse Dynamics based Energy Analysis and Simulation). The IDEAS framework can be used to model novel heating and renewable systems dynamically to produce results which are calibrated with SAP.

The thesis will provide an evaluation of the SAP procedure charting progress from conception to the currently available version of the methodology. Other assessment methods for energy performance of dwellings will be detailed and utilised to model Standard Test Case (STC) dwellings. Specific case studies highlighting the modelling of dwellings and renewable energy sources in SAP and dynamic simulation tools will be researched.

A focus of this thesis is the treatment of renewables in SAP and DSMs, leading to the comparison of SAP with Dynamic Methods. There is little published evidence comparing SAP with DSMs. Also a focus is an assessment temperatures used in SAP to determine what temperatures should be tracked by a dynamic model. The use of varying temperatures in SAP are not clearly documented or defined in SAP or elsewhere. This work is the foundation to the development of a new reduced parametric simulation method named IDEAS. IDEAS is then calibrated with SAP, but could be used with any calculation methodology. Hence, the aims of this thesis are as follows:

1. Evaluate the benefit which the SAP methodology allows for the use of solar renewables in dwellings. This evaluation will be compared to the treatment of solar renewables in dynamic simulation tools such as TRNSYS (Beckman et al., 1994) and PVSyst (Schoen et al., 2001). From this conclusions will be drawn to suggest why the differences arise and

where the SAP methodology could improve. This work will also assess the impact which weather profiling has upon SAP, based upon weather profile available from SAP, Meteonorm (Meteotest, 2011).

2. Fully analyse the treatment of temperatures in SAP; the temperatures assumed in SAP are unclear and this is a major component of calibrating an advanced dynamic calculation method with SAP.

3. Present a new SAP compliant advanced dynamic calculation method (IDEAS) which can be used in the energy modelling of dwellings. IDEAS is novel due to its use of an inverse dynamics based controller and the perfect control law RIDE (Robust Inverse Dynamics Estimation) to guarantee that the SAP standard occupancy profile is met. This method will bridge the current gap which currently exists between SAP and Dynamic Building Simulation by producing SAP compliant results. IDEAS will meet the Credibility, Repeatability and Discrimination of reduced parametric simulation methods as highlighted in Table 1.4. The IDEAS method will aim to improve on the Transparency and Ease of Use factors of typical reduced parametric simulation methods.

4. Validate IDEAS against SAP, to ensure that SAP comparable energy consumption and mean internal temperatures are produce in IDEAS.

5. Highlight the use of IDEAS via case studies, and demonstrate areas such as monitoring of dwellings which could extend the method

Table 1.4– Relative rating of alternative calculation procedures (where # by the calculation method dictates the method complies with European Standard EN ISO 13790). Adapted from Source (Hitchin, 2010).

Calculation method	Credibility	Repeatability	Transparency	Discrimination	Ease of use
Full dynamic simulation#	*****	****	**	*****	**
Reduced parameter dynamic simulation#	****	****	**	****	***
Bin methods	***	*****	****	***	***
Degree-day	**	****	***	**	**
Monthly heat balance#	***	****	****	****	***
Full-load hours	**	*****	*****	***	****

1.6.2 Structure

- Chapter 1 – INTRODUCTION. Assessing the Energy Performance of Dwellings. A review of the UK domestic built environment is presented, highlighting the importance of advanced controllability of low and zero carbon homes with renewables, and MMC developments and systems. The scene for the energy assessment of dwellings is demonstrated by introducing SAP. Research objectives are outlined along with a description of the thesis structure.

- Chapter 2 – LITERATURE REVIEW. Assessment Procedures for Dwellings Energy Ratings. Demonstrates the research context and applicability - presents a background to the SAP Methodology from 1981 and charts the malleability of the methodology to 2011. The updates made from SAP2005 to SAP 2009 are presented. Passive House is introduced and compared with the SAP method. The SAP empirical

methodology and dynamic simulation methods (DSM) are compared and contrasted. Advanced controllability is introduced highlighting similarities between its use in aerospace and dwellings.

- Chapter 3 – SOLAR ENERGY TECHNOLGIES IN DWELLINGS. Focus is on the comparison of SAP and DSMs to measure the performance of renewables which are largely building independent and most prevalent: Solar Energy Technologies in Dwellings. Demonstrate the use of SAP and DSMs. Use of DSMs for Renewables in Dwellings. The importance of Renewables for homes is highlighted. Commonly installed implementations of Renewables installed in the UK domestically (PV and SDHW) are assessed with DSMs (TRNSYS, PVSyst) and SAP.

- Chapter 4 – METHOD. Advanced Energy Modelling of Dwellings. The IDEAS method is introduced and described; enhanced controllability of dwelling systems within SAP. The development and progression of the IDEAS method is presented from initial conception to final version which produces results are well matched with SAP.

- Chapter 5 – RESULTS AND DISCUSSION. Results and discussion are presented from the use of SAP and dynamic simulation tools (chapter 3), and from the new IDEAS method (chapter 4)

- Chapter 6 – CASE STUDIES. Use of the IDEAS model. Demonstrate that the IDEAS model can be used by others and is malleable, transparent and usable – present an industry and academic test case. Heat Pumps - building dependent technology. Practical work carried out: Monitoring of the first PassiveHouse in Scotland.

- Chapter 7 – OUTCOMES AND RECOMMENDATIONS FOR FURTHER WORK

CHAPTER TWO

2 METHODS OF ENERGY ASSESSMENT OF DWELLINGS

2.1 Energy Rating of Dwellings

As Governments around the world look to increase the energy efficiency of dwellings for a multitude of reasons such as health factors, regulatory compliance and mitigating climate change, the accuracy of the methodology employed to assess the energy performance of dwellings becomes imperative. The European Directive on the Energy Performance of Buildings (European Parliament, 2003), referred to as the Energy Performance of Buildings Directive (EPBD), stipulates that all EU member states must produce an Energy Performance Certificate (EPC) and make this available to the next prospective occupier. The EPC is a legal requirement for all EU nations to have implemented by January 2009; determined by Directive 2002/91/EC of the European Parliament and the Council of 16th December. The main purpose of the directive is to assist the implementation of the Kyoto Treaty by EU member states: the directive creates a European wide framework where member states are encouraged to make efficiency savings in one of the largest independent sources of energy use – the built environment. EPCs are designed to evaluate the efficiency of a dwelling by using a scale of A-G, similar to the European Commission Energy Labelling of Domestic Appliances (European Commission, 2011) commonly used in White Goods. EPCs have to be renewed every ten years or when a property is placed on the market, generating the need for a new EPC.
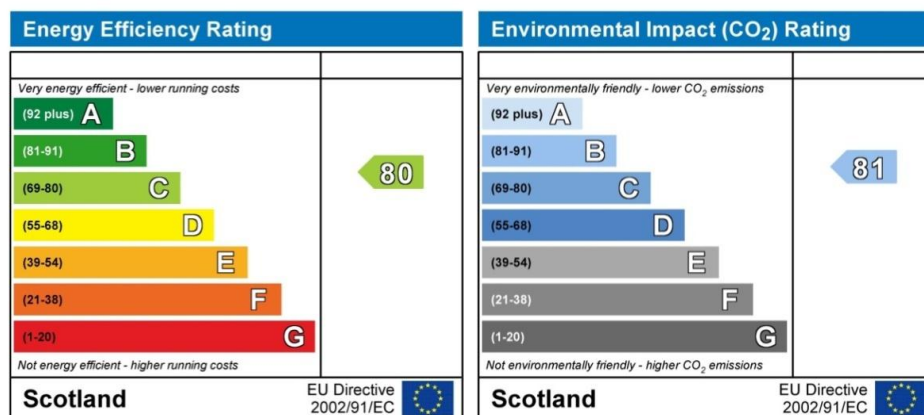
Figure 2.1 Sample SAP derived Energy Efficiency and Environmental Impact Ratings   21

In 2003 when the EPBD entered into force, only the UK, France, The Netherlands, Ireland and Luxembourg had a complete energy ratings system; other European countries had various degrees of Energy Rating Systems whilst Austria, Spain, Finland, Portugal and Sweden had no official building energy rating system (European Commission, 2006). The energy rating of dwellings in the EU has been researched previously to highlight the many different methodologies utilised throughout Europe to assess the Energy Performance of Dwellings (Míguez et al., 2006). Energy rating systems for dwellings are now becoming more prevalent in other parts of the world. The recent adoption by ASHRAE of the Building Energy Quotient Program – Advanced Building Energy Labelling (Jarnagin, 2009), illustrates the relevance of simplified assessment methods in the United States of America. The Building Energy Quotient Program is very similar to European EPCs and offers an update on the information and detail which can be recorded in the Energy Star labelling program (McWhinney et al., 2005). In the UK, SAP is the procedure used to generate an EPC for a dwelling.

2.2 SAP (Standard Assessment Procedure)

As introduced in the previous chapter, SAP was created by BRE and is the UK Government's recommended method of measuring the energy ratings of dwellings. SAP was initially published in 1993 (Griffiths, 2010) and has evolved to SAP 2009 (Table 2.1; History of SAP). SAP 2009 is used to demonstrate compliance under the Section 6 (Scotland), Part L (England and Wales) and Part F (Northern Ireland) building regulations. The SAP 2009 Energy Calculations are consistent with British Standard 13790 (Energy performance of buildings – Calculation of energy use for space heating and cooling; ISO 13790:2008) (European Committee For Standardization, 2008). SAP calculates the energy performance of a dwelling based upon a quasi-steady-state principle where temperatures and heat flow are independent of time (Hens, 2007). The

challenge represented by this method is the creation of appropriate definitions of constant factors for parameters such as U – Values.

Table 2.1 - History of SAP

SAP Version	Detail
BREDEM Version 9.53 = SAP (1993)	SAP rating scale is from 1 to 100 Yearly calculation Energy is measured in GJ
SAP 9.60 (1998)	SAP rating scale is from 1 to 100 Energy is measured in GJ
SAP 9.70 (SAP 2001)	Carbon Index is introduced SAP rating is raised is on a scale from 1 to 120 Energy is measured in GJ
SAP 9.80 (SAP 2005 October 2005)	SAP rating scale is revised to be from 1 to 100 A rating is 100 is a dwelling which has zero energy cost EI Rating introduced Scale of 1 - 100 www.bre.co.uk/SAP2005 RdSAP first introduced for existing dwellings in 2007 Energy is measured in kWh
SAP 9.90 (SAP 2009)	Current version of SAP www.bre.co.uk/SAP2009 Move to Monthly Calculation Method

The main change between SAP 2005 and SAP 2009 is that SAP 2009 has moved to a monthly calculation method. Other changes in the move to SAP 2009 include the addition of space cooling and the update of weather data used: SAP 2005 uses average weather data from year 1960>1979, SAP 2009 has been updates to use an average weather data from the years 1987->2006. The main

reasons for the move to a monthly method in SAP are due to modelling low energy dwellings, "Calculation for each month is more satisfactory for very low energy dwellings with shorted heating seasons especially as regards solar gains and solar collectors"(Anderson, 2011). The change to a monthly version of SAP would not have an effect upon a newly developed calculation methodology (such as IDEAS) other than confirming that a like-for-like calibration process was carried out by matching inputs and comparing outputs of the two methods. SAP 2009 calculates ratings for Energy Efficiency (EE) and Environmental Impact (EI), usually in the range of 1 to 100 although higher values are possible. The higher the score, the more energy efficient the home is and the less impact the home will have on the environment. The ratings are grouped into alphabetised bandings; 1-20=G, 21-38=F, 39-54=E, 55-68=D, 69-80=C, 81-91=B, 92 and over=A. Figure 2.1 details an example of SAP derived Energy Efficiency and Environment Impact Ratings, as applicable to Scotland. This constitutes an important part of the Energy Performance Certificate (EPC) for the UK as required by the EPBD. In the UK, there are subtle differences between the devolved administrations (such as the Scottish Government) in relation to dwelling assessment and so energy efficiency and environmental impact ratings produced by SAP will state Scotland, England and Wales or Northern Ireland. This will clarify where that dwelling is located and where ratings are applicable. In other European countries, where the EPBD also applies similar Energy Efficiency Ratings are produced by various tools (Andaloro et al., 2010, Dyrbøl and Aggerholm, 2008, Thomsen, 2008). The UK SAP Model has been adopted by the Republic of Ireland (SEAI, 2011) and Cyprus (Hitchin and Davidson, 2009).

Relevant studies highlight that the CO_2 produced by dwellings must be reduced, and SAP ratings of dwellings must increase. The "40% House Project" (Boardman et al., 2005) highlights the importance of SAP and states that new

housing association dwellings in Scotland must obtain a SAP rating of 85-90. One aim highlighted by the 40% House Project is that by 2050 the average existing property will have a SAP rating of 80 and no homes will remain will a SAP rating lower than 51. The accuracy of SAP ratings are therefore critical to ensure a good result. BRE has produced a vast number of publications which highlight the requirement for sustainable house building and refurbishment (Plimmer et al., 2008) and energy efficiency (MacKenzie et al., 2010). The importance of SAP is highlighted and the probable housing stock of the UK in the future is assessed. Modelling future complex buildings and their servicing systems will require an advanced calculation method.

The major uses of SAP are to demonstrate a dwellings compliance with Building Regulations and the production of UK Energy Performance Certificates.

2.2.1.1 SAP Mean Internal Temperature

It is important to differentiate between the different uses of the word **temperature** in dwelling energy performance research. **Demand temperature** is the temperature that the houses are trying to achieve, e.g. in SAP this is 21°C for Zone 1, the living area of the dwelling. The **background temperature** is the temperature which the dwelling would naturally revert to without heating. Internal temperature will differ from the demand temperature when the dwelling is heating up or the outside temperature is cold. The demand temperature could be exceeded if there is a heating system which is poorly controlled, therefore controllability must be a focus of an energy assessment methodology. Mean Internal Temperature (MIT) is a figure which differs from the demand temperature as it is concerned with the periods when the heating is off as well as when it is on. MIT will be altered by the U-Value of the dwelling fabric components. With a cold external temperature in a poorly-insulated house, the MIT will drop quicker and reach a lower level than in a well-

insulated dwelling. Therefore, as a U-Value in a dwelling is decreased due to building fabric improvement, the MIT will rise. **A minimum acceptable MIT is not set in SAP, but the demand temperature must be perfectly met.**
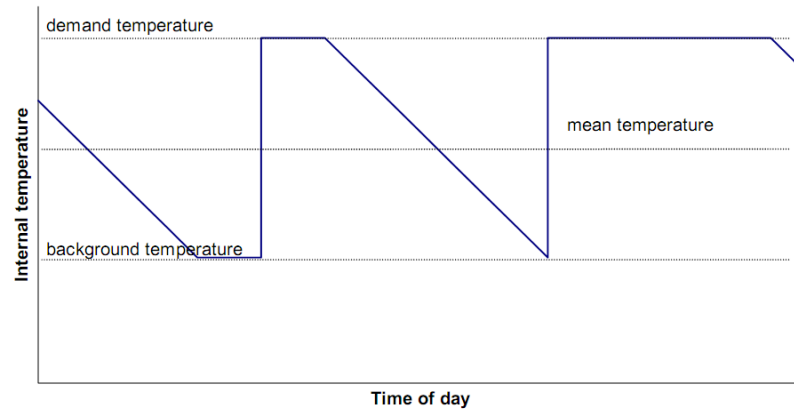
Figure 2.2 - An idealised temperature time graph (Anderson et al., 2001b)

Figure 2.2. highlights the idealised geometrical relationship between the temperature variation of a dwelling heated twice per day – 2 hours in the morning and 7 hours in the evening. Demand temperature is the heating required by the occupants; 21°C in SAP for Zone 1 between 7am->9am & 4pm->11pm weekdays and 7am->11pm weekends. Background temperature is the temperature which the air in the dwelling will fall to if the heating is turned off for a period of time. There is no figure set for background temperature in SAP, it is allowed to set back naturally based upon the dwelling and environmental characteristics.

2.2.1.2   *What is SAP Mean Internal Temperature?*
It is unclear in SAP what MIT exactly refers to. **It is not stated in SAP if MIT is taken as being air temperature or a comfort temperature.** If MIT is taken as being a comfort temperature then it is not clear what ratio should be applied to each of the main components of the dwelling. If a comfort ratio is determined by a combination of air temperature, furniture and internal mass and the structure, then it is unclear what ratio of each should be used so that a comfort temperature as defined by SAP is achieved.

Temperatures are not well documented in SAP, a major outcome of this research is therefore an analysis of temperatures in SAP to determine what the MIT is in SAP. If the MIT in SAP is air temperature alone then queries will be raised as therefore SAP will assume that MIT is less affected by the structure of the dwelling or furniture & internal mass. If MIT in SAP is a comfort temperature then queries will be raised with regard to what ratio of each of the main components is appropriate to use in advanced calculation methods so that SAP MIT can be fairly compared. For a dynamic simulation tool to produce SAP compliant results, the temperature which is perfectly tracked in SAP must be known. The same temperature must then be tracked perfectly in the advanced calculation method.

Research is therefore required to determine what exactly the MIT is in SAP. Additionally if MIT is a comfort temperature, then the ratio used to determine the impact of each dwelling component to construct that temperature requires analysis. From this an analysis of the implications of tracking air temperature as opposed to a comfort temperature is also required. This thesis will provide answers to these questions. The process to calculate MIT in SAP is outlined in the following section, using a STC dwelling.

2.2.1.3 Calculation of MIT in SAP:

MIT is recorded in SAP 2005 9.82 for SAP Worksheet #70. This is selected from SAP Table 8: (Mean Internal Temperature). See Figure 2.3.

Number in brackets is from the 'heating type' column of Table 4a or 4d.
HLP is item (38) in the worksheet

HLP	(1)	(2)	(3)	(4)	(5)
1.0 (or lower)	18.88	19.32	19.76	20.21	20.66
1.5	18.88	19.31	19.76	20.20	20.64
2.0	18.85	19.30	19.75	20.19	20.63
2.5	18.81	19.26	19.71	20.17	20.61
3.0	18.74	19.19	19.66	20.13	20.59
3.5	18.62	19.10	19.59	20.08	20.57
4.0	18.48	18.99	19.51	20.03	20.54
4.5	18.33	18.86	19.42	19.97	20.51
5.0	18.16	18.73	19.32	19.90	20.48
5.5	17.98	18.59	19.21	19.83	20.45
6.0 (or higher)	17.78	18.44	19.10	19.76	20.42

Notes:
1   Use heating column (1) when dwelling is heated by community heating.
2   Use linear interpolation between rows of the table.

Figure 2.3 - SAP Table 8 – Mean Internal Temperature of Living Area (BRE, 2010)

The number in brackets is from the 'heating type' column of Table 4a or 4d. In this Standard Test Case, a wet system with radiators has been selected. The corresponding table to this heating type is from SAP Table 4d:

Heat emitter	Heating type	Responsiveness (R)
Systems with radiators:	1	1.0
Underfloor heating (wet system):		
pipes in insulated timber floor	1	1.0
pipes in screed above insulation	2	0.75
pipes in concrete slab	4	0.25

Figure 2.4 - SAP Table 4d - Heating Type and responsiveness for wet systems with heat supplied to radiators or underfloor heating (BRE, 2010)

Heating Type is 1 for this Standard Test Case dwelling with a wet heating system and heat supplied by radiators. HLP (Heat Loss Parameter) is from item (38) on the workshop. Figure 2.5 is an example section from the SAP 2005 Worksheet for this Standard Test Case Dwelling. The full SAP 2005 worksheet referred to in this section is available in Appendix S: SAP 2005 Sample Worksheet.

3. Heat losses and heat loss parameter

Element	Area (m²)	U-value (W/m²K)	A × U (W/K)	
Doors	7.60	3.00	22.80	(26)
Windows	16.90	(2.10) 1.94	32.74	(27)
Roof windows	0.25	(2.30) 2.11	0.53	(27)
Ground floor	52.00	0.22	11.44	(28)
Walls	118.50	0.30	35.55	(29)
Roof	51.75	0.16	8.28	(30)
Total area of elements	247.00			(32)
Fabric heat loss			111.34	(33)
Thermal bridges (0.15 × total area)			37.05	(34)
Total fabric heat loss			148.39	(35)
Ventilation heat loss			64.70	(36)
Heat loss coefficient			213.08	(37)
Heat loss parameter (HLP)			2.05	(38)

Figure 2.5 – Sample SAP Worksheet Section 3

HLP in SAP is calculated as follows:

- U-Values for building elements are inputted into SAP worksheet items

(26) –> (30)

- The total area of elements are calculated in item (32) by summing the element areas

- Fabric heat loss (W/K) is calculated in item (33) by summing the element U – Values * Areas

- Thermal bridges are kept as a default value of $\psi = 0.15$ where ψ = linear thermal transmittance W/mK.

- Thermal Bridging is detailed in SAP Appendix K – where SAP table K1 (figure 2.6) details values of ψ for different types of junctions conforming with Accredited Construction details.

Junction detail in external wall	Ψ (W/m·K)
Steel lintel with perforated steel base plate	0.50
Other lintels (including other steel lintels)	0.30
Sill	0.04
Jamb	0.05
Ground floor	0.16
Intermediate floor within a dwelling	0.07
Intermediate floor between dwellings [a]	0.14
Balcony within a dwelling [b]	0.00
Balcony between dwellings [a] [b]	0.04
Eaves (insulation at ceiling level)	0.06
Eaves (insulation at rafter level)	0.04
Gable (insulation at ceiling level)	0.24
Gable (insulation at rafter level)	0.04
Corner (normal)	0.09
Corner (inverted)	-0.09
Party wall between dwellings [a]	0.06

Figure 2.6 - SAP Table K1 – Thermal Bridging Values of ψ

- ψ can also be calculated (Ward and Sanders, 2007)

- Thermal bridges are then multiplied by the total area. In this example, $0.15 * 247 = 37.05$ W/m²K. This is recorded in SAP item (34)

- Total fabric heat loss is calculated by sum of SAP item (33), the fabric heat loss (111.34W/K), and SAP item (34) Thermal Bridges (37.05 W/K),

to give 148.39W/m²K in this example

- The ventilation heat loss is SAP Item (36). It is defined by SAP Item (25), the effective air change rate, * 0.33 * SAP Item (6), the dwelling volume. SAP Ventilation Rate: the rate at which air leaves and enters the building. In this example, SAP item (25) is calculated as 0.75, where 0.7 is for natural ventilation and 0.05 is added for two extract fans. The dwelling volume is 262.6m³. So, 0.75*0.33*262.6 = 64.7 W/m³K

- The heat loss coefficient is calculated by the sum of SAP item (35), Total Fabric Heat Loss, and (36), Ventilation Heat Loss. This is recorded as SAP item (37), in this example, this is 148.39 + 64.7 = 213.08W/K

- The heat loss parameter (HLP) (W/m²K) is calculated by SAP item (37), the heat loss co-efficient, / SAP item (5), Total Floor Area (TFA). In this example, 213.08W/K / 104m² = 2.0539 W/m²K

2.2.1.4 Heat Loss Parameter used to calculate MIT:

Referring to figure 2.3 detailing SAP Table 8 – Mean Internal Temperature of Living Area, the HLP = 2.0539 W/m²K and Heating Type (1) is selected for this example. Therefore, from using linear interpolation SAP Table 8, MIT of the living area is 18.85°C. If the heating type was less responsive (e.g. Underfloor heating), the MIT would be higher due to the lack of responsivity.

2.2.1.5 Process to Calculate MIT in SAP:

- Mean Internal Temperature of the living area is recorded as SAP Item (70), 18.85°C for the STC.

- Temperature Adjustment is made from Table 4e if required. For a Boiler System with 'Programmer and at least two room thermostats', the temperature adjustment in Table 4e is 0°C

- Adjustment for gains is calculated based upon the following calculation

[(SAP item 69) / (SAP item 37)]-4.0)* 0.2 * R. Where (69) is the SAP calculated figure for Internal Gains (987W in our example), (37) is the Heat Loss Coefficient (213.08 W/K), and R is Responsiveness from SAP Table 4a or 4d. In this example, Table 4d provides a Responsiveness of 1 for a Wet System with radiators. Therefore, [(SAP item 69) / (SAP item 37)]-4.0) * 0.2 * R => ([(987) / (213.08)]-4.0) * 0.2 * 1 = 0.13

- Adjusted living room temperature (SAP item 73) = (SAP item 70) + (SAP item 71) + (SAP item 72) => 18.85 + 0 + 0.13 = 18.98°

- Temperature Difference in Zones is taken from SAP Table 9.

1. Number in brackets is from the 'control' column of Table 4e.
2. HLP is item (38) in the worksheet

HLP	(1)	(2)	(3)
1.0 (or lower)	0.40	1.41	1.75
1.5	0.60	1.49	1.92
2.0	0.79	1.57	2.08
2.5	0.97	1.65	2.22
3.0	1.15	1.72	2.35
3.5	1.32	1.79	2.48
4.0	1.48	1.85	2.61
4.5	1.63	1.90	2.72
5.0	1.76	1.94	2.83
5.5	1.89	1.97	2.92
6.0 (or higher)	2.00	2.00	3.00

Use linear interpolation between rows of the table.

Figure 2.7 - SAP Table 9: Difference in temperatures between Zones

- The difference in temperature between zones is calculated by using linear interpolation from SAP Table 9. The example figure for HLP is 2.05. The number in brackets is 'control' taken from Table 4e. In this example, Table 4e provides us with a Control of 2 for a Wet System with radiators with a programmer and at least two room thermostats. Therefore, the calculated figure for difference in temperature between zones, SAP figure (74) is 1.58 °C

- Living Area Fraction (0 to 1.0), SAP Figure (75) is calculated by the

Living Room Area / SAP Figure (5). In our example, 55m² / 104m² = 0.529; The largest public area in entered as the Living Room area; in this example a large open plan public area of 55m² is modelled.

- The rest-of-house area fraction is simply calculated by 1 – SAP Figure (75), therefore 1- 0.529 = 0.471, this is SAP Figure (76)

- The Mean Internal Temperature (MIT) is SAP Figure (77) and is calculated by (SAP item 73)-[(SAP item 74)*(SAP item 76)] => 18.97-(1.58 * 0.471) = 18.23°C

This example has demonstrated the many steps and complexities which are involved in the calculation of one value in a quasi-steady-state method, SAP. SAP is simple to use in comparison with detailed simulation tools, but even in SAP there is scope for user input error. As the complexity of a methodology increases, the scope for user error increases. Therefore an energy assessment methodology must be as simple to use as possible for the user. This example also highlighted the use of controls and responsivity of systems to bring heater dynamics into SAP. **An energy assessment methodology must therefore deal with advanced controls; this will become more pertinent as buildings become more complex and more responsive.**

2.2.2 BREDEM (Building Research Establishment Domestic Energy Model)
SAP is based on the Building Research Establishment Domestic Energy Model (Anderson et al., 1985), known as BREDEM. BREDEM calculates the energy required by a UK dwelling for space heating, water heating, cooking, lights and electrical appliances. SAP is based on a 2 zone model as defined in BREDEM, with zone 1 being the living area of the home and zone 2 the bedrooms. BREDEM defines the heating demand temperature of these areas to be 21°C and 18°C for 2 heating profiles, covering the weekday and weekend.
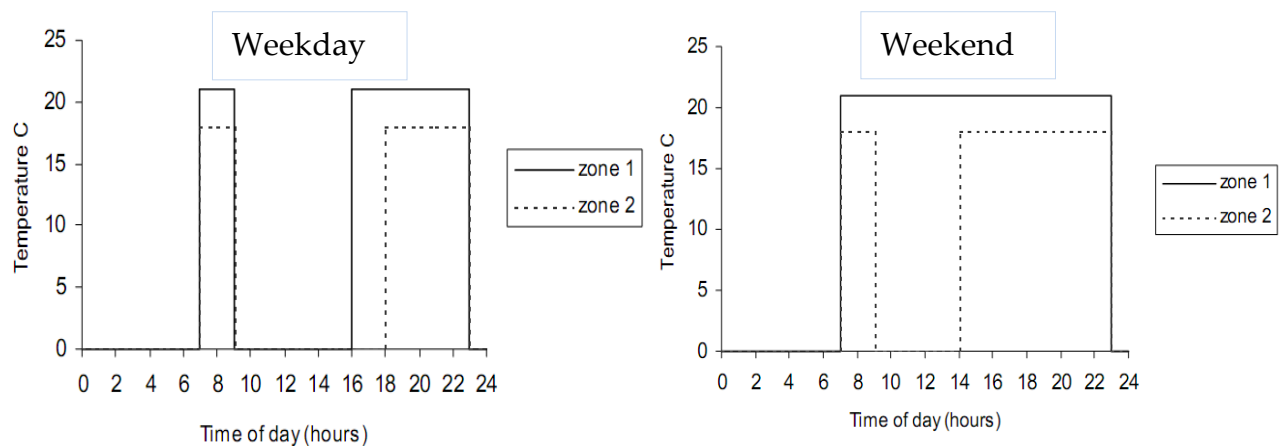
Figure 2.8 - BREDEM Weekday and Weekend heating profile for two zones (Anderson et al, 2001)

Some coefficients in SAP are empirical and derived from extensive studies. The BREDEM weekday and weekend heating profiles for two zones are used to determine the yearly energy consumption and MIT of a dwelling. They are based upon temperature testing and recording of measured data of homes throughout the UK as highlighted by the figures below. Monitored data was used extensively in the development of BREDEM.
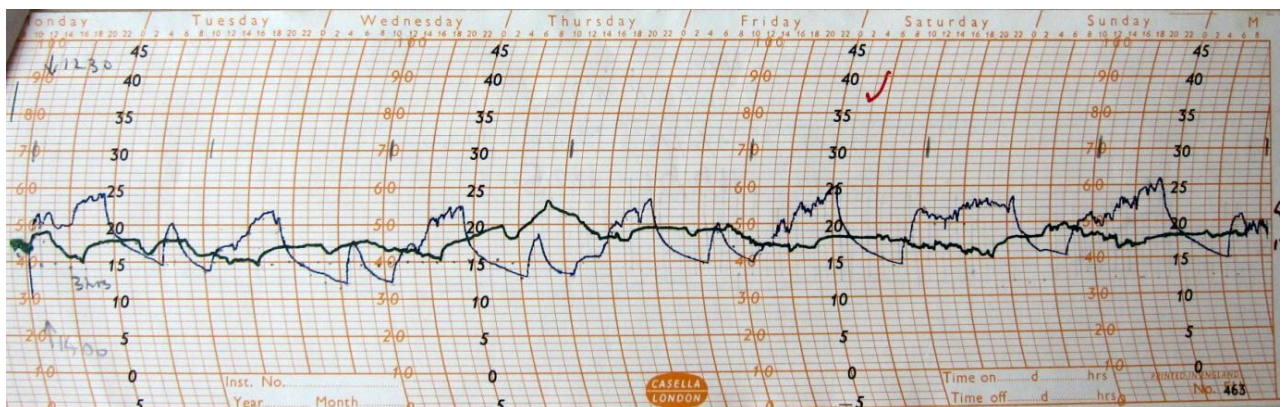
Figure 2.9 – Sample Recorded Temperature Profiles used in the construction of BREDEM heating profiles

Source: © G.B.MURPHY www.flickr.com/murphygb
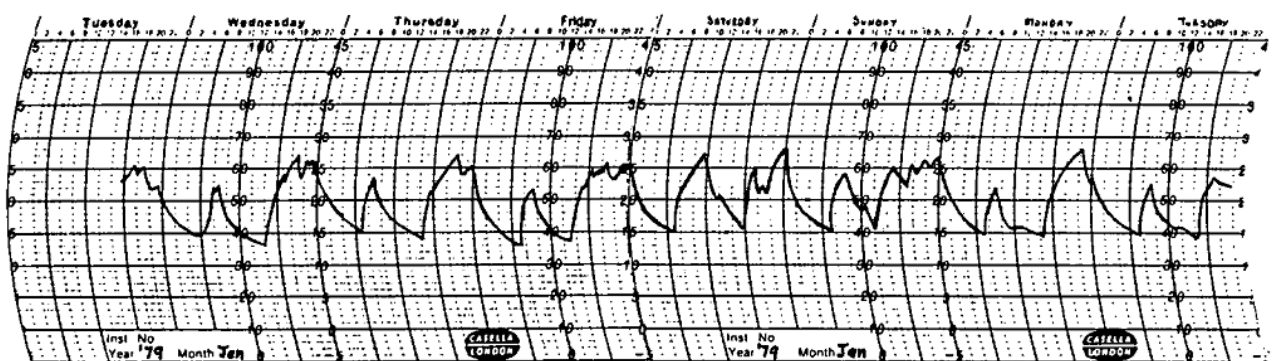
Figure 2.10 - Typical temperature profiles recorded in living rooms of occupied houses with responsive heating systems, two heating period per day. (Anderson et al., 1985)

33

The background to the BREDEM / SAP methodology has been researched in depth (Tuohy, 2009). The SAP/BREDEM model has evolved through much iteration since its conception in 1981 (Uglow, 1982, Uglow, 1981) when the procedure was initially developed which came to be known as BREDEM 1. The SAP/BREDEM model has constantly evolved for three decades; this evolution must continue if SAP is to remain at the forefront of assessing the energy performance of dwellings in the UK.

A number of assumptions are used in BREDEM based upon the Total Floor Area for a dwelling. For a dwelling with a TFA (Total Floor Area) of less than 450m^2, BREDEM defines the standard number of occupants in a dwelling as follows: $N = 0.0365 \, TFA - 0.00004145 \, TFA^2$

Therefore, for a TFA of 100m^2, BREDEM would calculate 3.6 occupants $(3.65 - 0.041445)$ for a dwelling of that size. The TFA is used to determine factors such as hot water demand for a dwelling. A schematic of the BREDEM 12 methodology is presented in the figure below.
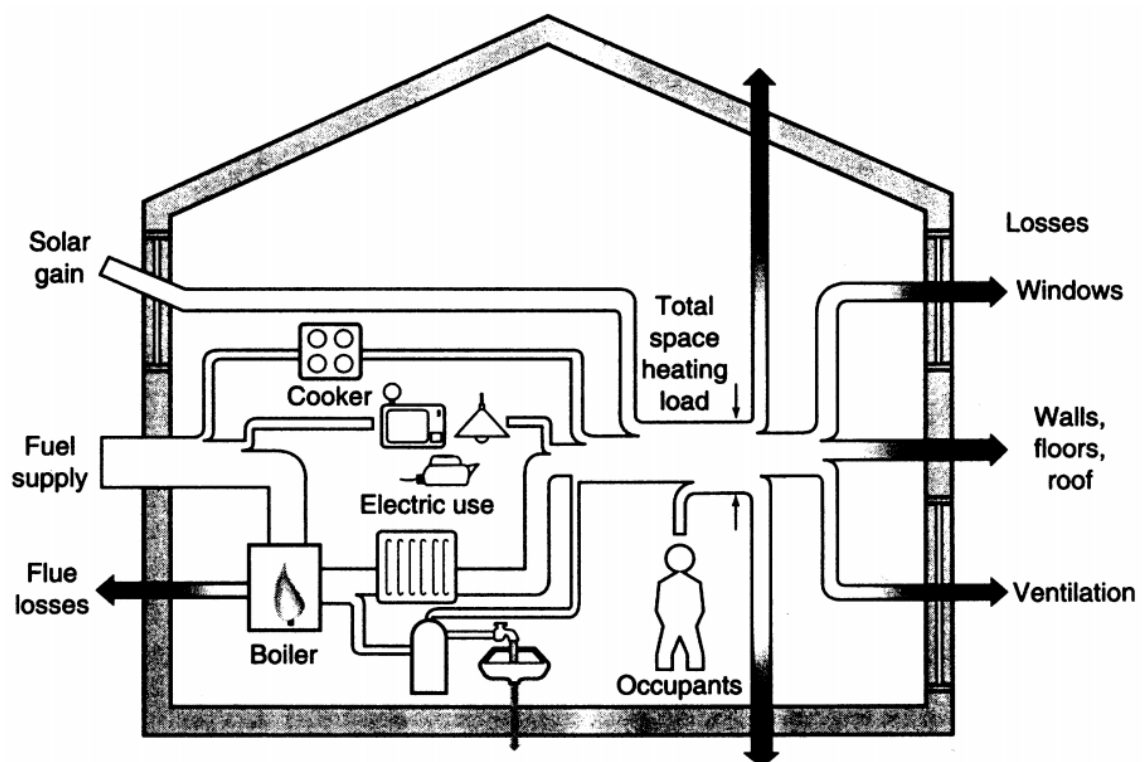
Figure 2.11 - BREDEM 12 Energy Balance Schematic, (Anderson et al., 2001b)

34

2.2.3   SAP Extension Worksheet

Originally designed for the retrofit for the future Technology Strategy Board (TSB) competition (TSB, 2009), the SAP Extension Worksheet highlights an example of a modification of SAP to develop a baseline of CO2 emissions.

2.2.3.1   *Purpose*

- Extend SAP V9.81 to make a whole house energy model, including appliances, and the ability to model substantial reductions in them

- Extends SAP to a whole house model, resetting the constant whole house demand temperature to 21° (in line with Passive House standards)

2.2.3.2   *Input: SAP Extension Worksheet*

SAP extension worksheet

This sheet extends SAP 9.81 to make a whole house energy model.

It also adjusts SAP to a constant whole house temperature of 21 C

and accounts for lower gains from appliances when appropriate

Uses SAP 2005 9.81 emission coefficients

low energy lights proportion	100%= all lighting low energy	50%
low energy appliances proportion	100%= all AA++ appliances	50%
low energy cooking: fuel & saving	100%:= Microwave, induction, AA	50%
low energy cooking fuel		mains gas ▼

Figure 2. 12 Extension of the SAP Methodology

The extension of the SAP methodology as highlighted above demonstrates that the SAP methodology is not rigid; it is an ever developing method.   This development process must continue if SAP is to be used as the energy calculation methodology of the UK, and other countries, in the future. The SAP Extension Worksheet signifies that there is a need for SAP to be directly comparable to PHPP and so a constant whole house temperature is used. **The SAP Extension Worksheet states that in highly insulated homes a constant whole house temperature modelled with a single zone is more appropriate**

than differentiating between zones as SAP does currently (TSB, 2009).

2.2.3.3   Output: SAP Extension Worksheet
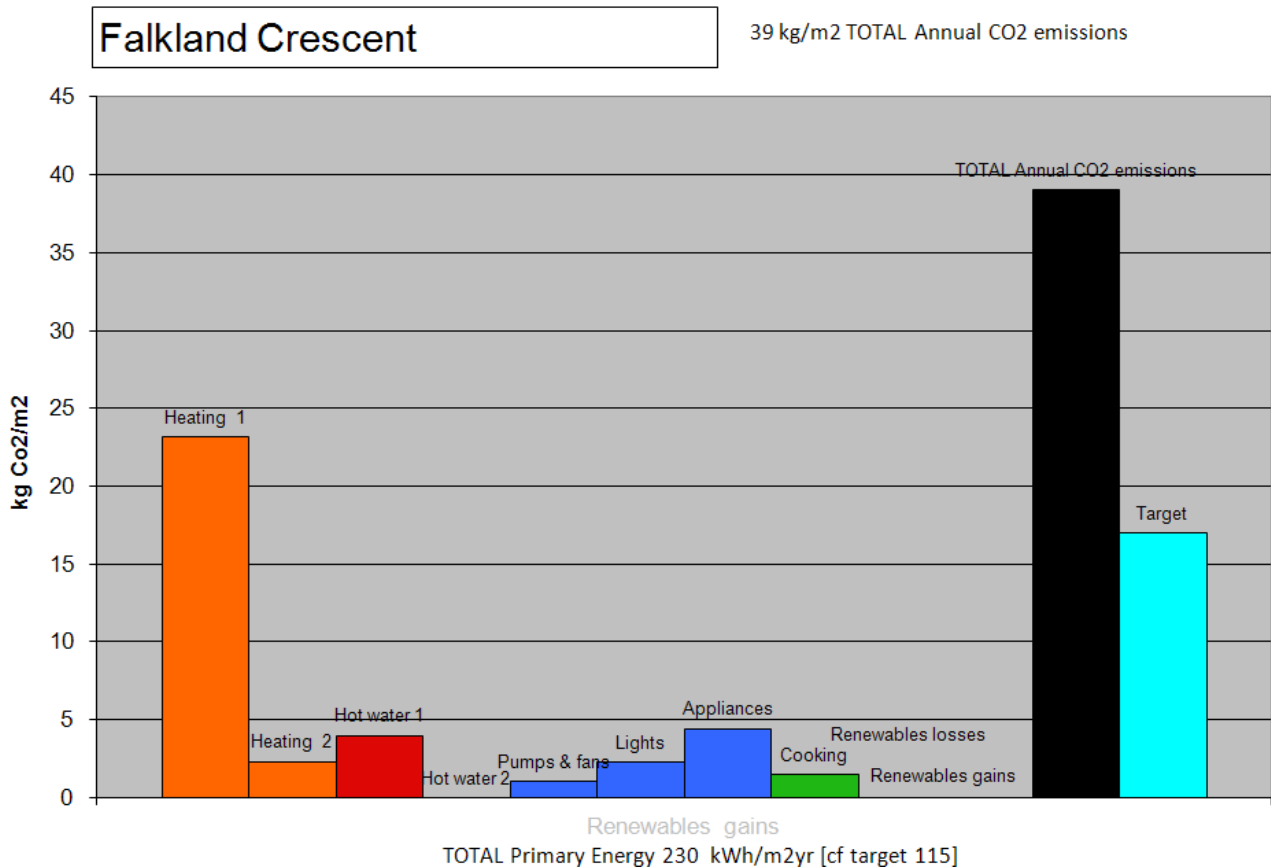
Figure 2.13 – Example Emissions Chart generated from SAP Extension Worksheet

The above figure details the use of the SAP Extension Worksheet to produce an emissions chart for a poorly insulated home. In a home of this type (which is a prime candidate for retrofit) space heating can be seen to be the primary use of energy. In the above graph, the target bar highlights the level of CO_2 emissions which demonstrate an 80% reduction in CO_2 from an average 1990 baseline.

2.3   Passive House

The term Passive House, from the German PassivHaus, refers to a standard used to define highly insulated energy efficient buildings. Passive House standard can be reached by both domestic and commercial buildings. To be

termed a Passive House, the building must meet a set of core fundamentals (Table 2.2).

Table 2.2 – Passive House Criteria

Area	PassiveHouse Criteria
U – Value of Exterior Dwelling Elements	≤ 15 kWh/m2a
Thermal Bridges	Thermal Bridge Free Design
Air Tightness	0.6 air changes / hour @ 50 Pa
Entire Specific Primary Energy Demand	Max 120 kWh/m2a
Glazing	U-Value ≤ 0.8 W/m2K Solar Energy Transmittance (G Factor) of at least 50% to achieve net heat gains in winter
Mechanical Ventilation Heat Recovery	MVHR is critical in a PassiveHouse, a system with a high efficiency (>75%) must be used
Domestic Hot Water Generation and Distribution Systems	Minimal Heat Losses

"A simple collection of appropriate components is not sufficient to construct a building as a PassiveHouse – the integration as a whole is greater than the sum of the individual parts", (Feist and PassivHaus Institut, 2007). The UK Secretary of State for Energy and Climate Change stated at the inaugural UK Passivhaus Conference held in London on October 11th 2010 that the PassiveHouse standard was a "a watershed moment in our relationship with the built environment (and that he) would like to see every new home in the UK reach the standard" (Cutting the Carbon, 2010). The CEPHEUS project (Schnieders, 2003, Schnieders and Hermelink, 2006) details the results from measurements of over 100 Passive Houses in Europe. It states that principle idea of a Passive House as the reduction of heat losses, through increased insulation, so that the use of internal gains, appliances / people / solar largely

negate the need for a separate heating system.

Detailed comparisons of SAP and PHPP have been conducted (Reason and Clarke, 2008, Tuohy, 2009). The main differences between SAP and PHPP are presented in Table 2.3.

Table 2.3 - Passive House vs. SAP Comparison

Area	Passive House	SAP
Test Data	Based on Real Data: Darmstadt Kranichstein Terraced Houses Hanover Kronsberg Freundorfer House Oberaudorf CEPHEUS Projects throughout Europe	Based on Real Data: Milton Keynes Energy Park Recording of measured data from houses located throughout the UK
Thermal Bridges	PHPP requires the PSI value PSI value = "The heat loss per unit length of thermal bridge, measured in W/mK" Repeating Thermal Bridges are included in the U-Value calculation Non-Repeating Thermal Bridges must be accounted separately	SAP uses y values (default) or PSI values A default y-value of 0.15 W/m2 is assumed PSI values are calculated based upon BR 497 Repeating Thermal Bridges are included in the U-Value calculation
Air Tightness	This is expressed in the German fashion of air changes / hour @ 50 Pascals An air tightness equal or lower than 0.6 ac/h @50Pa must be achieved for Passive House criteria to be met The internal volume measured for air tightness in PH is based upon European Euronorm Methodology where all internal partitions, stairs, floors, voids are discounted to result in a lower overall internal volume.	The pressurisation test should be carried out in accordance with BS EN13829. The air permeability measured in this way, q50, expressed in cubic metres per hour per square metre of envelope area. m3/h.m2 The internal volume measured in SAP for air tightness is the entire volume inside the thermal envelope Equivalence SAP assumes: A PH air tightness of 0.6 ac/h @50Pa is equivalent to a SAP air tightness of 0.6 m3/h.m2 @ 50Pa

MVHR	Temperature must not rise above 58°C to prevent any burning smell The efficiency of an MVHR can be entered	The efficiency of an MVHR system cannot be entered
Humidity	As Cold Air can carry very little moisture (in Central European Climates especially), Passive Houses can have very dry air.	Humidity is not recorded in SAP
Zones	Single Zone - 20°C All air assumed to be stratified and an even temperature created throughout the dwelling Difficult to cool bedrooms	Two Zone Living Area heated to 21°C Rest of House heated to 18°C
Internal Gains	Assumes lower internal gains than SAP	assumes a figure based upon number of occupants See SAP 2009 Table 5 – internal heat gains (in W) Appendix L: Energy for Lighting and Electrical Appliances

SAP and PHPP are both consistent with a number of international standards as presented in table 2.4.

Table 2.4 – International Standards adhered to by SAP and Passive House

Area	Passive House Referenced Standard / Passive House Criteria	SAP
Measurement of the air tightness of dwellings	The Air Change Rate must be <0.6m³/h at 50 Pascals, according to EN 13829	No air change limit is set
Calculating U-Value for Glass in a building	Glazing must have U-Values below 0.8W/m²K. according to BS EN 673	BS EN ISO 10077 Thermal performance of windows, doors and shutters – Calculation of thermal transmittance
Glass in building. Determination of luminous and solar characteristics of glazing	Glazing must have a high total solar energy transmittance (g) of at least 50% according to EN 410 to achieve net heat gains in winter	No glazing limit is set

Calculating the Thermal Performance of Glazing	2-D Calculations with a tool such as THERM (see Appendix G: Glazing and Structure Thermal Bridging using THERM) can be carried out under the guidelines of EN 10077 to highlight the requirement for PH windows	There is no set glazing requirement in SAP
Ventillation for Buildings	EN 13053	BS EN ISO 13789 Thermal performance of buildings – transmission and ventilation heat transfer coefficients – Calculation method
Ventillation for non-residential buildings	EN 13779	N/A, SAP is for dwellings only
Assessment parameters for assessing indoor air quality	EN 15251	Indoor air quality is not recorded in SAP
U-Value	The Overall heat transfer coefficient (U-Value) is calculated in accordance with the standard DIN EN ISO 6946	BS EN ISO 6946 (Building components and building elements – Thermal resistance and thermal transmittance Calculation method)
Thermal Conductivity, Lambda value (λ)	Thermal conductivity, λ, according to DIN 4108-4, DIN EN 12524 or national technical approval.	No minimum thermal conductivity values are set
Thermal Bridges	Thermal Bridges should be calculated as per DIN EN ISO 10211	No minimum thermal bridge limits are required in SAP
Space Heating Balance	Space Heating and Cooling Balance should be calculated according to EN ISO 13790	Space Heating and Cooling Balance should be calculated according to EN ISO 13790
Thermal Imaging	Thermal Imaging of Buildings must be carried outwith principles defined by EN 473 – Non Destructive Testing	Thermal Imaging is not a requirement is SAP but if a SAP assessor did with to use Thermal Imaging, it would have to be non-destructive

Heat Losses via the ground	According to ISO 13370 calculations can be carried out for 4 standard situations: -floor slab on ground (without basement) -floor slab in the ground -ceiling above unheated rooms -suspended floor slab	Based on entered U-Value and area of floor. SAP assumes that ground temperature = air temperature.

PassiveHouse and the use of Microsoft Excel for the creation of PHPP highlights the importance of the tool used to deliver the method of energy estimation. Human Computer Interaction (HCI) and usability engineering highlight (Nielsen, 1993) that a tool should be designed for the user and not for the developer. Excel is a good choice for an energy assessment of dwellings tool as users are familiar with Excel through the proliferation of Microsoft Office. Excel has a high installed user base and has the ability to generate powerful graphs. **As has been demonstrated by PHPP, Excel is a powerful medium for a comparatively user friendly tool to assess the energy efficiency of dwellings.**

2.4   Simplified Building Energy Model (SBEM)

Another Excel based method used to assess the energy performance of buildings is the Simplified Building Energy Model (SBEM). Created by BRE, SBEM is freely available and is used to generate EPCs and measure the buildings compliance of a commercial building. SBEM is not used for dwellings. There are similarities between SAP and SBEM but they are two independent entities for two different purposes.

2.5   Dynamic Building Simulation

Dynamic Building Simulation, also referred to as Dynamic Simulation Methods (DSMs) is an alternative method of modelling dwellings to that employed by largely empirical methods such as SAP and PHPP. It is deemed important for

this research of SAP that an assessment of DSMs is provided. Direct comparisons between results produced by DSMs and SAP can then be made. There are many DSM software tools available for the modelling of a dwelling and its system components. Some are open source whilst the majority are sold under a commercial business model. Standardisation between the systems involved can be an issue (Crawley et al., 2008) and detail on factors assumed by each system can be difficult to de-construct. Therefore, there can be an issue with transparency of DSMs. Validation of dynamic building simulations can be also be a long-term complex task (Strachan et al., 2008). DSMs can have "a very steep learning curve and require large amounts of data and time to produce useful results" (Counsell et al., 2010).

2.5.1 PVSyst

DSMs software has been developed for the assessment of specific applications which can affect the energy performance of dwellings. PVSyst is PC oriented software which can be used to simulate, analyse and study various Photovoltaic (PV) systems. For the purposes of this research, PVSyst was employed as one detailed simulation tool to model building integrated PV systems. PVSyst is an assessment and benchmarking tool used by PV industry professionals (Lyle, 2009) and PV researchers (Wittchen, 2003). PVSyst allows for building independent modelling of PV systems to be made. Climactic data can be selected from sources such as Meteonorm (Meteotest, 2011), and detailed selections can be made for PV panel, pitch, orientation and PV Inverter. A detailed assessment of a commonly installed PV installation will be made in PVSyst and compared with SAP results to state the benefit given to the Energy Assessment of a Dwelling by the addition of domestic PV.

2.5.2 TRNSYS

In a similar fashion to PVSyst for PV dynamic modelling, the Transient System Simulation Tool (TRNSYS) can be used for the dynamic modelling of Solar

Domestic Hot Water (SDHW) systems. TRNSYS can also be used to model other Buildings Systems and whole dwellings using TRNBUILD. For SDHW, the modelling of the entire dwelling is not required and inputs specific to a dwelling size (such as amount of hot water used per day by a dwelling of a specific size) can be inferred from SAP and entered directly into the TRSNYS model. TRNSYS is based upon the modelling of a series of connected Types, where a TRNSYS Type can represent any required component in a system such as an evacuated tube solar array, a boiler or piping. TRNSYS is referenced in British and European Standards, such as EU ENV-12977-2, for Solar Thermal Systems, and was used as the reference tool in several projects of the International Energy Agency's (IEA) Solar Heating and Cooling Programme (Perers, 1993). The core TRNSYS package can be supplemented by additional modelling of Types from the Thermal Energy Systems Specialists (TESS) Libraries. A detailed assessment of a commonly installed SDHW will be made in TRNSYS and contrasted with SAP. The benefit of using TRNSYS for this as opposed to other DSMs tools is that SDHW can be modelled in detail with no hidden assumptions made.

2.5.3 ESP-r

The Environmental Systems Performance research (ESP-r) dynamic simulation tool is an integrated modelling tool for the simulation of the thermal, visual and acoustic performance of buildings and the assessment of the energy use and gaseous emissions associated with the environmental control systems and constructional materials (ESRU, 2011b). ESP-r is a "finite-volume (or finite difference) discretisation approach to the conservation of energy is employed to represent the opaque and transparent fabric, internal air spaces, and plant components" (Veken et al., 2004). Created by the Energy Systems Research Unit (ESRU) at the University of Strathclyde in Glasgow, ESP-r has been available free as an open source software project under the GNU license since

2002 (Hand, 2009). ESP-r allows for detailed simulations to be produced with a high number of input parameters. The ESP-r detailed simulation process results in production of detailed information and a tool which can be time intensive to use (Hand, 2008).

The core text book for ESP-r is Energy Simulation in Building Design which was first published in 1985. The second edition (Clarke, 2001) details a brief history of simulation and commences by stating that "energy systems are complex" and to "pretend otherwise is to design for certain failure". ESP-r has been under continuous development for over three decades, approximately the same length of time that SAP / BREDEM has been under continuous development. Appendix A of Energy Simulation in Building Design details thermophysical properties taken from datasets used by ESP-r; this is an important reference for energy assessment tools. The issue of reliability of data used in simulation is highlighted here as the source of much of the data was found to be difficult to ascertain. Appendix B of the text describes the 'deficiencies of simplified methods'. The objection to simplified assessment methods such as SAP is summarised: "if significant energy saving can only be achieved by going beyond the constraints of the regulations then the designer may not be able to rely on simplified methods to provide the necessary evidence…this problem is compounded if additional technical complexity is introduced through the incorporation of … advanced control systems or renewable energy technologies".

The contribution to the field of dynamic simulation made by ESP-r, and by all of the researchers involved in the continuing development of ESP-r, is therefore vast (U.S. Department of Energy, 2011). Quasi steady state methodologies such as SAP could learn from the work carried out by ESP-r. Research is required to determine if the complexity of ESP-r is suitable for a

domestic setting or if a simplified assessment method such as SAP could add a degree of complexity to help combat the issues raised but still remain simple and easy to use.

A focus on the treatment of advanced controls and renewable energy systems in SAP is therefore recommended.

2.5.4 IES-VE

IES – Virtual Environment (VE) is similar to ESP-r as it is used primarily for the modelling of whole buildings. It differs from ESP-r in that it is a commercial product which is used heavily in Industry. Additionally, the user interface is more user friendly in IES-VE than in ESP-r. This raises an important point about the importance of the usability of an energy assessment too. One of the major reasons why IES-VE is popular amongst groups of users such as architects is deemed to be attributed to its "user friendly GUI and its template driven approach…that facilitate quick entry and supports a progression…from getting quick answers in early design to detailed analysis in later design stages" (Attia et al., 2009). Good usability is key.

The importance of creating a tool which can provide detailed results in a user friendly manner is therefore highlighted. **If a simplified tool such as SAP wishes to be able to accurately model elements such as advanced controls and integrated renewables then it must do so in a user friendly manner, so as to not alienate the building professionals who commonly use SAP.**

2.5.5 EnergyPlus

First released in 2001, the most popular dynamic simulation tool in the USA is EnergyPlus 2.0. Developed by the US Department of Energy, it is available under a No-Cost End User License Agreement for research purposes. EnergyPlus has been verified by the IEA (Neymark et al., 2008).

EnergyPlus was built upon the foundations of BLAST and DOE-2 programs, carefully considering HCI and the GUI from the outset (Crawley et al., 2000, Crawley et al., 2001). One of the main reasons for the development of a new dynamic simulation tool was that the foundations of simulation methods was in some cases from the 1960s and designed in a non modular fashion, so the addition of new elements such as advanced controls and renewables was difficult. Links were developed by EnergyPlus to simulation tools such as TRNSYS to take advantage of the capabilities which other tools offer.

The creation of a new dynamic energy simulation program is therefore a very large task which is normally carried out by a large group of researchers over a significant length of time. **A modular design has been highlighted as being important to allow for advanced controllability and more advanced systems such as renewables to be modelled.**

2.6 Non Building Focused Dynamic Simulation Tools

Isaac Newton demonstrated dynamic system modelling in his Laws of Motion. Newton's Second Law States:

$$F = \frac{d(m.v)}{dt}$$

In symbolic modelling, the symbols are always available. A benefit of symbolic modelling is that a symbolic model deals with disturbances such as free heats gains or external temperature, it does not need to know what they are. Relatively simple symbolic models are required for the buildings industry, symbolic models are powerful and ideally are low order (Khalid, 2011).

A relatively simple symbolic model could therefore offer a solution to tools used for assessing the energy performance of a dwelling. Low order lumped parameter models may be advanced enough to deal with elements such as advanced control and renewables but simple enough to be used by

those familiar with primarily steady state methods such as SAP. Detailed performance modelling, especially for complex dwellings such as the Scottish Parliament building, would require a more complex tool which could emulate the future, such as ESP-r.

2.6.1 Modellica

Modellica is a modern programming language and tool built on OOP (Object Oriented Programming) methods (Elmqvist et al., 1998) which facilitates modular design of reusable code. A fundamental philosophy of the design of Modellica is the reuse of code and models. Modellica is a graphical model where most of the programming can be hidden from the user if so required. The design group for Modellica is extensive which again highlights the magnitude of a task which seeks to create or amend a tool suitable for the energy assessment of dwellings. Modular design and usability is again highlighted.

2.6.2 ESL

ESL is a dynamic simulation language and tool initially developed for the European Space Agency, hence the original name of European Simulation Language. ESL has been used to model areas of building simulation such as electric storage heaters in conjunction with the HTB2 program (Wright, 1997). The use of ESL to carry out the complex advanced control work required to dynamically model electric storage heaters highlights an area when simplified tools such as SAP are at a disadvantage. This study also presented interesting work on the notion of comfort temperature and comfort bands on a zonal basis; again this is an area which in depth research is required when a new energy assessment methodology is under development or consideration. **SAP could learn from the advanced controls capability which tools such as ESL hold.**

2.6.3   Matlab / Simulink

Matlab is commonly used to model signal processing intensive systems (Vanderperren and Dehaene, 2006) and can be flexibly integrated with other programming languages to offer malleable solutions which could also be used for dwellings (Mendes et al., 2003).   SIMULINK can be used as a graphical interface to Matlab projects.   Simple building modelling procedures have been developed in Matlab / Simulink for commercial properties (Hudson and Underwood, 1999) and dwellings (Achterbosch et al., 1985).   These studies found that Matlab / Simulink is a powerful tool which could be used to model buildings.

Matlab / Simulink could offer a powerful development avenue for energy assessment methodologies such as SAP.

2.7   Conclusions

Each tool / methodology described above has plus and minus points which have been highlighted. The literature review has highlighted the importance of having a methodology for energy assessment of dwellings which is:

- Simple to use, by the targeted user base

- Modular in design

- Produces consistent and reliable results

- Capable of modelling advanced controls and renewables

- Suitable for the job at hand

The following chapter will detail a study which compares SAP to DSMs to highlight the areas where SAP and DSMs tools differ and why:

- The focus will be applications of renewable energy systems which are largely dwelling independent

- This will allow SAP to be compared with DSMs which focus primarily on renewable energy aspects which is an area where there is limited amount of published research available

- The study of renewables will be solar focused as these are most commonly installed: PV using PVSyst and SAP and SDHW using TRNSYS and SAP

- The impact of differing weather profiles on the performance of renewables will also be taken into account

From this, the differences between SAP and DSM results for PV and SDHW will evaluated. From this suggestions can be made to improve SAP performance in rating the performance of renewables. Further to this the research focus of this thesis will be the creation of a new dynamic symbolic energy estimation method for dwellings (IDEAS), producing SAP compliant results.

CHAPTER THREE

3 SOLAR ENERGY TECHNOLOGIES IN DWELLINGS

3.1 An evaluation of the advantage given to SAP ratings by the installation of typical Photovoltaic (PV) and Solar Domestic Hot Water (SDHW) systems

Research (Syed et al., 2007) clarifies the benefit that PV offers to the residential sector; even in northerly situated countries. Domestic and distributed PV systems account for more than 75% of the 7.8 GWp installed in IEA PVPS countries at the end of 2007 (IEA, 2009). Domestic solar thermal applications represent the biggest portion of installed solar heat capacity (128 GWth) and produced energy (77 TWh) (Weiss et al., 2008). This is especially important given that recent studies demonstrate the importance of water heating in a domestic environment (Allen et al., 2010). This underscores the importance for building regulations and energy rating procedures such as SAP to represent accurately the benefits of solar thermal and photovoltaic systems.

The SAP methodology used to assess the energy performance of dwellings is based on simple physical equations and empirical evidence; this is also true for the assessment of building-integrated solar thermal and photovoltaic systems. The UK government has recognised the requirement for SAP to accurately model low and zero carbon technologies (Utley and Shorrock, 2008). The SAP methodology has been compared to detailed simulation for low-energy buildings (Cooper, 2008). This study found discrepancies for low energy dwellings and the benefits of some passive solar features. The literature survey produced no research which directly compares the SAP methodology for PV and SDHW with more detailed assessment methods. This chapter seeks to address this situation by investigating the comparison of SAP methodology calculations with more detailed assessment methods.

This chapter aims to compare the PV and SDHW calculations in the SAP methodology with more detailed methods of analysis. It is split into three main sections. The first section will detail a series of Case Studies where comparisons are made between the SAP results for PV and a more detailed numerical simulation of various domestically installed PV systems. The second will measure a standard UK installation of a SDHW system in both SAP and a more detailed analysis. The third will conduct an analysis of a BRE Innovation Park dwelling incorporating both PV and SDHW.

3.2 SOFTWARE TOOLS

There are a number of different software tools available, some commercially, to assist with the calculation of a SAP rating for a dwelling. The SAP software selected to calculate SAP ratings for this research was designed in-house by BRE. This software was used to derive a SAP rating for a defined STC dwelling. The software calculated the SAP rating and Carbon Dioxide emissions, of the STC Dwelling, according to the SAP worksheet. Commercially available BRE approved SAP calculation tools are available. For the sake of conciseness, SAP calculated EE (Energy Efficiency) ratings are the focus in this chapter and they are referred to as "SAP ratings".

PVSyst is PC oriented software which can be used to simulate, analyse and study various PV systems. PVSyst can simulate PV systems in grid connected, stand alone, pumping or DC grid connected scenarios. During this research, only grid connected systems were considered and analysed. PVSyst performs a detailed simulation in hourly values and uses this to provide a PV generation figure in kWh/year for each PV system modelled. PVSyst allows for different weather profiles to be entered based upon either the Meteonorm standard or TMY (Typical Meteorological Year) files. The development of PVSyst was assisted by the IEA PVPS Task 7 (Schoen et al., 2001).

The TRNSYS 16 Simulation Engine was selected as the detailed SDHW modelling tool for this chapter. TRNSYS has been commercially available since 1975 and is a transient systems simulation program (Duffy et al., 2009). During this research TRNSYS was selected as the DSM to model SDHW due to the software offering a great flexibility in selecting the assumptions for system configuration, controls, and component parameters and therefore allowing SAP to be compared accurately. TRNSYS has also been validated by users against other simulation tools and experimental data (Kummert et al., 2004). TRNSYS also has a component for the modelling of a whole dwelling, TRNBUILD, which would be useful in modelling renewable systems which have more closely linked to the building, such Heat Pumps. Recent work has seen links with TRNSYS to Google SketchUp (Murray et al., 2009).

TRNSYS is referenced in British and European Standards, such as EU ENV-12977-2, for Solar Thermal Systems, and was used as the reference tool in several projects of the International Energy Agency's Solar Heating and Cooling Programme (Perers and Bales, 2002).

3.3 METHODOLOGY

A Standard Test Case (STC) dwelling was initially modelled in SAP. The STC is a detached dwelling with dimensions detailed in Table 1.

Table 3. 1 - STC Dwelling SAP Input Listings

Element	Gross area [m²]	Openings [m²]	Net area [m²]	U-Value [W/m²K]
Ground floor			52.00	0.22
First floor			52.00	0.22
Walls	143.00	24.50	118.50	0.30
Roof	52.00	0.25	51.75	0.16
Doors			7.60	3.00
Windows			16.90	2.10
Roof windows			0.25	2.30

SAP v9.82 was used to produce the SAP ratings. A detached house with a total floor area of 104 m² was modelled. This house is part of a set of BRE developed archetypes to represent the existing building stock. Dimensions, openings and U-Value ratings in W/m²K are recorded in Table 3.1. Thermal bridging was recorded and set at the SAP default of 0.15 * Total Area of Elements (247m²) and was calculated to be 37.05 W/K. Double glazing with a U-Value of 2.10 W/m²K was modelled with standard external solid timber doors embracing a U-Value of 3.00 W/m²K. A space and water heating system typical of that installed in a standard dwelling in the UK was modelled in SAP. An air change rate of 15m³/hour.m² at 50 Pascals was assumed with a natural ventilation system including 2 intermittent extract fans. 50% energy efficient lighting was also assumed. A regular gas boiler with an efficiency of 90.2%, an Ariston Clas HE R 18, was modelled based upon a selection from the SEDBUK database (Todd, 2001). The controls for the boiler were recorded as a programmer and at least two room thermostats.

As discussed in Chapter 2, the controllability of a heating system has the effect in SAP of altering the difference in temperature between SAP zones, based upon a calculated Heat Loss Parameter. The Ariston Clas HE R 18 boiler was modelled to supply a stored water system which was sized at 300 litres, of which 180 litres was dedicated to solar storage. A secondary heating system was also modelled in the STC dwelling, standard electric room heaters. These are commonly installed in the UK and were modelled to reflect the standard nature of this dwelling – the addition of direct acting electric heaters to the SAP calculation results in a decreased SAP score, due to the increased use of carbon intensive electricity. This STC dwelling modelled in SAP achieves a SAP rating of C 72.

The SAP produced EPC also provides suggestions of improvements

which are specific to each dwelling modelled. In the case of the STC dwelling, the following suggestions were made to improve the energy efficiency and environmental impact of the home: 100% low energy lighting, addition of SDHW and PV.

3.3.1 PV SIMULATION

The modelled PV system has a peak power of 2 kWp, which is a typical value for a commonly installed PV system in the UK (Energy Saving Trust, 2011a). kWp refers to the Kilowatt Peak Power of a PV array which has been tested under standard test conditions of 1000Watts / m^2. A 2 kWp system could provide approximately 50% of the average household's electricity; based upon a typical annual electricity consumption of 2500 kWh for a three bed-roomed property (Bahaj and James, 2007) The addition of a PV array with a peak power output of 2 kWp improved the SAP rating from C 72 to B 81. The SAP calculation used to calculate the amount of generated electricity is described below.

3.3.2 SAP calculation to determine kWh/year - PV

In SAP v9.82 the following calculation is used to determine the available energy at inverter output in kWh/year produced by a PV system:

Electricity Produced by the PV Module = $0.80 * kWp * S * Z_{PV}$

Where:

0.80 – SAP empirical factor for PV

S – Annual solar radiation

Z_{PV} – shading factor

The SAP empirical factor for PV of 0.80 cannot be altered by the users of SAP and therefore is comprised of the typical efficiencies for important factors

in determining the output of PV systems, such as DC to AC inverters. The SAP empirical factor of 0.80 for PV is an example of a 'SAP Typical' factor. A SAP typical factor is a figure comprised of fair averages for components which have an effect on the SAP rating. **A SAP Typical factor is pre-defined by the SAP Methodology and cannot be altered by a SAP Assessor.**

Details from SAP Table H2 (Table 3.2) are used in SAP for the purposes of calculating the system output energy of a PV system. These values are tabulated for Sheffield, which was selected by SAP designers as the nominal centre of the UK. Using one reference weather location allows for dwellings throughout the UK to be compared directly.

Table 3. 2 - Sap Table H2 – Annual Solar Radiation, kWh/m²

Tilt of Collector	Orientation of Collector				
	South	SE/SW	E/W	NE/NW	North
Horizontal	933				
30°	1042	997	886	962	709
45°	1023	968	829	666	621
60°	960	900	753	580	485
Vertical	724	684	565	427	360

For a 2 kWp system installed in the STC, south facing with no shading with a collector tilt of 30°, the SAP calculated available energy, at the inverter output is 1667 kWh/year.

3.3.3 Use of PVSyst to determine kWh/year

To compare the SAP results directly with the results from PVSyst, the location of Sheffield, UK was taken with a PV system of 2 kWp. Weather data for Sheffield, UK is not included with PVSyst by default but it was imported into the software, using a data file from Meteonorm (Remund and Kunz, 1997). An

SMA Sunny Boy 2100TL 2.0 kW inverter was selected with an array of 10 Kyocera KC 200GHT-2 Polycrystalline 200 Wp PV modules, to represent components typically installed in the UK (Lyle, 2009). The modules were connected according to the voltage requirements of the inverter and all default PVSyst options were kept. No shading was assumed. The PVSyst-calculated output was 1632 kWh/year, which can be directly compared to the SAP figure of 1667 kWh/year. The 2% difference between SAP and PVSyst results had no significant effect to the SAP rating, which remained at B 81 for the STC.

3.3.4 Effect of PV components on SAP rating

SAP allows for the modelling of a generic PV system based upon the peak power in kWp. PVSyst allows for different PV components systems to be modelled and provides an extensive database of modules and inverters available on the market.

Table 3. 3 - Available Energy at Inverter Output

Method	PV panel and material	Inverter	Yield [kWh/y]	SAP rating
PVSyst	Sulfurcell SGC50 HV-F (CIS)	SMA Sunny-Boy 2100GT	1824	B 82
SAP	N/A	N/A	1667	B 81
PVSyst	Kyocera GHT200 (Polycrystalline)	SMA Sunny-Boy 2100GT	1632	B 81
PVSyst	Eurener PEPV 200 (Polycryst.)	Suntechnics STW1900	1514	C 80

As detailed in Table 3.3, a selection of 2 kWp systems, for a Sheffield, UK weather location, with a 30° angle and South azimuth, were modelled in PVSyst - to match the size of the system modelled in SAP, to determine if PV components had any effect on SAP rating. Three combinations of PV Panels /

Inverters were modelled in PVSyst; each with a peak power of 2kW. An array of 40 * 50Wp Sulfurcell SGC50 HV-F panels was modelled with a SMA Sunny Boy 2100GT inverter. This was compared with an array of 10 * 200Wp Kyocera GHT200 panels modelled with a SMA Sunny Boy 2100GT inverter. The final test case was an array of 10 * Eurener PEPV 200 panels with a Suntechnics STW1900. Table 3.3 indicates the variability of available energy (kWh/year). Table 3.3 also shows that different selections of PV panel and inverter can lead to a variation of the PV output of approximately +/- 10% without altering any of the assumptions. The variation in PV output can account for an adjustment to the SAP rating of +/- 1.

SAP results are consistent with PVSyst for a typically installed 2kW PV system in the UK.

3.3.5 Effect of Weather Location

A typical PV system was then modelled in PVSyst for different UK locations (see figure 3.1), to determine the effect on SAP ratings. The location of Sheffield was selected to match the location of SAP. Efford was selected as a reference point for the south of England. Eskdalemuir was selected as a reference weather location for Southern Scotland.
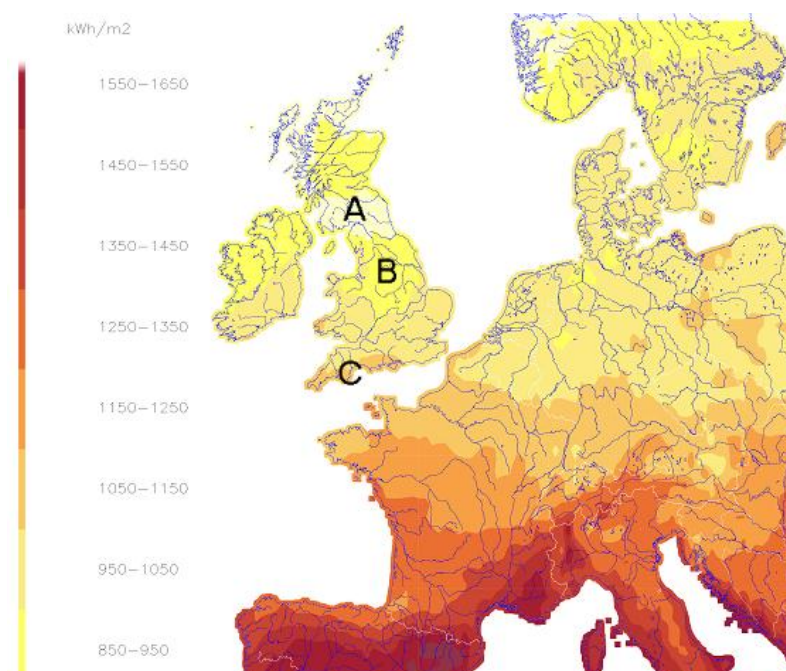
Figure 3.1 - European Radiation, annual mean 1981 – 2000. Weather Locations utilised in detailed simulation noted. Adapted from Source: (Meteonorm, 2009) 58

Table 3. 4 – Solar Availability for several locations based upon 2kWp South Facing PV System at 30°.

Locations used in Detailed Simulation	Location of Weather Stations utilised by Meteonorm	Solar Availability - Meteonorm (kWh/m²)	Solar Availability – SAP (kWh/m²)
A	Eskdalemuir, South Scotland	917	1042
B	Sheffield, Northern England – approximate SAP representative location of the UK	1013	1042
C	Efford, South England	1225	1042

The three weather data files used in PVSyst were generated by Meteonorm to ensure consistency. The two additional weather stations were selected because of the availability of measured solar radiation, which improves the quality of Meteonorm-generated weather data files.

Table 3.5 details available energy at Inverter Output in kWh/year: the Eskdalemuir location shows a reduction of over 187 kWh/year as calculated by PVSyst (-11%), which would be equivalent to a SAP rating of B 80. The Efford location highlights an improvement of 316 kWh/year over SAP (+19%), resulting in a SAP rating of B 83. SAP can be used to rank energy saving investments and a small difference of one or two points in SAP ratings could in fact be significant. In this respect, it could be argued that PV systems do not get the credit they deserve in some locations (e.g. South England) while their savings are overestimated for other locations (e.g. North Scotland).

Table 3. 5 – Results for several locations based upon 2kWp South Facing PV system at 30°

Calculation methodology	Location	Inverter output [kWh/y]	SAP rating
PVSyst	Efford	1983	B 83
SAP	Sheffield	1667	B 81
PVSyst	Sheffield	1632	B 81
PVSyst	Eskdalemuir	1480	B 80

3.3.6 Combined effect of PV systems and Weather data

A combination of varying PV systems and UK Weather locations were modelled in PVSyst to establish the effect that this combination would have on kWh/year and SAP rating. The Sulfurcell SGC50 HV-F panels (efficiency per module area of 6.41%) are an example of thin film technology. An area of 33m² would be required to include a 2 kWp array would be required if this was to be implemented. The Eurener PEPV 200 (efficiency per module area of 11.64%) and Kyocera GHT200 panels (efficiency per module area of 14.2%) are examples of single crystalline PV, 17m² and 14m² would be required to install these 2kWp systems. The nominal rating of each PV system was provided by manufacturer supplied data via PVSyst, which is the rating power of each module at standard operating conditions. These conditions stipulate an irradiation of 1000kWh/m2 with a module temperature of 25°C.

Table 3.6 highlights that, in comparison to the SAP calculated figure of 1667 kWh/year and rating of B 81, +33% kWh/year and +3 SAP points variation can be demonstrated from the 2 kWp Sulfurcell system installed in Efford. The 2 kWp Eurener system modelled in Eskdalemuir highlights a -18% kWh/year and -1 SAP point variation.

Table 3.6 - Results for several locations and components: 2kWp South Facing PV system at 30°

Method and location	PV panel and material	Inverter	Yield [kWh/y]	SAP rating
PVSyst (Efford)	Sulfurcell SGC50 HV-F (CIS)	SMA Sunny-Boy 2100GT	2183	B 84
PVSyst (Sheffield)	Sulfurcell SGC50 HV-F (CIS)	SMA Sunny-Boy 2100GT	1824	B 82
SAP (Sheffield)	N/A	N/A	1667	B 81
PVSyst (Sheffield)	Kyocera GHT200 (Polycrystalline)	SMA Sunny-Boy 2100GT	1632	B 81
PVSyst (Sheffield)	Eurener PEPV 200 (Polycrystalline)	Suntechnics STW1900	1514	C 80
PVSyst (Eskdalemuir)	Eurener PEPV 200 (Polycrystalline)	Suntechnics STW1900	1363	C 80

3.3.7 Other differences between SAP and PVSyst

Results for a slope of 30° and an azimuth of due south have been discussed so far. Other calculations were performed for different slopes and azimuths, combining different locations and different system components.

Table 3.7 details the comparison between kWh/year output from PVSyst and SAP based upon a combination of varying PV slopes and azimuths. A 2 kWp system was simulated in PVSyst based upon a SMA Sunny Boy 2100TL 2.0 kW inverter and 10 Kyocera KC 200GHT-2 Polycrystalline 200 Wp PV modules. The PV system modelled in SAP remained at 2 kWp and matched the PV slopes and azimuths used in PVSyst, to allow for a comparison to be made.

Table 3. 7 - Results for several PV pitch and azimuths based upon a 2kWp PV System in a Sheffield, UK location.

Azimuth	PV Pitch	SAP - Yield [kWh/y]	PVSyst - Yield [kWh/y]	% Difference
0º (South)	0º	1493	1395	7
0º (South)	30º	1667	1632	2
0º (South)	60º	1536	1536	0
0º (South)	90º	1157	1143	1
-90º (West)	30º	1418	1320	7
-90º (West)	60º	1205	1132	6
-90º (West)	90º	936	843	10
90º (East)	30º	1418	1325	7
90º (East)	60º	1205	1141	5
90º (East)	90º	904	852	6
180º (North)	30º	1134	973	14
180º (North)	60º	776	610	21
180º (North)	90º	576	444	23

The differences calculated between SAP values for different orientations are generally within 10% of the differences calculated by PVSyst for the same orientations. SAP neglects the impact of incidence angle and seems to overestimate the performance for unfavourable orientations, such as vertical north where the difference between PVSyst and SAP kWh/year yields was

found to be 23%. SAP results were always higher than PVSyst bar 60° south where results from PVSyst and SAP were identical. A possible improvement to SAP would be to add a table detailing solar radiation that is corrected for the incidence angle effects. An example of information which could be detailed is the radiation transmitted through a single glazing instead of the incident radiation – this value would be useful for transmission through windows, glazed solar thermal collectors and PV.

3.4   SDHW SIMULATION

A typically installed SDHW system in the UK was taken to be a glazed flat panel with an aperture area of 5 m^2 (Energy Saving Trust, 2011b), south facing, with a 300 litre dual coil domestic hot water cylinder. SAP requires aperture area, collector type (evacuated tube, flat panel or unglazed), collector efficiency (zero-loss collector efficiency and linear heat loss coefficient of collector, W/m^2K), roof orientation, pitch and shading. The SAP calculation to obtain the solar input is detailed below.

3.4.1   SAP v9.82 calculation to determine contribution to domestic hot water

$Q_s = S * Z_{panel} * A_{ap} * \eta_0 * UF * f(a_1/ \eta_0) * f(V_{eff}/V_d)$

Where:

Q_s = solar input, kWh/year

S   = total solar radiation on collector, kWh/m^2/year (from SAP Table H2)

Z_{panel} = shading factor for the solar panel

A_{ap} = aperture area of collector, m^2

η_0 = zero-loss collector efficiency (from certified test or SAP default values)

UF   = utilisation factor

a_1 = linear heat loss coefficient of collector, W/m²K

$f(a_1/\eta_0)$ = collector performance factor = $0.87 - 0.034 (a_1/\eta_0) + 0.0006 (a_1/\eta_0)^2$

V_{eff} = effective solar volume, litres

V_d = daily hot water demand, litres (from SAP tabulated data versus TFA)

$f(V_{eff}/V_d)$ = solar storage volume factor = $1.0 + 0.2 \ln(V_{eff}/V_d)$ subject to $f(V_{eff}/V_d) \leq 1.0$

Qs details a dwelling's kWh usage saved due to the installation of a SDHW system. The required auxiliary energy is then calculated taking into account the hot water energy required and distribution losses and tank losses. This auxiliary energy is then used in the main SAP worksheet where it is combined with the energy used for space heating, etc. to obtain the SAP rating. SAP also adds a fixed amount of 75 kWh/y to the electricity usage of a house to account for the energy required by the solar thermal circulating pump.

For the STC dwelling with the typical SDHW system described above, SAP provides default efficiency values for solar collectors in Table H1 (see Table 3.8). It can be noted that the default efficiency for glazed collectors (flat-plate and evacuated tube) is significantly lower than values recommended by the IEA-SHC programme based on collector tests (Murphy and Cedar, 2005). The first-order heat loss coefficient (a_1) in Table 3.8 is more than double of typical IEA values, so that the efficiency of evacuated tube collectors under nominal operations specified in the same IEA document is 0.76 for the IEA typical, and 0.6 for the SAP default.

SAP designers have deliberately designed the panel efficiency default figures to be lower than some collector efficiencies such as those noted from the IEA-SHC program. SAP allows the user to enter the efficiency of specific

collector base upon manufacturer supplied data, and therefore deliberately provides a low collector efficiency to encourage the use of real data in SAP.

Table 3. 8 - SAP Table H1 - Default Collector Parameters. (IEA–SHC Figures in Brackets)

Collector Type	η_0	a_1	Ratio of aperture area to gross area
Evacuated Tube	0.6 (0.76)	3 (1.2)	0.72
Flat Plate, Glazed	0.75 (0.78)	6 (3.2)	0.90
Unglazed	0.9 (0.90)	20 (20)	1.00

In SAP, hot water energy requirements are directly related to the total floor area (TFA) of a dwelling.   The TFA of the STC dwelling is 104m^2. SAP Table 1 (Hot Water Energy Requirements) states that a dwelling with a 104 m^2 TFA would have a hot water usage of 119 litres per day, with an Energy Content of Heated Water (including distribution losses) of 2532 kWh/year. One key parameter is the loss coefficient of the hot water storage tank. In this study, it was assumed that the storage tank is at the upper limit of band "B" in standard EN 15332, i.e. 2.49 kWh per 24 h for a 300 litre tank. SAP-calculated output of the auxiliary water heater is 3450 kWh without a solar system, and 1929 kWh with the system described above (assuming the same 300 litre storage tank is used in both cases). The calculated solar input is 1186 kWh and the losses in the 300 litre tank drop from 559 kWh/y to 224 kWh/y. The SAP rating for the STC dwelling increases from C 72 to C 74.

3.4.2   Use of TRNSYS to determine kWh/year

TRNSYS allows the detailed modelling of a solar thermal system. An identical Flat Plate Collector system to that modelled in the STC was modelled in TRNSYS, using standard components from the TESS libraries (TESS, 2009). The TRNSYS simulation was setup to represent a typical good practice system. The flow rate is set to 50 l/h·m^2 with a 25 W pump, solar primary piping losses are

set to 0.2 W/m·K. The domestic hot water profile is set to three draw-offs per day at 7am, 12pm and 5pm, with respectively 40%, 20% and 40% of the daily volume. The tank loss coefficient was set to the same value as in SAP, i.e. 2.49 kWh per 24 h. The loss coefficient in EN 15332 is calculated for standardised temperatures (room = 20 °C, hot water = 65 °C) and SAP applies a "temperature factor" of 0.6 to this loss coefficient to allow for the tank not being continuously maintained at 60°C. This would result in a very large discrepancy between SAP storage losses and TRNSYS storage losses if a hot water temperature of 60 °C was assumed. The TRNSYS simulation therefore assumes a hot water setpoint of 50 °C with a thermostatic valve bringing it down to 45 °C, and the daily load is adapted (170 litres per day at 45 °C). The mains water temperature is 10 °C in average and varies by +/- 2.6 °C over the year. SAP and TRNSYS results are presented in Table 8.

Table 3. 9 - SDHW results overview

Solar collector	Location	Slope and azimuth	Solar input [kWh]		Water heater output [kWh]	
			SAP	TRN SYS	SAP	TRN SYS
SAP FP	Sheffield	30°, S	1186	1461	1924	1782
IEA Flat-Plate	Sheffield	30°, S	1395	1840	1714	1488
	Eskdalemuir	30°, S		1635		1647
	Efford	30°, S		2237		1191
SAP ET	Sheffield	30°, S	1241	1548	1869	1714
IEA Evacuated tube	Sheffield	30°, S	1530	2246	1580	1220
	Efford	30°, S		2626		965
	Sheffield	45°, S	1521	2344	1588	1141
	Sheffield	60°, S	1493	2371	1617	1110
	Sheffield	90°, S	1353	2184	1757	1199

TRNSYS results for the typical system described above, using SAP default efficiency parameters (η_0 = 0.75 and a_1 = 6 W/m²K), show a solar input of 1461 kWh/y and a value of 1782 kWh for the water heater output. It is interesting to note that the solar input is 23% higher than the SAP value but the water heater output is only 7% lower. This is partly due to the different tank losses (357 kWh/year, i.e. 63% higher than the SAP value of 224 kWh/year). The tank losses from TRNSYS are for the entire tank whereas SAP only directly counts losses from the main store section of a combined cylinder tank. The losses from the solar store section are not included in the SAP tank losses figure and are dealt with in SAP in the collector performance factor (f(a_1/ η_0)). Therefore, a further evaluation of tank losses could be made between 214 kWh (TRNSYS), based upon 357 kWh / (300 litres / 180 litres), in comparison between the SAP losses of 224 kWh/year. TRNSYS results for tank losses are therefore within 4% of SAP tank losses.

As described above for the PV simulations, it is possible to calculate the SAP rating obtained if the SDHW system was simulated in TRNSYS and that result utilised in the main SAP calculation. The water heater output calculated in TRNSYS is then used rather than the solar input, so that the different tank losses are taken into account. For the system described above, the SAP rating is unchanged at C 74.

3.4.3   Effect of Collector parameters

SAP calculations and TRNSYS simulations were performed for collectors with parameters matching the typical values recommended by IEA (Murphy and Cedar, 2005). For glazed flat-plate collectors, the TRNSYS solar input is 32% higher than the SAP value, while the water heater output is 13% lower. For IEA typical evacuated tube collectors, TRNSYS predicts a 47% higher solar input

and 23% lower water heater output. For both IEA typical collectors, the SAP rating increases from C 74 to C 75 if TRNSYS results are utilised in the SAP calculation.

Another interesting comparison is between a SAP calculation using the default SAP efficiency for evacuated tubes and a TRNSYS simulation using default IEA parameters for evacuated tubes. The latter gives a solar input 81% higher and a water heater output 35% lower than SAP calculations with default parameters for evacuated tubes. The SAP rating would be C 75 instead of C 74. This underlines the importance of using certified performance data in SAP rather than default values, which have been designed to always be lower than typical figures.

3.4.4 Effect of SDHW Weather Location

TRNSYS was used to simulate an identical system (system described above with typical IEA flat-plate performance) for a number of UK weather locations. Figures were calculated for a northerly and southerly location in the UK, as in the PV section.

The TRNSYS calculated values for solar input are 17% higher in Eskdalemuir and 60% higher in Efford, with a water heater output respectively 4% lower and 31% lower. The equivalent SAP rating would increase from C 74 to C 75 in Sheffield and Efford but remain at C 74 for the Eskdalemuir location. Weather location can therefore play a highly significant factor in determining the output of SHDW (and PV) systems, which are at present not taken into account by SAP due to its use of one weather location for the UK.

3.4.5 Other differences between SAP and TRNSYS

Simulations were performed for different slope and azimuth angles, different locations and different collector parameters. A selection of these results is shown in Table 8. The most striking differences appear for high performance

collectors such as the IEA-typical evacuated tubes, for which differences in solar input reach +72% (in Efford) and differences in water heater output reach -39%, leading to a different SAP rating (C 75).

Another interesting conclusion from these results is that the influence of the collector slope is different in SAP and TRNSYS. Systems with a higher slope than 30° always perform worse in SAP, while the optimum slope in TRNSYS is 45° for maximum solar input and 60° for minimum water heater output. A higher tilt angle will increase the performance of SDHW systems in winter while the performance in summer will be affected less, especially for systems with a high solar fraction. This increases the match between supply and demand, and is not taken into account in SAP. For Sheffield, the difference in solar input between TRNSYS and SAP moves from 47% to 59% for IEA evacuated tubes when the slope goes from 30° to 60° (South-facing). Both systems have a rating of C74 in SAP and C75 when TRNSYS results are taken into account.

Finally, using a rated pump power of 25 W the TRNSYS-calculated pumping energy was between 50% and 75% of the SAP value (which is set to 75 kWh in all configurations).

3.5 BRE INNOVATION PARK ANALYSIS

The BRE Innovation Park (based at BRE, Garston, UK) allows companies to construct homes of the future, demonstrating implementations of Renewables and Modern Methods of Construction.

3.5.1 Stewart Milne Sigma Home

A study of the Sigma Home was conducted. The Sigma Home has been designed in a similar fashion to a standard UK Victorian Dwelling built during the period 1837 to 1901, offering compact, adjustable living over 4 floors. The Sigma Home meets level 5 of the Code for Sustainable Homes (Stewart Milne

Group, 2009) which rates the sustainability performance of a dwelling on a scale of 1 to 6. The dwelling has a total floor area of 116 m² which can be compared with a typically sized a new detached 3 bed-roomed dwelling completed in the UK of 94 m² (Scottish Government Social Research, 2009). The Sigma Home is equipped with PV and SDHW systems which will be modelled as part of this research. The Stewart Milne Sigma Home also has a Micro Wind Turbine installation, which is not considered here. A recent Post Occupancy Evaluation Research Programme has been concluded for the Sigma Home; this details that the Micro Wind Turbine installation underperformed and generated little effective electricity (Stewart Milne Group, 2009).

Figure 3. 2 - Stewart Milne Sigma Home - BRE Innovation Park, Garston, UK. Adapted from source: Stewart Milne, 2008

Discussions with Stewart Milne and the project development company (RD Energy Solutions Ltd) who sourced the Renewables allowed for access to

plans of the dwelling and installed Renewables. The SIGMA home was modelled with the best understanding of the data received (Dalgarno, 2009, Lyle, 2009). One main simplification is that existing shading is ignored both in the SAP assessment and in the detailed modelling.

3.5.2 SAP modelling of SIGMA Home

As detailed in Table 3.10, the Sigma Home was modelled in SAP and produced a SAP Rating of C 73 disregarding all renewables. SAP suggested improvements were the addition of Solar Water Heating, Solar Photovoltaic (PV) Panels and a Wind Turbine.

Table 3. 10 - Sigma House SAP Input Listings

Element	Gross Area (m²)	Openings (m²)	Net Area (m²)	U-Value (W/m²K)
Ground Floor			33.13	0.13
Exposed Floor	4.00		4.00	0.13
Walls	174.79	44.35	130.44	0.15
Roof (1)	21.02		21.02	0.13
Roof (2)	16.17		16.17	0.11
Doors			1.89	2.00
Windows (1)			42.46	0.70
Windows (2)				1.40
Roof Windows			0.25	2.30

3.5.3 SIGMA Home + PV Modelled in SAP

The installation of PV at the Stewart Milne Sigma House utilises Kyocera KC200GHT PV Panels. 4.8 kWp are installed on an east facing low pitch (10°) and 1.2 kWp are installed on the south facing vertical façade; with a Mastervolt QS6400 inverter (Dalgarno, 2009, Lyle, 2009). The east facing PV pitch was taken as 0° (i.e. horizontal) with no shading in SAP for the purposes of this preliminary study (PVSyst uses the correct pitch).

4.8 kWp of horizontal PV and 1.2 kWp of vertical PVs have been inputted into SAP. The area of vertical PVs were adjusted in SAP to the equivalent kWp if they were 0° using SAP Table H2 (1.2 x 724 / 933 = 0.93kWp). In total, 5.73 kWp of horizontal PVs were entered into SAP, with very little shading selected.

3.5.4 SAP Calculation to determine kWh/year – PV

The SAP calculation to determine useful energy production of PV, in kWh/year, was employed:

```
Electricity Produced by the PV Module =

0.80 * kWp * S * Z_PV
```

5.73 kWp of horizontal PV with no shading will generate 4278 kWh/year (0.80 * 5.73 * 933 * 1.0). The effect of the installation of this PV array is to increase the SAP Rating to A 94, an increase of 21 SAP points.

3.5.5 SIGMA Home PV modelled in PVSyst

Matching the installation at the SIGMA home, a 4.8 kWp east facing roof mounted array (10° pitch) combined with a 1.2 kWp vertical south facing array was modelled in PVSyst. To closely match the system installed at the Sigma Home, a Mastervolt SunMaster QS 6400 5.2 kW inverter was selected with an array of 30 Kyocera KC200GHT-2 Polycrystalline 200 Wp PV modules. 24 panels were modelled as being roof mounted with 6 panels modelled as a south facing façade array. When modelled in PVSyst, 3796 kWh/year is calculated for available energy at the inverter output. This is detailed in the PVSyst generated Sankey Diagram, detailing losses for the installed Sigma Home PV system.

923 kWh/m² — **Horizontal global irradiation**

-8.8% **Global incident in coll. plane**

-4.2% IAM factor on global
Effective irradiance on collectors

806 kWh/m² * 42 m² coll.
efficiency at STC = 14.2% PV conversion
efficiency at STC = 14.2%

4843 kWh

-10.2% PV loss due to irradiance level

+0.3% PV loss due to temperature

-3.4% Module quality loss

-2.2% Module array mismatch loss

-1.1% Ohmic wiring loss
Array virtual energy at MPP

4080 kWh

-6.9% Inverter Loss during operation (efficiency)

0.0% Inverter Loss over nominal inv. power

-0.1% Inverter Loss due to power threshold

0.0% Inverter Loss over nominal inv. voltage

-0.0% Inverter Loss due to voltage threshold
Available Energy at Inverter Output

3796 kWh

Figure 3. 3 - Sankey Diagram detailing PV Production for Sigma Home

This value is 12% lower than the SAP-calculated value (4278 kWh/year), which is consistent with the tendency of SAP to overestimate the performance of PV for non-optimal orientations (due to SAP's lack of Solar Incidence Angle Modifier). The SAP rating obtained by replacing the SAP-predicted PV output with the PVSyst value is A 93, i.e. a reduction of one SAP point.

3.5.6 SIGMA Home + SDHW modelled in SAP

The installation of SDHW at the Sigma Home utilises 4 SCHOTT EPC 16 Evacuated Tube SDHW collectors and 2 Schuco 200 L dual coil unvented cylinders. The solar collectors are on a pitched roof facing South, with a slope of 30°. In the absence of manufacturer data the thermal loss coefficient of each

200 litre tank was assumed to be at the higher end of "B" band in EN 15322, i.e. 1.94 kWh per 24h (3.88 kWh/day for two tanks). Hot water usage per day was set to be 126.7 litres, as defined in SAP Table 1; see table 3.11.

Table 3. 11 - SAP Table 1, highlighting the relationship between TFA and hot water energy requirements

Floor Area TFA (m²)	(a) Hot water usage V_d (litres/day)	(b) Energy content of water used (kWh/year)	(c) Distribution loss (kWh/year)
30	63	1146	202
40	71	1293	228
50	79	1437	254
60	87	1577	278
70	95	1713	302
80	102	1846	326
90	109	1976	349
100	116	2102	371
110	123	2225	393

3.5.7 SIGMA Home + SAP v9.82 calculation to determine contribution to domestic hot water

With SCHOTT ETC 16 Technical Information:

```
Qs = S * Zpanel * Aap * η0 * UF * f(a1/ η0) * f(Veff/Vd)

Qs = 1042 * 1 * 3.232 * 0.773 * 0.646 * 0.823 * 1

Qs = 1384 kWh/year
```

Based upon the technical information available for the Schott ETC 16 Evacuated Tube Collector (SCHOTT-Rohrglas GmbH, 2009), a zero loss collector efficiency, η_0, of 0.773 and a collector heat loss coefficient, a_1, of 1.09 were utilised. A total aperture area of 3.232 m² was selected in SAP based upon

the Sigma Home specification of 4 Schott ETC 16 collectors, each with an aperture area of 0.808 m².

The Solar Input, Qs, was calculated to be 1384 kWh/year. This increased the SAP rating of the SIGMA Home from C 73 to C 78, an increase of 5 SAP points.

3.5.8   SIGMA Home SDHW modelled in TRNSYS

The installation described above was modelled in TRNSYS. The calculated solar input is 1839 kWh (25% above the SAP value of 1384 kWh/year) and the water heater output is 1831 kWh (8% under the SAP value) of 1998kWh/year.

TRNSYS derived tank loses for the SIGMA home SDHW system were 620kWh for the entire tank, sized at 400 litres. This cannot be compared directly with the SAP calculated tank losses of 321 kWh/year for the SIGMA Home, as this is based upon a tank sized at 160 litres. In considering a combined tank SAP only directly considers losses from the section of the tank which is controlled by the boiler. The losses from the solar store section of the combined tank are stored in the SAP collector performance factor (f(a_1/ $\eta 0$)). Therefore, for a direct comparison of losses the TRNSYS losses for the SIGMA home tank should be 248 kWh/year based upon 620kWh / (400litres / 160litres). Based upon a combined tank the losses from TRNSYS for the non solar portion of the tank is therefore 23% lower than those recorded in SAP (248 kWh vs. 321 kWh). For a system with a separate solar cylinder, the SAP tank losses would be 801 kWh/year.

The SAP rating obtained by using the TRNSYS-calculated water heater output in SAP is unchanged at C 78 (the actual value increases from 77.74 to 78.45, both of which round to 78).

3.5.9   SIGMA Home + SDHW + PV modelled in SAP

With the previously described PV and SDHW modelled together in SAP, the

calculated SAP Rating is A 99.

If the results of PVSyst and TRNSYS are used in the main SAP procedure, the calculated rating is unchanged at A 99 (it actually decreases from 99.39 to 98.64, both round to 99). The PV output is adjusted downwards and the solar thermal input is adjusted upwards, resulting in a small downwards adjustment overall.

A good agreement is therefore seen between the SAP results and the combination of SAP results with the addition of detailed modelling results.

3.6 Conclusion
This research has shown a good agreement between SAP results and detailed simulations for PV and a reasonable agreement for SDHW systems, when the most typical system configurations are used. It was highlighted that SAP is restrictive as specific values for PV panels, inverters and SDHW systems cannot be entered. Detailed simulation programs can be time consuming to input and calculate results, and more prone to user input error. As SAP relies upon a series of simple equations, there is less scope for errors to occur in calculations. This contrasts with detailed analysis tools such as TRNSYS and, to a lesser extent, PVSyst. These software programs offer a greater degree of detail to be modelled, but the learning curve required to use them is as high as the opportunity to make errors inputting data or selecting components and system configurations. Therefore simplified methodologies such as SAP must focus on the most important variables and factors utilised in dynamic simulation to ensure accurate results, whilst keeping inputs to a minimum to ensure speed and ease of use. This study has highlighted that this can be a difficult balance to achieve.

SAP could benefit from the addition of some of the flexibility and

added detail which dynamic simulation tools have.

3.7 Inverse Dynamics Energy Assessment and Simulation (IDEAS)

UK Building Professionals are familiar with SAP. The SAP user interface is easy to use (E.G. Wall = area + U-Value) and is defined by a worksheet which lets you see what changes with different parameters. There are some concerns about the accuracy of some of its results particularly for very energy efficient modern homes (AECB, 2008).

DSMs can provide very detailed results but may suffer from a steep learning curve and over parameterisation (Counsell et al., 2010). There is a gap between the current SAP methodology and dynamic simulation methods for a new advanced energy modelling of domestic systems method.
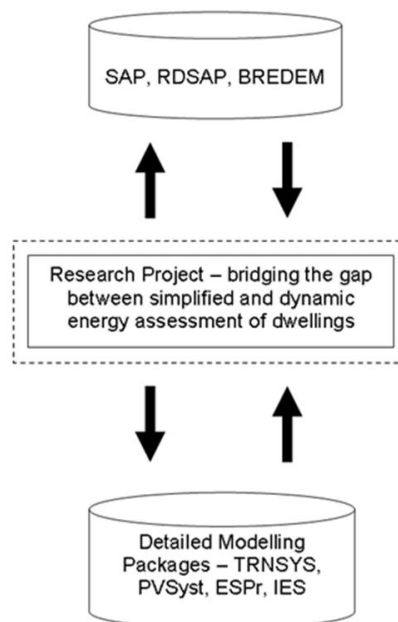
Figure 3.4 - Bridging the gap between simplified and dynamic energy assessment of dwellings

The drive towards a low carbon home has seen dwellings increasingly utilise many different systems simultaneously, such as MVHR, advanced heating systems and applications of renewable energy. The use of such systems simultaneously can increase the complexity of their control. Understanding the

dynamics and sizing of these systems at the conceptual design stage will allow for better design. **Assessing the dynamics of such systems in relation to energy consumption is an area where simplified methods such as SAP are limited.**

IDEAS is a simplified dynamic method of assessing the controllability of a building and its servicing systems, such as ventilation, heating and renewable systems. The fundamental difference in the approach taken in this dynamic model is the use of Inverse Dynamics and the RIDE perfect control algorithm. This dynamic method produces SAP compliant results and looks to suggest where advanced controllability of dwelling systems and a dynamic framework could supplement SAP. As highlighted in figure 3.5, uncertainty is an issue for both complex and simple calculation methods; the new IDEAS method will aim to reduce uncertainty where possible.
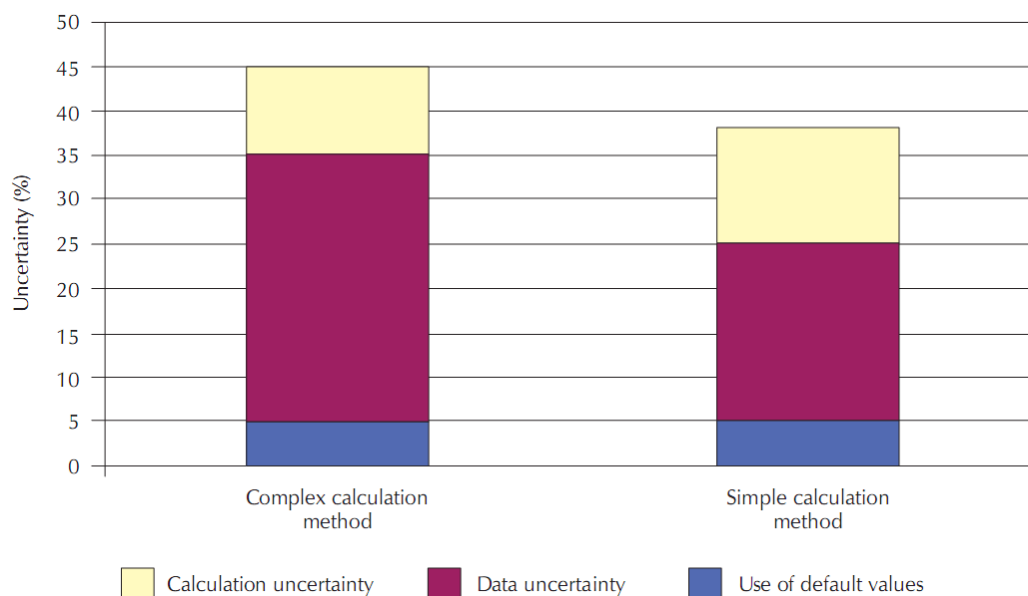
Figure 3. 5 – Comparison of uncertainty of results with complex and simple calculation methods. Adapted from source (Hitchin, 2010).

The knowledge for this method has been transferred from design processes and methods used in the design of aircraft flight control systems (Counsell, 1992) to

establish a modelling and design process for dwellings and its systems. IDEAS is underpinned by a holistic approach to the mathematical modelling of the dynamics of the building and its systems. This model is used to analyse the controllability of a dwelling using Non-linear Inverse Dynamics RIDE based controller design methods used in the aerospace and robotics industry.

The major control theory areas which feed into the RIDE methodology are presented in Figure 3.6. The major control theory areas are described in detail in (Franklin et al., 2010) and are summarised in Appendix F of this thesis. The development of the various control theory areas leading to RIDE are presented in (Khalid, 2011). RIDE is fully described and an example of the use of RIDE in the design of autopilots for high performance missiles is presented in (Bradshaw and Counsell, 1992).
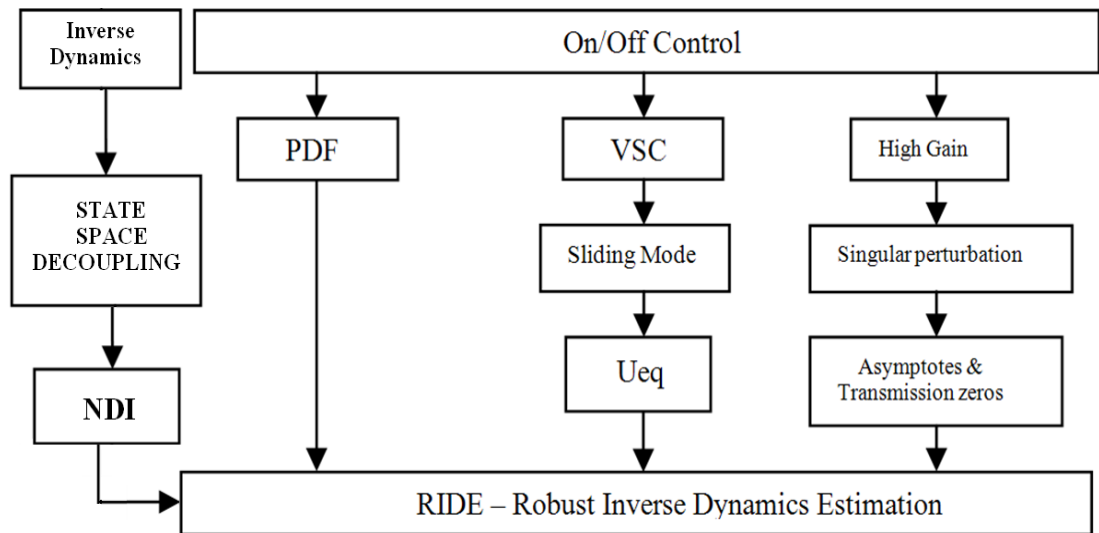
Figure 3.6 – Block Diagram of the major components which feed into the RIDE Methodology, defined in (Khalid, 2011). Appendix F also provides further detail on these components.

Past uses of the RIDE controllability algorithm have been mainly focused on controllability of aerospace applications. There is wealth of experience and literature on the use of RIDE to control aerospace applications. The application of RIDE to a methodology such as SAP to create an adaptable development environment such as IDEAS is novel. The use of RIDE allows the same controllability experience to be used in a buildings environment as was

used in aerospace. RIDE has been used in the past to calculate aspects of aerospace controllability where limits and disturbances are in place but the RIDE based controller can perfectly deal with them: For example there are power limits associated with a missile and there are constraints which the missile must deal with such as the impact of wind. By transferring the RIDE theory to buildings, and using this as a basis for the IDEAS framework (which is then calibrated with SAP) it is possible to apply many of the same techniques to a building environment. The missiles power limits can be contrasted with the power limits of a heating system, the process of using RIDE is the same for each case. For a missile, the example of a disturbance of wind can be correlated to the disturbances which a dwelling must deal with: where dwelling disturbances can be seen to be in the form of free heat gains to the dwelling and external temperature. In IDEAS (and in a real dwelling) dynamic free heat gains will vary due to factors such as internal occupancy patterns, IT usage and solar gains based upon the emissivity of glazing. Similarly, the external temperature will fluctuate dynamically. The use of a RIDE perfect controller ensures that, in the same manner that a missile will stay on target, a SAP standard occupancy setpoint profile (or any entered profile that is wishes to be tracked just as a missile can follow any course) will be perfectly tracked.

As described in chapter 1, standard occupancy demand temperature has to be met for the SAP / IDEAS comparison to be valid. It is possible to compare results from SAP and IDEAS only if the SAP standard occupancy profile can be met by IDEAS perfectly. The issue which is raised by this is 'how do we control the dwelling so that a standard occupancy profile is met?' To answer this question, the following defined challenges are required to be met:

- A new dynamic model, IDEAS, is required to derive the perfect control law RIDE; without this new model we cannot solve the problem.

- o A model which maps into control theory is required. With this new model we can then use Inverse Dynamics to find the perfect control law RIDE (Muir and Bradshaw, 1996).

- o With the perfect control law RIDE, IDEAS can perfectly track the SAP standard occupancy profile. This is required for a fair comparison to be made between IDEAS and SAP. No other energy calculation method has a perfect control law integrated into the method.

- The challenge is to create and then validate this model with SAP.

The focus of this thesis is the development of a new Inverse Dynamics based modelling environment, IDEAS, which can be represented in state space and allows the perfect control law RIDE to be employed. The IDEAS method with the RIDE perfect control law algorithms defined could be implemented in various programs such as Microsoft Excel, Matlab / Simulink or even in complex detailed DSMs such as ESP-r and IES. Verification and calibration of the IDEAS model would be possible using results from many other methods such as ESP-r, IES, PHPP, SBEM or SAP. This thesis will select SAP as the exemplar comparison methodology and seek to develop the new method and then calibrate results with SAP across a range of modelling parameters. The focus of this research is therefore domestic properties but IDEAS could also be applied towards commercial buildings and IDEAS could be applied with different assessment methods. The following chapter details the research and development of the IDEAS model and its subsequent verification and calibration with SAP.

CHAPTER FOUR

4 ADVANCED ENERGY MODELLING OF DWELLINGS:

Inverse Dynamics based Energy Analysis and Simulation (IDEAS)

4.1 Introduction

This chapter describes a new simplified single zone dynamic method of assessing the controllability and energy estimation of a dwelling and its servicing systems: IDEAS. This method integrates with the SAP methodology and produces dynamic results which are comparable to SAP. From this the IDEAS model looks to suggest where advanced controllability of dwelling systems and a dynamic framework could supplement SAP.

The knowledge for this method has been transferred from design processes and methods used in the design of aircraft flight control systems (Counsell, 1992) to establish a modelling and design process for dwellings and its systems. The chapter describes a holistic approach to the modelling of the non-linear and linear dynamics of the integrated building and its systems. This model is used to analyse the controllability of a dwelling using Non-linear Inverse Dynamics controller design methods used in the aerospace and robotics industry.

For a fair comparison with SAP, the IDEAS model must satisfy the comfort requirements. This is only possible by the use of the use of a Non-linear Inverse Dynamics controller and the perfect control law RIDE. With the perfect control law RIDE, IDEAS will perfectly track the comfort requirements. This novel work is not currently possible in other dynamic simulation methods.

4.1.1 Rationale of a Dynamic Approach to enrich SAP

The SAP Methodology is well established and is the culmination of three

decades of research commencing with BREDEM 1 (Uglow, 1982, Uglow, 1981). SAP is based on BREDEM (Building Research Establishment Domestic Energy Model). BREDEM 12 and BREDEM 8 have been described in depth (Anderson et al., 2001a, Anderson et al., 2001b). It is the recognisable method used in the UK to generate EPCs and for building professionals to meet Buildings Compliance. The UK buildings industry is familiar with SAP. The rationale of the approach documented in this chapter is to work with SAP and not against it. Due to the role of SAP, it is possible to work within the current regulatory framework by utilising the current SAP procedure as a foundation for the IDEAS Methodology.

SAP is assumed to be fully steady state, but in fact, SAP has many factors (inherited from BREDEM) which are used dynamically to calculate factors such as the Mean Internal Temperature (MIT) of the dwelling or the responsiveness of a heating system. The current SAP methodology uses a heating systems controllability rating to help derive the MIT of a dwelling. The rationale taken with this dynamic approach for SAP is to augment the current SAP method by creating a dynamic framework. With IDEAS it is possible to take into account statistical parts of the model such as impact of casual heat gains and solar gains by inheriting this from the current SAP model. Therefore, it is possible to create a model which is more advanced but is also backwards compatible with the SAP. The underlying theory is that the use of more detailed data in the IDEAS model will produce more detailed results. A methodology is only as accurate as the foundation of data upon which it rests.

There is also scope for a dynamic version of SAP to be used at a building design stage; there is currently no design version of SAP. Controllability assessment at the conceptual design stage will help to prevent current problems of poor control and high-energy costs that arise later in the detailed design

phase or at post construction stage. The cost of removing poor control performance in the later stages of design is normally excessive and must be avoided if possible (French, 1999).

The buildings industry uses the SAP methodology to calculate a rating for Energy Efficiency and Environmental Impact of that specific dwelling. The SAP methodology does not currently allow for advanced controllability of systems to be modelled. In order to achieve this, a simplified mathematical model is required with enough detail to know which factors are affecting the controllability. The rationale of IDEAS is to initially use a linear thermodynamic model with the non linearities associated with power limitations such as there is no cooling system. **IDEAS is a nonlinear dynamic model.**

4.1.2 Inverse Dynamics in Microsoft Excel

The fundamental difference in the approach taken in this dynamic model is the use of Inverse Dynamics (ID) and the RIDE perfect control algorithm. The use of ID and RIDE allows for the perfect control at each model timestep. At each timestep there is no need to solve an iterative or numerical process. By using ID, the value at each model timestep is known. This is very powerful and also allows IDEAS Dynamic Simulation to be put into Microsoft Excel.

Figure 4.1 – Inverse Dynamics; the Control System calculates the input required for a desired input

Without this formula for ID it would be impossible to place this model in Microsoft Excel. ID is an enabler, which allows IDEAS results to be calculated at each timestep. Detailed DSMs are a complex unfamiliar environment for many in the buildings industry and for the majority of the users of SAP

(Counsell et al., 2010). Microsoft Excel is an environment that many users will be familiar. It can be seen that there are other tools (such as PHPP and SBEM) using excel due to the simplicity of operation, familiarity of environment and high installed user base it provides.

4.2 METHODOLOGY

4.2.1 Building Physics and Mathematical 3rd Order Model

A fundamental building physics model was created to represent heat transfer between the dwelling and the outside environment. The differential equations were derived from first principals. Once differential equations were created they were converted into state space for controllability analysis.

The IDEAS model is specifically developed to allow the controllability of a dwelling and its servicing systems to be simulated in detail. In this thesis the development and philosophy of the IDEAS model is presented leading to a comparison with SAP that confirms that IDEAS produces SAP compliant energy ratings. It would also be possible to use the IDEAS method to enrich other predominately steady state methods, such as SBEM or PHPP, or any of the various simplified methods that are employed throughout the world; such as those employed in meeting the EPDB or Energy Performance of Buildings (EN13790) requirements. (Míguez et al., 2006, U.S. Department of Energy, 2011, European Committee For Standardization, 2008). The IDEAS model describes the energy and mass balance of air in the dwelling having a heating system. The assumptions inherent in constructing this model are numerous, as is the case with all building simulation tools as highlighted over the previous chapters. However, the purpose of the model is not to emulate future reality and base design decisions around it, as advanced integrated software packages, such as ESP-r (ESRU, 2011a) already exist.
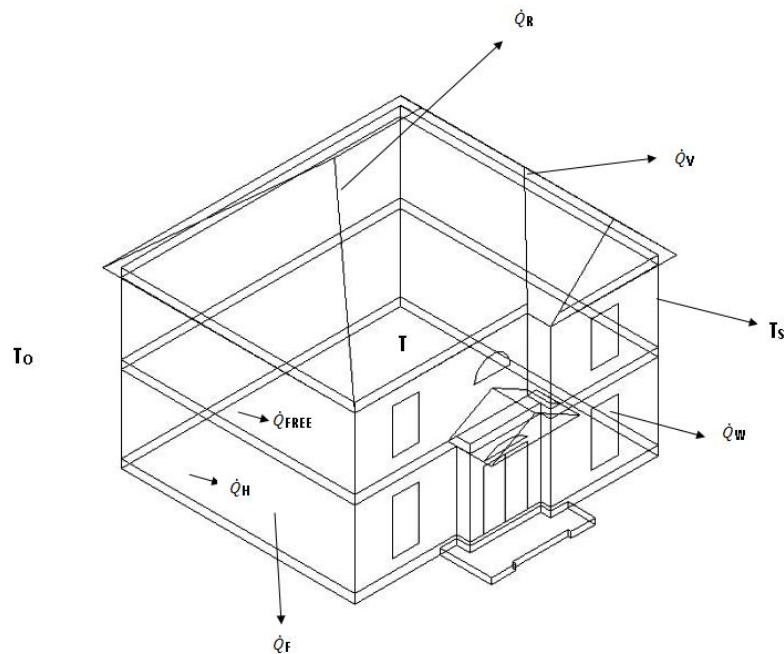
Figure 4.2 - Relationships which can affect the Energy Estimation of Dwellings

The simplified model assumes that the indoor zone air is fully mixed at constant pressure and is stratified for natural ventilation. Relative Humidity is not recorded in IDEAS, or SAP; IDEAS is based upon the boundary conditions of SAP but there is scope to extend the model. The dwelling glazing, roof and floor are considered to be in steady state, using U-Values taken directly from SAP. This leads to far less complex dynamic equations, but detailed enough to analyse controllability. Since IDEAS uses U-Values taken from SAP, the IDEAS model is based upon the conductive heat transfer between modelled elements. At each timestep, the furniture & internal mass in the dwelling is modelled in addition to the structure and air temperature.

4.2.2   Heat Flow through the Dwelling

The walls are sources of heat storage. The heat transfer is between the wall temperature and the internal temperature. Heat from external air is stored in the structure. When the temperature drops in the zone the heat is transferred into the room. In the same way when the wall temperature drops below the room temperature then heat is transferred to the wall.

It is assumed that the energy stored in windows, roof and floor are all

negligible compared with the air mass and structure, such that:

Windows Heat Loss is:

$$\dot{Q}_w = U_w A_w (T(t) - T_o(t))$$

(1)

Where Floor Heat Loss is:

$$\dot{Q}_F = U_F A_F (T(t) - T_g(t)) \quad *$$

(2)

Where Roof Heat Loss is:

$$\dot{Q}_R = U_R A_R (T(t) - T_o(t))$$

(3)

Where Furniture and Internal Mass Heat Loss is:

$$\dot{Q}_{FT} = U_{FT} A_{FT} (T(t) - T_{FT}(t))$$

(4)

The above equations state that there is constant heat loss through windows, furniture and internal mass, roof and floor and thus these building elements are always in steady state condition.   This assumption fits with U-Values and their use in SAP.   The heat loss through a solid wall is approximated by one energy store, the thermal mass of the bricks and the overall U-Value for conductions through the wall. The focus of the method is for a structure of uniform material; hence one node for Ts is used.
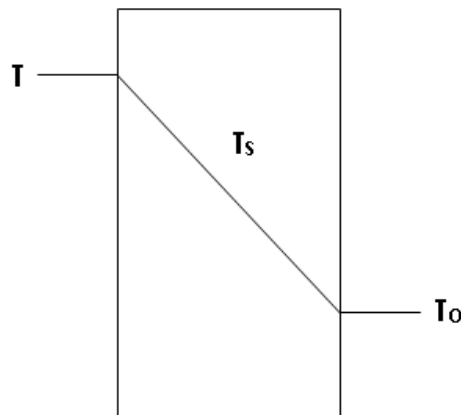
Figure 4.3 - Relationship between Temperature inside and Outside of Solid Wall of a Home.

---

* Tg is assumed to be To. IDEAS is based upon the boundary conditions of SAP.

4.2.3 Rate of Change of Stored Heat

Thermal corner effects are neglected so that internal and external wall areas can be assumed the same. U-Values (overall thermal transmittance coefficient) are used to model the heat transfer through the building fabric. While the thermal resistances and thermal capacities can be calculated, a weighted average of these resistances and capacities was used for a single capacity equivalent of a multi-layer wall construction to simplify the model for controllability analysis.

The rate of heat stored in the bricks is:

$$\dot{Q}_{STORED} = M_S C_S \frac{dT_S(t)}{dt} \tag{5}$$

This also equates to the difference between the rate at which heat is entering and leaving the wall:

$$\dot{Q}_{STORED} = 2U_S A_S (T(t) - T_S(t)) - 2U_S A_S (T_S(t) - T_o(t)) \tag{6}$$

Where a factor of 2 in equation (6) is used to prevent the heat transfer being halved at steady state (Khalid, 2011). Such that:

$$\frac{M_S C_S}{2} \frac{dT_S(t)}{dt} = U_S A_S (T(t) - T_S(t)) - U_S A_S (T_S(t) - T_o(t)) \tag{7}$$

When the rate of change of the structure temperature (Ts) is zero (steady state mode assumes that the structural temperature of a dwelling is constant), SAP equivalent results should be produced. When the wall temperature has reached a steady state value, this as expected will be given by:

$$T_S(t) = \frac{T(t) + T_o(t)}{2} \tag{8}$$

Where To is the external zone temperature connected to the wall, and T is the temperature inside the dwelling; Heat Loss from the room:

$$\dot{Q}_{RoomHeatLoss} = 2U_S A_S \left(T(t) - \left(\frac{T(t) + T_o(t)}{2} \right) \right) \tag{9}$$

Steady State structure heat loss:

$$\dot{Q}_{Sss} = U_S A_S (T_S(t) - T_o(t)) \tag{10}$$

4.2.4 Rate of Change of Air Temperature

In IDEAS, the assumption is made that the air is fully mixed at constant pressure so that we have a constant temperature in the building. The air in the room is described as:

$$M_A C_A \frac{dT(t)}{dt} = \dot{Q}_H(t) + \dot{Q}_{FREE}(t) - \dot{Q}_S(t) - \dot{Q}_F(t) - \dot{Q}_R(t) - \dot{Q}_W(t) - \dot{Q}_V(t) - \dot{Q}_{FT}(t) \tag{11}$$

Where $\dot{Q}_{FREE}(t)$ is free heat gain from:

- Appliances
- People
- Lighting
- Solar Gain

For which normal SAP derived figures are updated so that real measured data is used, at a sampling resolution of 5 minutes. Climate data for Sheffield, UK was imported into IDEAS, using a data file from Meteonorm

(Meteotest, 2011); this was used to provide a figure for Solar Gain. Appliance Gains were taken from an International Energy Agency / Energy Conservation in Buildings and Community Systems Program (ECBCS) Annex 42 study based upon real UK test data for 69 monitored dwellings (IEA, 2006). Metabolic Gains are calculated based upon the number of occupants in each particular dwelling. This figure is derived from the SAP provided Total Floor Area figure TFA. Lighting gains are taken into consideration in the Appliance Gains figure. $\dot{Q}_H$ is the heating system under control and $\dot{Q}_V$ is from the natural infiltration (air leakage through the introduction of outside air into a dwelling).

4.2.5 Controllability Analysis

The differential equations are factorised and simplified for controllability analysis.

Temperature of Internal Dwelling Air:

$$M_A C_A \frac{dT(t)}{dt} = \begin{bmatrix} \dot{Q}_H + \dot{Q}_{FREE} - \dot{M}_V C_A (T(t) - T_o(t)) - 2U_S A_S (T(t) - T_S(t)) \\ -U_F A_F (T(t) - T_o(t)) - U_R A_R (T(t) - T_o(t)) \\ -U_w A_W (T(t) - T_o(t)) - U_{FT} A_{FT} (T(t) - T_{FT}(t)) \end{bmatrix} \tag{12}$$

Temperature of Dwelling Structure:

$$M_S C_S \frac{dT_S(t)}{dt} = 2U_S A_S (T(t) - 2T_S(t) + T_o(t)) \tag{13}$$

Temperature of Dwelling Furniture & Internal Mass:

$$M_{FT} C_{FT} \frac{dT_{FT}(t)}{dt} = U_{FT} A_{FT} (T_a(t) - T_{FT}(t)) \tag{14}$$

To Simplify (12), Temperature of Internal Dwelling Air, the brackets are multiplied out and the equation is factorised in terms of variables: $\dot{Q}_H$, $\dot{Q}_{FREE}$, T, T_S , T_{FT} and T_o:

$$\frac{dT(t)}{dt} = a_{11}T(t) + a_{12}T_S(t) + a_{13}T_{FT}(t) + b_{11}\dot{Q}_H + d_{11}\dot{Q}_{FREE} + d_{12}T_o(t) \qquad \textbf{(15)}$$

Where Constants are defined as follows:

$$a_{11} = \left[\frac{-\dot{M}_V C_A - 2U_S A_S - U_F A_F - U_R A_R - U_w A_W - U_{FT} A_{FT}}{M_A C_A} \right]$$

$$a_{12} = \left[\frac{2U_S A_S}{M_A C_A} \right] \quad a_{13} = \left[\frac{U_{FT} A_{FT}}{M_A C_A} \right] \quad b_{11} = \left[\frac{1}{M_A C_A} \right]$$

$$d_{11} = \left[\frac{1}{M_A C_A} \right] \quad d_{12} = \left[\frac{\dot{M}_V C_A + U_F A_F + U_R A_R + U_w A_W + U_{FT} A_{FT}}{M_A C_A} \right] \qquad \textbf{(16)}$$

The same procedure of simplification is carried out for (Temperature of Dwelling Structure), equation (13):

$$\frac{dT_S(t)}{dt} = a_{21}T(t) + a_{22}T_S(t) + d_{22}T_o(t) \qquad \textbf{(17)}$$

Where a_{21}, a_{22} and d_{22} are given by:

$$a_{21} = \left[\frac{2U_S A_S}{M_S C_S} \right] \quad a_{22} = \left[-\frac{4U_S A_S}{M_S C_S} \right] \quad d_{22} = \left[\frac{2U_S A_S}{M_S C_S} \right] \qquad \textbf{(18)}$$

The same procedure of simplification is carried out for (Temperature of

Dwelling Furniture and Internal Mass), equation (14);

$$\frac{dT_{FT}(t)}{dt} = a_{31}T(t) + a_{33}T_{FT}(t) \tag{19}$$

Where a_{31} and a_{32} are given by:

$$a_{31} = \left[\frac{U_{FT}A_{FT}}{M_{FT}C_{FT}}\right] \qquad a_{33} = \left[-\frac{U_{FT}A_{FT}}{M_{FT}C_{FT}}\right] \tag{20}$$

4.2.6   State Space Model

In order to apply the aerospace controllability science (Bradshaw and Counsell, 1992), the mathematical model detailed in dynamic equations must be represented in linear State Space representation (Franklin et al., 2010).

$$\dot{x}(t) = Ax(t) + Bu(t) + Dd(t) \tag{21}$$

Where (21) is the state equation, $\dot{x}(t)$ is the State Vector, A is the State Matrix, B is the Input Matrix and D is the Disturbances Matrix. $u(t)$ is the system input and $d(t)$ is the disturbances vector.

$$y(t) = Cx(t) \tag{22}$$

Where (22) is the output equation for output $y(t)$ and C is the output state matrix.

This state space model describes the dynamic behaviour of the building and its systems for a small amplitude perturbation δ about a steady state equilibrium condition. Where y(t) is the measured output vector, x(t) is a vector of state variables, u(t) is a vector of system inputs (i.e. controller outputs) and d(t) is a vector of disturbances. A, B and D are time invariant matrices consisting of constants which have been derived in the Controllability Analysis

section. The linear statespace model (21) describes the dynamic behaviour of the dwelling for a small amplitude perturbation δ. The two equations can be put together in state space form:

$$
\begin{bmatrix} \dot{T}(t) \\ \dot{T}_S(t) \\ \dot{T}_{FT}(t) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix} \begin{bmatrix} T(t) \\ T_S(t) \\ T_{FT}(t) \end{bmatrix} +
$$
$$
\begin{bmatrix} b_{11} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \dot{Q}_H(t) \end{bmatrix} + \begin{bmatrix} d_{11} & d_{12} \\ 0 & d_{22} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{Q}_{FREE}(t) \\ T_o(t) \end{bmatrix}
$$

(23)

4.3 CONTROLLABILITY

The engineering science presented in this thesis is based on 'A Perfect Control Philosophy' (Khalid, 2011, Counsell et al., 2010, Counsell, 1992). This philosophy aims to establish for a given design, if perfect control is feasible whilst maintaining stability for the closed loop control system. The value of this feasibility strictly is in allowing the designer to assess the ease in which perfect control could be achieved. The assumption is that the easier it is to achieve perfect control then in reality the easier the real system will be to control. The author believes that is a sound and thorough philosophy to adopt to establish the controllability of a dwelling.

In order to estimate the energy required to maintain an ideal standard occupancy temperature and time profile (such as that defined by BREDEM), the dynamics of the system have to be inverted to establish what power input is required at a system time to achieve the target temperature. This requires the solution to PERFECT control, which can be obtained using RIDE (Muir and Bradshaw, 1996) control algorithms. The RIDE Theory utilises Inverse Dynamics, firstly defining the system output in state-space form. **A feedback control system can only control (i.e. track) what it feeds back as measured system outputs. Thus, to analyse the controllability of the measurements,**

they must be defined. **In SAP, it is not stated what the MIT is. For the controllability of the 3rd Order model a temperature is required to be tracked.** In this case, it has been hypothesised that the SAP MIT is the air temperature. Therefore if the dwelling air temperature is the system output:

$$Y(t) = Cx(t) \tag{24}$$

$$Y(t) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} T(t) \\ T_S(t) \\ T_{FT}(t) \end{bmatrix} \tag{25}$$

$$Y(t) = T(t) \tag{26}$$

Here, the air temperature T is controlled, so $Y(t) = T(t)$ (equation 26). **From equation (25) it is clear that the temperature controlled in this example is 100% air temperature. The temperature controlled has no element of either structure or furniture & internal mass temperatures. The aim is to measure and control the energy requirement of the dwelling so that the demand temperature is met.** To invert the static space model the perfect inverse control law RIDE is applied:

$$U(t) = g(CB)^{-1} \big(v(t) - y(t) \big) + U_{eq}(t) \tag{27}$$

Equation (27) and $U_{eq}(t)$ inverts the building model. Equation (27) is the control algorithm where:

$U(t) =$ Heater demand, determined by the controller to maintain the required air temperature. U(t) will provide the heat required at each model timestep to meet that temperature which is tracked. For calculation purposes, U(t) is limited by the boundaries of the heating system; for example if a gas boiler is the heating system then the

boundaries could be 20kW with a lower limit of 0kW as there is no cooling. This highlights the interaction between a simplified building model and control theory: the whole building model is inverted by equation (27) so that the exact heat required to perfectly track the provided setpoint is given. This heat requirement is then limited by the realistic limits of real heating systems to allow sizing of systems in IDEAS which is not possible in SAP. Sizing of systems could be the basis of a future application within the building industry to assess the impact of sizing of heating systems to a buildings MIT and energy consumption.

$g(CB)^{-1}$ = It is referred to as the Controller Gain Matrix where, g is the Global Scalar Gain and determines the speed of the closed loop response. C is the C Matrix and B is the B Matrix; therefore all of the inputs (B Matrix) and outputs (C Matrix) of the dwelling modelled are inverted.

$(v(t) - y(t))$ = Difference between what is required $v(t)$ (the SAP defined standard occupancy setpoint), and what is measured and outputted $y(t)$ (i.e the actual dwelling air temperature). This is known as the error signal.

$U_{eq}(t) = -(CB)^{-1}CAx(t) - (CB)^{-1}CDd(t)$ This will provide extra help (it is an estimate) to the controller to calculate the correct heater setting (i.e. U(t)), to raise the air temperature to the required level (V). CB = C Matrix * B Matrix, CA = C Matrix * A Matrix, CD = C Matrix * D Matrix. This will also help the controller deal with disturbances and compensate for slow dynamics, for example those associated with a buildings structure.

CB will tell the direction of the asymptotes, whilst CB inverse is used to align the asymptotes towards the stable region. In this proposed method,

advanced controllability is used to align the direction of the asymptotes towards the negative real axis of the root locus. This is where the system is PERFECTLY controllable. Appendix F (Fundamental Control Theory Areas researched in the development of IDEAS) details the control theory concepts researched in IDEAS and highlights the links between controllability used aerospace design and buildings.

4.3.1 **Closed Loop System Response with ID Control Law**

When a system is controlled perfectly with the RIDE control law, the closed loop system response is a perfect first order system such that:
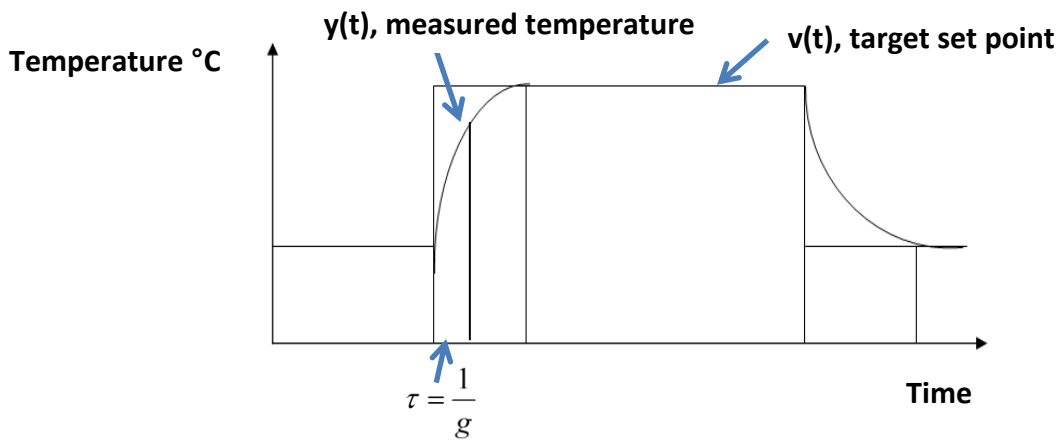
Figure 4.4 - System Response: Step Response Profile, where τ is the time constant

Figure 4.4 highlights the controller time constant τ (tor) which is 1/g. The g value highlighted in Figure 4.4 is the same g value described in equation (27): the g value can be used in IDEAS as a measure of the responsiveness of a heating system. An iterative process, involving comparisons with SAP outputs for various heating systems with various factors for responsiveness, was used to derive values for g which are representative for heating systems with varying levels of responsivity. It was found that for a heating system which responds slowly, such as an underfloor heating system, a very low g value will be used: g= 2.2222e-004 is appropriate for a slow acting system. For a heating system which responds quickly, such as a direct acting electric heating system, a higher g value would be used: g=0.0011 is appropriate for a fast acting system. This

allows the responsiveness of a heating system to be directly entered into the IDEAS model, this is imperative for the addition of Optimum Start to the IDEAS framework:

$$\frac{y(s)}{v(s)} = \frac{g}{s+g} \Rightarrow y(t) = v(t)\left(1 - e^{-gt}\right)$$

(28)

Where: $\dfrac{y(s)}{v(s)} = \dfrac{g}{s+g}$ is figure 4.4 in transfer function terms

$y(t)$ = measured output vector (the actual dwelling air temperature)

$v(t)$ = is the target room temperature (the profile tracked, where we want the measured output vector to be)

$$\text{As } T(t) \longrightarrow \infty, \quad y(t) \rightarrow v(t)$$

(29)

Equation (29) states as the temperature of the air in the dwelling tend towards infinity, the system output (the temperature of the air which varies with time) tends to the target room temp (which also varies with time).

$\dfrac{1}{g}$ is the time constant of the closed loop response. From this the step response as detailed in figure 4.4 can be seen produced in IDEAS in figure 4.5.
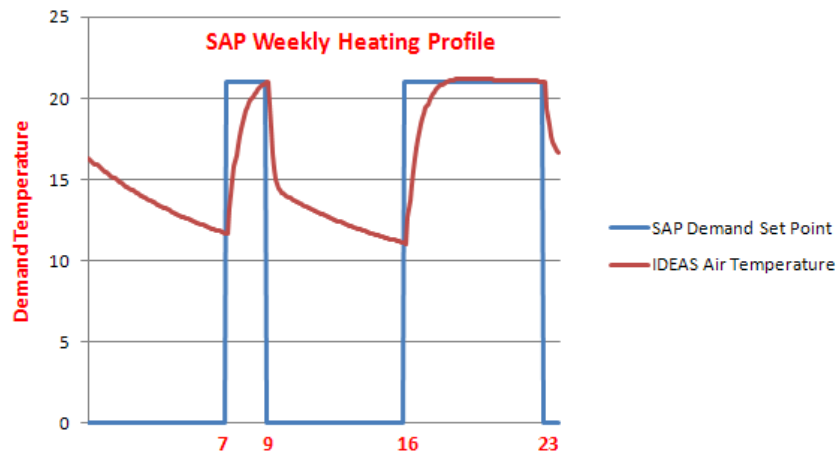
Figure 4.5 - Output from IDEAS model; Transient response highlights the tracking of a SAP daily setpoint on cold winters day

97

Figure 4.5 demonstrates IDEAS tracking air temperature. The step response profile demonstrates that the responsivity of the heating system can be assigned, and therefore allow the heating system to integrate within the SAP environment. Parameter g is the heating system response, which can be entered in minutes, and v(t) is the target room temperature. $\frac{1}{g}$ is the response time which has an effect – this is already built into SAP. BREDEM 12 records the responsiveness of a primary heating system (Rp) on scale from fully responsive (1) to completely unresponsive (0). Thus, this relationship can be used to back substitute into the control law as a prediction to take into account the system's response characteristic. In this case let us assume that g is very large as in the case of a direct electric heating system. Thus the control law in this case is given by:

$$U(t) = \dot{Q}_H(t) = \begin{bmatrix} gM_A C_A \left(v(t) - T(t) \right) \\ -\left(\begin{array}{c} -\dot{M}_V C_A - 2U_S A_S \\ -U_F A_F - U_R A_R - U_w A_W \end{array} \right) T(t) \\ -\left(2U_S A_S \right) T_S(t) - \left(U_{FT} A_{FT} \right) T_{FT}(t) \\ -\dot{Q}_{FREE}(t) - \left(\begin{array}{c} \dot{M}_V C_A + U_F A_F + U_R A_R \\ +U_w A_W + U_{FT} A_{FT} \end{array} \right) T_o(t) \end{bmatrix} \tag{30}$$

4.3.2 Optimum Start

Optimum start is required so that the IDEAS model can satisfy the comfort criteria as determined by SAP. Optimum start is a technology frequently employed especially in commercial buildings (Yang et al., 2003, Kummert et al., 2001, Dexter, 1981). An example of its use in a real life situation would be when an office zone has to reach a specific temperature (e.g. 21°C) at a set time (e.g. 8am): if the temperature of the zone is 15°C at 7:59am and if the heating system is switched on at 8am then it is unlikely that the desired 21°C will be reached by

8am. The mechanism used to compensate for the fact that there will be a delay from the time that a heating system is switched on; to the time that the temperature in a zone reaches a desired setpoint is Optimum Start. In the example of the office zone, the optimum start controller may compute that the heating system should in fact switch on at 7:30am so that the desired 21°C is met at 8am. In IDEAS an Optimum Start algorithm can take into account all of the parameters of the modelled dwelling such as the U-Value of the structure and also the disturbances such as external temperature and free heat gains.

The challenge is to include an Optimum Start algorithm to the IDEAS model so that SAP compliant results can be achieved for all heating systems and so that heating systems which respond poorly can be accurately modelled. Minimal optimum start is required for fast acting heating systems (heating systems which respond quickly), such as direct acting electric heating. However, optimum start is critical to a slow acting heating system (heating systems which respond slowly), such as underfloor heating systems. Without optimum start it will impossible for a slowly responding heating system to meet the SAP comfort requirements as defined by the SAP standard occupancy profile, as defined in Figure 2.8 - BREDEM Weekday and Weekend heating profile for two zones. Optimum start is built into SAP and is taken into account by use of the responsiveness factor as highlighted in Figure 2.14 - SAP Table 4d - Heating Type and responsiveness for wet systems with heat supplied to radiators or underfloor heating. Optimum start will adjust the start time of a heating system so that a heating setpoint is always met in time. To add optimum start to IDEAS, we compensate for $\dot{Q}_H$ max where $\dot{Q}_H$ max is the maximum size of the heating system in Watts. The rate of change of temperature T, which varies with time (t); described as follows:

$$\dot{T}(t) = a_{11}T(t) + a_{12}T_S(t) + a_{13}T_{FT}(t) + b_{11}\dot{Q}_H(t) + d_{11}\dot{Q}_{FREE}(t) + d_{12}T_o(t) \quad \text{(31)}$$

For optimum start and optimum control of our heater, the requirement is to run the heating system ($\dot{Q}_H$) as hard as possible for as short a time as possible. Therefore:

$$\dot{Q}_H = \dot{Q}_H \, \text{max} \qquad \qquad \text{(32)}$$

The bigger the heater, the bigger the $\dot{Q}_H$ max and therefore the shorter the optimum start time will be. A bigger heater should be more responsive than a smaller heater. Introducing $\dot{Q}_H$ max into the responsivity analysis in SAP could help sizing of heater in a SAP framework. In IDEAS the $\dot{Q}_H$ max of a heating system (in Watts) is recorded along with and the responsiveness of a heating system in hours, g.

For optimum start, the following is required:
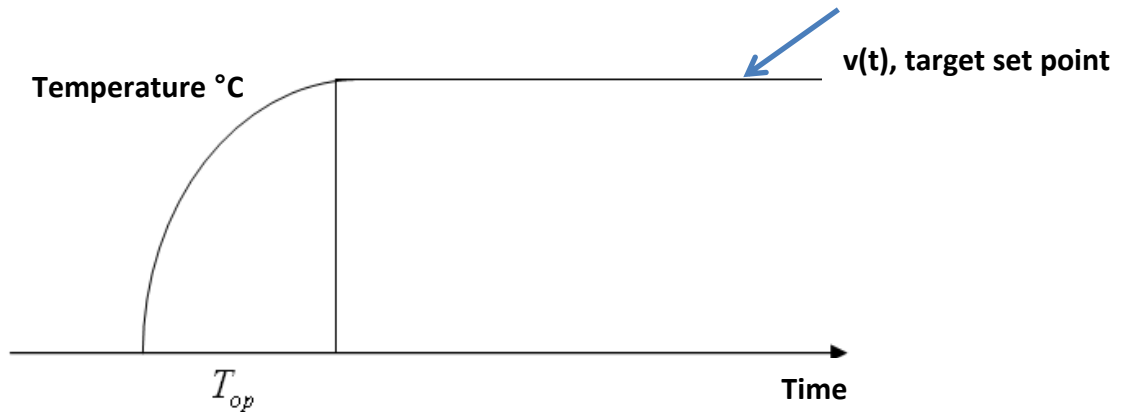
Figure 4.6 - Optimum Start Requirement

The optimum start requirement, T$_{op}$, as highlighted in Figure 4.6 cannot be shifted to be generic as the start temperature is unknown and the value of g can differ (due to the responsiveness of a system). So a ramp is added based upon the size of a heating system: Figure 4.7.
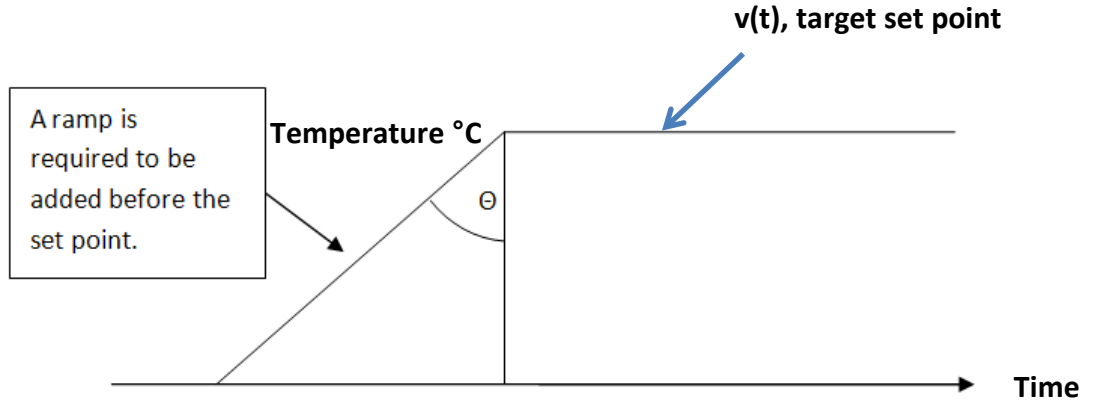
Figure 4.7 - Optimum Start, addition of a fixed ramp, where the ramp is the maximum output of the heating system. The internal zone temperature in the dwelling will hit the ramp where a higher internal temperature will hit the ramp at a higher level than a lower internal zone temperature.

The fundamental requirement of optimum start is to run the heating system at maximum power for as short as possible time. For controllability of the system the heating system is broken down into its fast and slow parts. Fast and Slow Decomposition of the Model:

$$\dot{T}_{MAX} = b_{11}\dot{Q}_H \max + (a_{11}T(t) + a_{12}T_S(t) + a_{13}T_{FT}(t) + d_{11}\dot{Q}_{FREE}(t) + d_{12}T_o(t)) \quad \text{(33)}$$

Where:

- $b_{11}\dot{Q}_H$ max is the controllable ramp (as shown in Figure 4.7) which is known based upon the b_{11} term is defined in equation (16) as $b_{11} = \left[\dfrac{1}{M_A C_A}\right]$ and $\dot{Q}_H$ max which is the maximum size of the heating system (W)

- $(a_{11}T(t) + a_{12}T_S(t) + a_{13}T_{FT}(t) + d_{11}\dot{Q}_{FREE}(t) + d_{12}T_o(t))$ is variable

The fast and slow decomposition of the model states that in the small time period where Optimum Start will be active, it is assumed that $b_{11}\dot{Q}_H$ max will dominate $(a_{11}T(t) + a_{12}T_S(t) + a_{13}T_{FT}(t) + d_{11}\dot{Q}_{FREE}(t) + d_{12}T_o(t))$ It is therefore assumed that in the period of time where Optimum Start is active, that the $(a_{11}T(t) + a_{12}T_S(t) + a_{13}T_{FT}(t) + d_{11}\dot{Q}_{FREE}(t) + d_{12}T_o(t))$ term when lumped together constitutes the slow modes of the heating system as they reach

steady state slowly; $b_{11}\dot{Q}_H$ max represents the fast parts of the heating system as they reach steady state quickly. Equation (33) sets a slope for the optimum start algorithm which is tracked by the heating system. The responsivity of the system is a combination of the amount of heat that can be delivered to the heater plus the effectiveness of the system itself (the systems time delay). Therefore a heater with an increased heat transfer for the same $\dot{Q}_H$ max will give a system with a higher responsiveness. It therefore could be possible to scale heating systems more accurately; a larger b_{11} term will give a more responsive system.

In the time frame within the Optimum Start Period it can be said that:

$$\dot{T}(t) = \dot{T}_S(t) = \dot{T}_{FT}(t) = \ddot{Q}_{FREE} = \dot{T}_o(t) = 0 \tag{34}$$

It is assumed that the rate of change of the Free Heats, Outside, Furniture and Internal Mass, Air, and Structure is equal to Zero, due to the fast and slow decomposition of the model for this Optimum Start Period

There are two main properties of a heating system to compensate for:

1. The Maximum Power of the system
2. The responsiveness of the system - The g factor – how stable the control system could be

In the above method (equation (34)) the size of the plant relative to the building (the parameters of the building) has been compensated for.

Figure 4.7 highlights the optimum start ramp to compensate for the maximum power of the heating system. The optimum responsiveness of the system is calculated, relative to the building. Compensation of the slope based upon the thermal lag of the system is required. Therefore the phase lag, which is the time constant of the system to react, is compensated for. The phase lag is

then shifted by $\dfrac{1}{g}$ to track the slope. This is the Steady State Tracking Error for a Ramp Input for a first order system (Franklin et al., 2010) where Figure 4.7 highlights the ramp which has to be tracked. A first order system with a time constant τ has a steady state tracking error of $\dfrac{1}{g}$ when tracking a ramp input. The response of a first order system lags the ramp input (Figure 4.7) by a period equal to the time constant, where the time constant τ is highlighted in Figure 4.4. Therefore, to track a ramp input it is necessary have pass the ramp input the time constant τ which is equal to $\dfrac{1}{g}$.

When heating a dwelling with a system with a very slow responsivity, such as underfloor heating, g will have to be set very low. And therefore the heating system will have to start earlier for a defined set point to be achieved. The maximum g setting which can be used without the system going unstable is the maximum performance which can be produced from a system with slow response, such as an underfloor heating system. A logical check is important in IDEAS to check that g is not infinity – if g was infinity then the optimum start time will be zero.
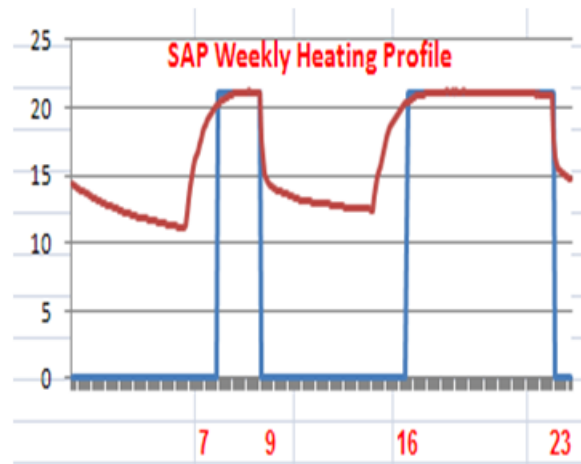
Figure 4.8 - Output from IDEAS model; Transient response highlights the tracking of a SAP daily setpoint– Optimum Start has now been added to IDEAS and so the SAP occupancy profile is perfectly met.

Figure 4.8 can be contrasted with figure 4.5 where it can be seen that IDEAS could not meet the SAP occupancy profile when modelling a slowly responsive system. Optimum Start implementation has resolved this issue.

4.4 IDEAS Implementation – 3rd Order Model

Equation (30) could be dynamically solved by Dynamics Modelling such as ESP and IES. An IDEAS model, created in Microsoft Excel is used to solve Equation (30) symbolically. In IDEAS, the building physics is represented by three linear Ordinary Differential Equations (ODEs); describing the Temperature of outside Air, Internal Air and Furniture & Internal Mass, which have been put into State Space form. Relating all the necessary parameters, Inverse Dynamics can be used to find out, for example, what instantaneous heat is required to meet a certain temperature. IDEAS is a linear model of the building, although the model as whole is non-linear. For example, constraints are placed into the model for maximum and minimum heat which can be delivered into the dwelling. Therefore the discontinuities associated with plant saturation for example are modelled.

4.4.1 Microsoft Excel – BREDEM 2009

The creation of a single zone version of BREDEM was required in excel to enable the comparison of IDEAS output with those expected from BREDEM / SAP. A two zone version of BREDEM 2009, implemented in Microsoft Excel, was supplied by the BREDEM development team at BRE Garston for developmental and comparative studies with the IDEAS framework. Work then commenced on re-engineering the 2 zone model into a single zone model for a fair comparison between the single zone IDEAS method.

This task was complicated and time consuming and highlighted issues with using Microsoft Excel as the basis of a complicated energy assessment tool. BREDEM 2009 in Microsoft Excel has three main sections, for input, calculations and reference tables. The total area covered by the three main sections is approximately 300 by 50 cells, giving a vast number of cells which require checking and potential modification. Creating a single zone version of BREDEM, was a difficult but fantastic learning experience which highlighted

that Excel can be used to host an energy assessment tool. The complete transparency into the BREDEM calculations used highlighted the benefit of using Excel as a development tool; unlike a detailed simulation tool such as IES-VE, total transparency of the methodology allowed for a far greater understanding of the method.

4.4.2 Microsoft Excel – 3rd Order IDEAS Model - Continuous RIDE

More demanding than the creation of a single zone BREDEM 2009 model was the creation of the 3rd Order IDEAS Model in EXCEL. This model was then integrated with the single zone BREDEM 2009 model. The process of creating the single zone BREDEM 2009 model and the 3rd Order IDEAS Model in EXCEL is detailed in Appendix E – Third Order Excel Model Definition. By amalgamating the two models into one Excel spreadsheet it was possible to reduce user input errors as values such as areas and U-Values need only be entered once for both models to calculate the energy use and resultant temperature of the dwelling. This allowed for a direct results comparison between the two methodologies.

4.4.3 3rd Order IDEAS Model in Excel:

Highly Insulated Standard Test Case – Summary

A new dynamic energy estimation model named IDEAS has been created. A single zone version of BREDEM 2009 has also been created. **IDEAS and BREDEM 2009 have been linked together in a novel manner using Microsoft Excel.** A good match was found between IDEAS and BREDEM with a highly insulated standard test case (STC) dwelling (as detailed in Appendix E). The values used for the highly insulated STC dwelling is detailed in Appendix H.

4.4.4 3rd Order IDEAS Model in Excel – Poorly Insulated Standard Test Case

To test the results from the IDEAS model and the comparison with BREDEM, a poorly insulated test case dwelling was modelled using both methods. The poorly insulated STC dwelling is defined in Appendix P. When the values as

detailed in appendix P were used in the IDEAS model in Excel, an instability was found was rendered the results from the IDEAS model, when using extreme values for a poorly insulated dwelling, unusable.

4.4.4.1 Time Delay Instability:

The longer the interval, the greater the potential for an instability; a time resolution of 5 minutes is set in the IDEAS model. At this time resolution, an instability is reached with the following values (used to represent a very poorly insulated Victorian Dwelling). Summary of U-values:

- Structure: 2.1W/m2K
- Roof: 2.3 W/m2K
- Windows: 5 W/m2K
- Floor: 0.7 W/m2K
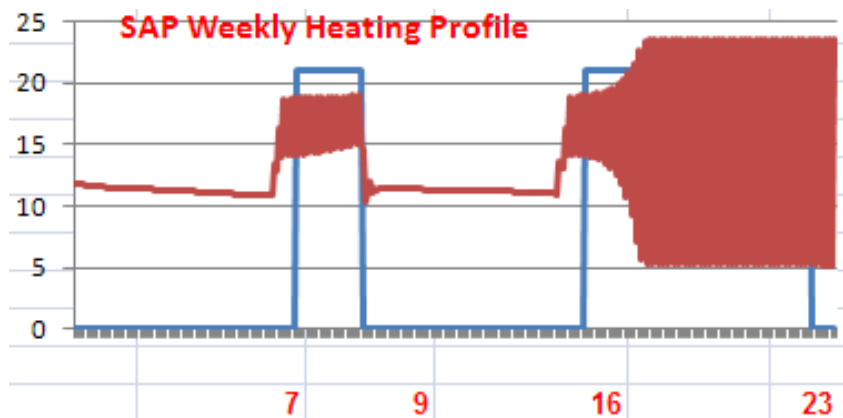
Figure 4. 9 - Air Temperature instability, Daily Example

The RIDE Control Algorithm is retrospective; it is one time frame behind. Therefore, a longer time delay will increase the opportunity for instability.

4.4.4.2 Conclusion of Continuous Model

Instabilities in the Continuous RIDE control algorithm were found with the use of certain parameters. Therefore, discrete time conditioning is required for the model to still operate at a 5minute time resolution. The time resolution is fixed in Excel as faster time resolution would result in a file which is unmanageable. The file size for the IDEAS model in Excel at a 5 minute time resolution is in the

region of 40Meg. The IDEAS model is still very fast to compute results (<15seconds on a 3 year old laptop) but a file of greater size will become unusable. Therefore, the focus is to implement a Digital version of RIDE in Excel and use this in place of the continuous version. With U-Values selected for the structure modelled in the range of 0.3 W/m²K -> 1.5 W/m²K, the 3rd order continuous IDEAS model performs well. With high U–Value used parameters such as 2.1W/m²K modelled for structure it is highlighted that the Continuous IDEAS model is unstable due to the 5 minute time resolution. Therefore, the IDEAS model is updated in Microsoft Excel so that the DIGITAL RIDE algorithm is used – this should allow for any U-Values to be used in IDEAS.

4.5   Digital RIDE Algorithm in Excel

A time delay is built into the algorithm to cancel out the time resolution delay. The Discrete Time Control Law for 5 minute sample period is required so that we can implement the Discrete Time RIDE Algorithm using Discrete Time Inverse Dynamics. The process of creating a Digital RIDE Algorithm in EXCEL is detailed in Appendix T – Continuous to Digital Transformation using a Zero-Order-Hold (ZOH). Now that Digital RIDE in the IDEAS model is functioning correctly in Microsoft Excel, IDEAS can now accept any U-Values or other values over any range, as passed from BREDEM.

4.5.1   IDEAS DIGITAL Monthly Energy Consumption vs. BREDEM:

Monthly Energy Consumption	DYNAMIC	BREDEM
January	4621.719	4120.35
February	4391.516	3534.24
March	3644.662	3243.34
April	2877.759	2610.33
May	1911.973	1806.28
June	1165.681	1144.97
July	608.9262	654.87
August	688.8825	729.00
September	1403.882	1329.24
October	2306.098	2158.53
November	3778.543	3188.76
December	4090.661	3783.58
TOTAL:	● 31490	○ 28303.48
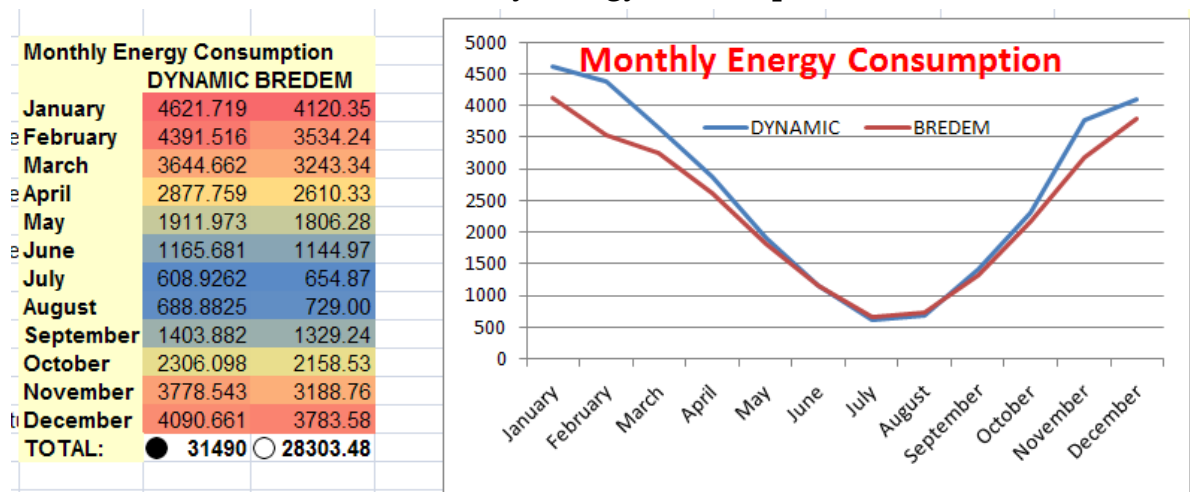
Figure 4. 10 - IDEAS DIGITAL Monthly Energy Consumption vs. BREDEM, highlighting a good curve fit but an Annual Energy Consumption Variation= 28303/31490 = 10%

4.5.1.1 *IDEAS DIGITAL Monthly Temperature vs. BREDEM:*

Mean Internal Temperature (MIT) over Heating Season (Where Heating Season = 12 Months in this example):

- IDEAS = 17.32° / BREDEM = 19.01°
- Annual Temperature Variation = 17.32/19.01 = 8%

4.5.1.2 *IDEAS Digital Air Temperature Instability*

Zone Air Averages	DYNAMIC	BREDEM	DIFF.	
January	287.95	14.95	17.59	-2.64
February	288.36	15.36	17.76	-2.41
March	289.26	16.26	18.32	-2.05
April	289.77	16.77	18.77	-1.99
May	290.99	17.99	19.51	-1.52
June	291.93	18.93	20.03	-1.10
July	292.86	19.86	20.48	-0.61
August	292.72	19.72	20.41	-0.69
September	291.68	18.68	19.87	-1.19
October	290.58	17.58	19.22	-1.64
November	289.37	16.37	18.27	-1.90
December	288.36	15.36	17.87	-2.51
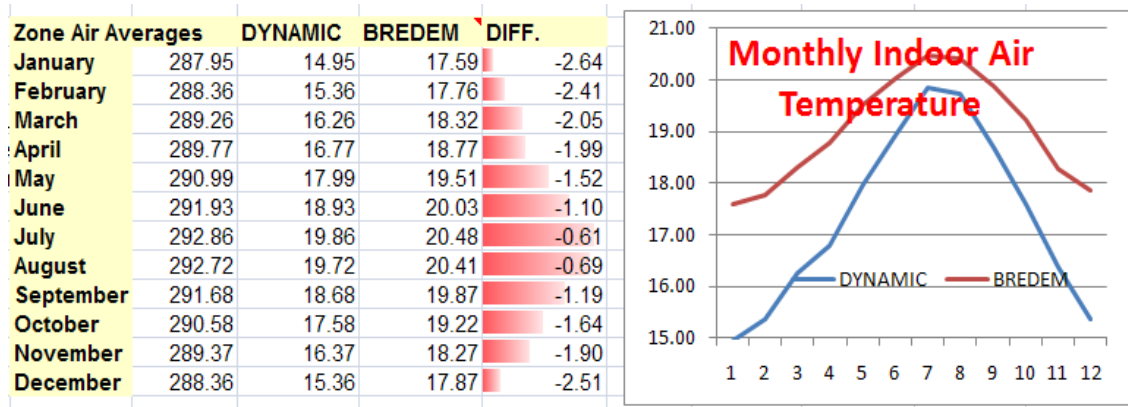
Figure 4.11 - IDEAS DIGITAL Monthly Indoor Air Temperature vs. BREDEM

Figure 4.11 demonstrates that a time delay instability exits in the IDEAS model when a digital RIDE controller is used and air temperature is controlled.
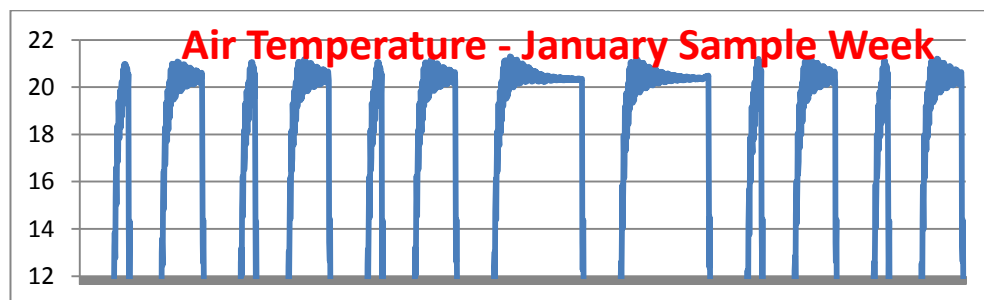
Figure 4.12 – IDEAS Digital RIDE model – Instabilities still exist with Air Temperature

4.5.2 Conclusion of Digital Model in Excel

Figure 4.9 above highlights that there exists a good energy match and curve fit between IDEAS and BREDEM, figure 4.11 highlights that the IDEAS temperature curve is similar to BREDEM but is significantly lower, figure 4.12 highlights that with the digital RIDE controller an instability still exists in the IDEAS model. **The issue highlighted in figure 4.12 and the low temperatures experienced in IDEAS could be resolved by tracking comfort temperature and not air temperature.** The modification of the IDEAS model in Excel to

track comfort temperature is raises technical difficulties. Additionally, it would be beneficial to run IDEAS at a lower resolution to resolve the instability errors which has not been fully resolved by the move to Digital RIDE. As IDEAS has 105,000 rows for the 5 minute resolution resulting in a file of 50Meg, a greater time resolution (and hence more data rows and a larger file size) is impossible.

The benefits of using Excel as a learning tool have been highlighted – full transparency of results and instantaneous and powerful graphs. IDEAS could remain in Excel but a file per season could be required. Excel is being pushed to the limits of its capabilities. So the decision was taken to move IDEAS to Matlab, where all of the work taken in IDEAS could be ported. Matlab is not as widely distributed or familiar to most users of SAP. However, Matlab has very powerful graphing capabilities and also allows the resolution of the model to be simply updated.

4.6 MATLAB – Continuous RIDE 3rd Order Model

4.6.1 Introduction to 3rd Order Model in MATLAB / SIMULINK

The 3rd Order IDEAS Model was created in MATLAB as highlighted in figure 4.12.
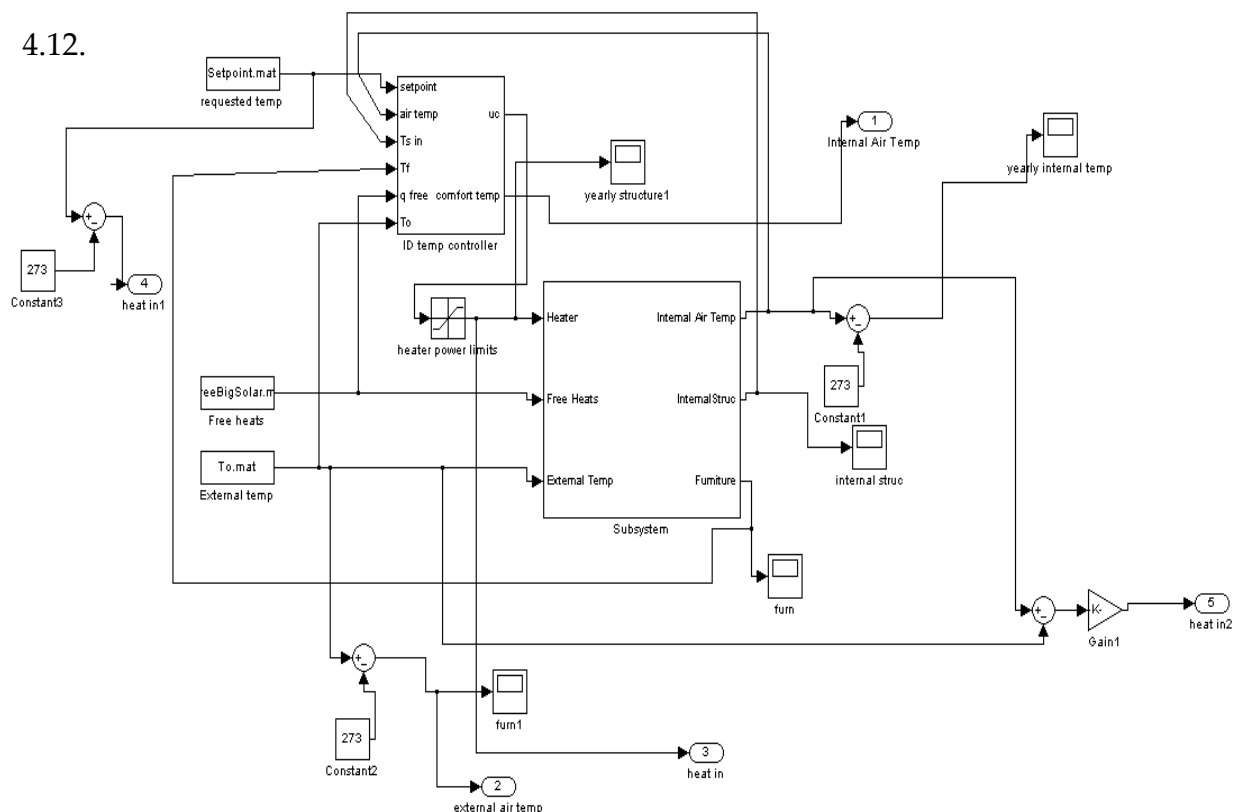
Figure 4.13 – 3rd Order IDEAS Model in MATLAB / SIMULINK

Having the 3ʳᵈ Order IDEAS Model in MATLAB allows for the time resolution to be modified quickly and simply. The resolution of the IDEAS model is increased from 5 minutely, as used and determined to be the maximum in Excel, to 1 minutely.

4.6.2   Comfort Temperature

Comfort temperature is very important – air temperature has been measured up until this point. The importance of comfort temperature is high as the air temperature cannot store a great deal of heat, but the structure and internal mass can.

The following parameters were used in the 3ʳᵈ Order Model in Matlab:

```
Mv  = 0.040156217; %FROM BREDEM     %(Kg/s)  Mass of the dwelling air
Ca = 1012;          %FROM BREDEM     %J/(kgK) Specific heat capacity of air
Us = 2.1;          %FROM BREDEM CELL AB47    %(W/m²K)    SAP Heat transfer coeff. of the
structure
As = 81.8;          %FROM BREDEM CELL AA47   %m^2       Surface area of structure
Ur = 2.3;          %FROM BREDEM CELL AB49    %(W/m²K)   Heat transfer coeff. of roof
Ar  = 44.4;         %FROM BREDEM CELL AA49    %(m²)      Area of Roof
Uw  = 4.167;        %FROM BREDEM CELL AB53    %(W/m²K)   Heat Transfer Co-Efficient of the
Windows
Aw  = 16.9;         %FROM BREDEM CELL AA53 %(m²)    Area of the Windows
Ma  = 249.795;      %FROM BREDEM     %kg          Mass of the air
Pa  = 1.22;         %FROM BREDEM     %kg/m3        Density of Air
Va  = 222;          %FROM BREDEM CELL AC6     %m3          Volume of Air
Ms  = 18203.73;     %FROM BREDEM (Total External Thermal Mass * 2/3)       %kg      Mass
of Structure Internal
Cs  = 800;              %J/(kg.K)   Specific Heat Capacity of Structure
Uf  = 0.7;          %FROM BREDEM CELL AB48    %(W/m²K)   Heat Transfer Co-Efficient of the
Floor
Af  = 44.4;         %FROM BREDEM CELL AA48    %(m²)      Area of the Floor
Mft = 8828.8;           %kg         Mass of the Furniture
Cft = 900;              %J/(kg.K)   Specific Heat Capacity of Furniture
% Value for Wood, oak
% http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html
Uft = 1;                %(W/m²K)   Heat Transfer Co-Efficient of the Furniture
Aft = 120.7         %FROM BREDEM     %m2         Area of Internal Mass in a Dwelling, 120.7 is
figure from BREDEM
```

A number of Comfort Ratios were used to determine the effect on comfort ratio to the temperature and energy consumption of the IDEAS model and the comparison with BREDEM.

4.6.2.1   Ratio: Ta = 0.33 / Ts = 0.33 / Tft = 0.33

Ta_Ratio = 0.33;

Ts_Ratio = 0.33;

Tft_Ratio = 0.33;
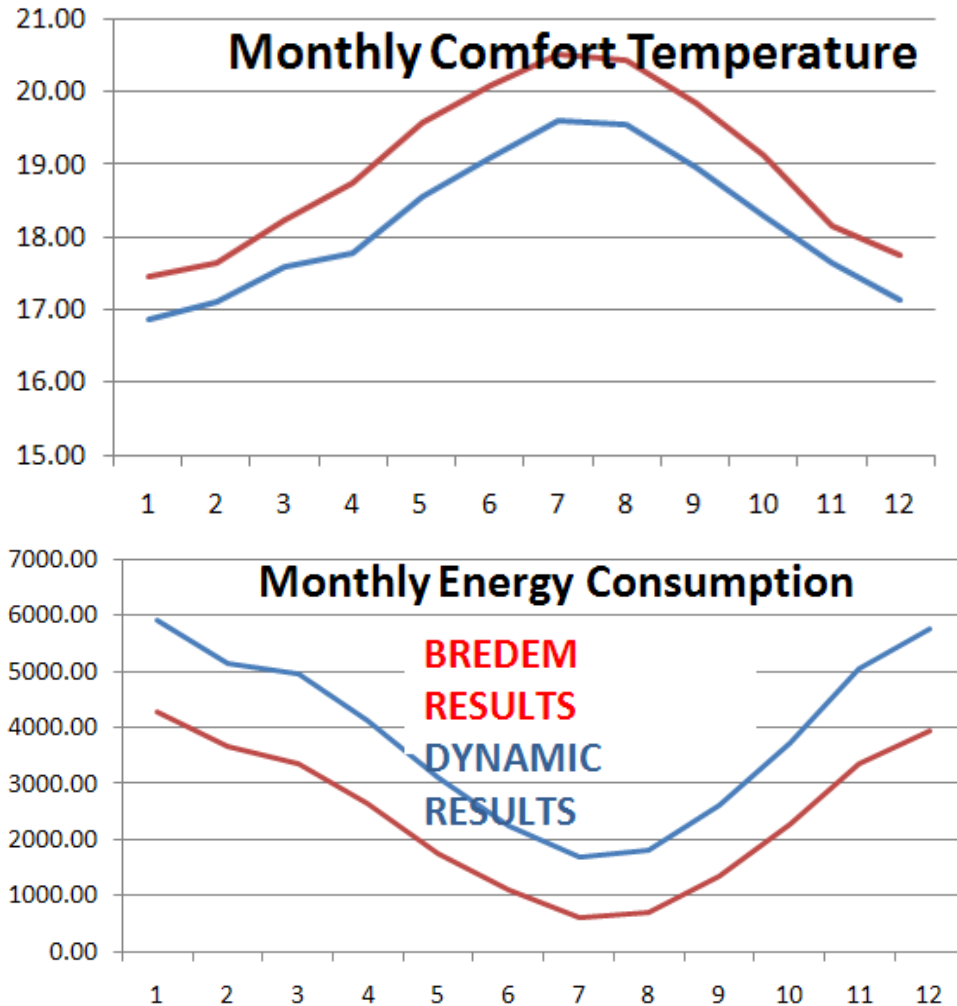
Figure 4. 14 – Comfort Temperature Ratio: Ta = 0.33 / Ts = 0.33 / Tft = 0.33; Comfort Temperature and Energy Consumption

The above figure highlights that with a ratio of Ta = 0.33 / Ts = 0.33 / Tft = 0.33, the Comfort Temperature and Monthly Energy Consumption are a good curve fit between the 3rd Order Continuous RIDE IDEAS Model and BREDEM 2009. The IDEAS comfort temperature is within 4% of BREDEM over the year. The monthly energy consumption is almost 50% higher than BREDEM over the course of a year.

111

4.6.2.2 Ratio: Ta = 0.4 / Ts = 0.0 / Tft = 0.6

Ta_Ratio = 0.4;

Ts_Ratio = 0.0;

Tft_Ratio = 0.6;
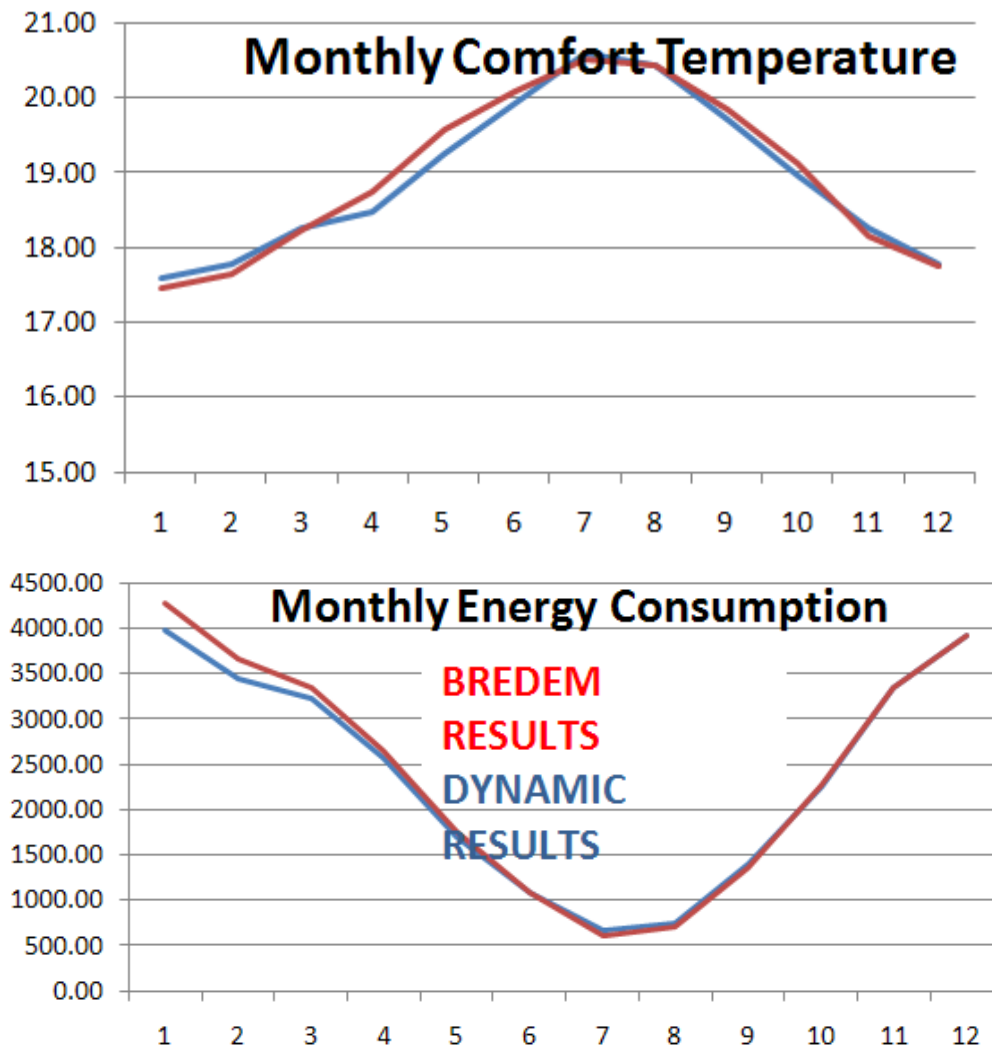
Figure 4. 15 - Comfort Temperature Ratio: Ta = 0.4 / Ts = 0.0 / Tft = 0.6; Comfort Temperature and Energy Consumption

The above figure highlights that with a ratio of Ta = 0.4 / Ts = 0.0 / Tft = 0.6, the Comfort Temperature is a near perfect fit between the 3rd Order Continuous RIDE IDEAS Model and BREDEM 2009. The Comfort Temperature and Monthly Energy Consumption match is shown to be very good in the 3rd Order Continuous RIDE IDEAS Model, with a 100% correlation

112

(99.80% for Comfort Temperature and 101.67% for Energy Consumption) over the year for each.

4.6.2.3 Comfort Ratio Conclusion

The conclusion of the results from the comfort ratio comparisons highlight the comfort ratio is very important to match the temperature results between IDEAS and BREDEM. In the Microsoft Excel incarnations of the IDEAS model, the air temperature alone was tracked; this had the effect of there being a mismatch between IDEAS and BREDEM results, with IDEAS temperature results being constantly lower over the winter months. Now that the comfort temperature is tracked, and not the air temperature alone, there is a good match between IDEAS and BREDEM for temperature. The ratio which provides the best match is found to be T_a = 0.4 / T_s = 0.0 / T_{ft} = 0.6. This is an interesting result and one which highlights the importance of tracking a comfort ratio which provides the best fit with SAP results but also the a comfort ratio which is representative of reality. With a comfort ratio of T_a = 0.4 / T_s = 0.0 / T_{ft} = 0.6 the relative coldness of the structure is negated and the important aspects are the temperature of the air and the temperature of the furniture and internal mass. **In reality the comfort temperature must take some account of the air temperature, the furniture & internal mass temperature and the structure temperature.** A comfort ratio of 0.33 for each would be closer to what is expected from CIBSE (CIBSE, 1999) and could therefore be a more accurate comfort ratio to use. **The third order model is not capable of reflecting the dynamic effect of the internal wall temperature as only one node is used for the entire structure.**

The modification of the Comfort Ratio also has an effect on Energy Consumption, for example a ratio with a higher percentage of the structure will require a greater amount of kWh for a setpoint to be achieved.

4.6.3   Conclusion of 3rd Order Model in MATLAB

The conclusion of the 3rd order IDEAS model is that by tracking the comfort temperature and not the air temperature it is possible to produce results in IDEAS which are very similar to BREDEM. The ratio which provides the best match is found to be T_a = 0.4 / T_s = 0.0 / T_{ft} = 0.6. Comparisons were made between IDEAS and BREDEM based upon a poorly insulated dwelling (structure U – Value: 2.1W/m²K) and a better insulated dwelling (structure U – Value: 1W/m²K). In both case a good match was found between IDEAS and BREDEM for both comfort temperature and energy consumption. The resolution and comfort temperature updates would have been very difficult to achieve in Microsoft Excel and so the move to MATLAB and Simulink has been vindicated. The 3rd order IDEAS model makes use of one lumped capacitance to represent the structure. This has the effect of cooling the comfort temperature dramatically. **A 3rd order simplified dynamic model is not suitable for use as an energy estimation tool which is calibrated with SAP.** Also having one lumped capacitance to represent the structure makes it difficult to model structures of composite materials. **Therefore to improve the flexibility of the model, the 3rd order IDEAS model was extended to 4th order by splitting the T_s term into two components to model the inner and outer structure temperatures.**

4.7   MATLAB – 4th Order Model

The MATLAB 3rd Order Model section highlights that there is a good agreement with BREDEM and IDEAS for both energy consumption and mean internal temperature, over a range of U-Values. This good agreement was possible due to the use of a time resolution of 1 minute, and the tracking of comfort temperature (with a ratio of T_a = 0.4 / T_s = 0.0 / T_{ft} = 0.6) instead of air temperature. **The comfort ratio used in the 3rd order model which provided the best match with BREDEM neglected the impact of T_s. This highlights**

how important the comfort ratio is. A comfort ratio which takes into account the structure would be more representative of reality. Also the issues raised regarding the single structure capacitor used suggested that a 4ᵗʰ order model with 2 structure capacitors could be more accurate and flexible.

4.7.1   Heat Flow through the Dwelling – 4ᵗʰ Order Model

3ʳᵈ Order IDEAS models the dwelling structure, Ts, lumped into one parameter. To check if more accurate results were possible, across a range of structures and U–Values the decision was taken to increase the degrees of freedom in the IDEAS model for the modelling of the structure. Additionally the expansion of the model to 4ᵗʰ Order will allow for more analysis to be carried out upon comfort ratios. Therefore a 4ᵗʰ Order Model was created, splitting the single structure node (Ts) to Internal (Tsi) and External (Tse) Sections, as follows:
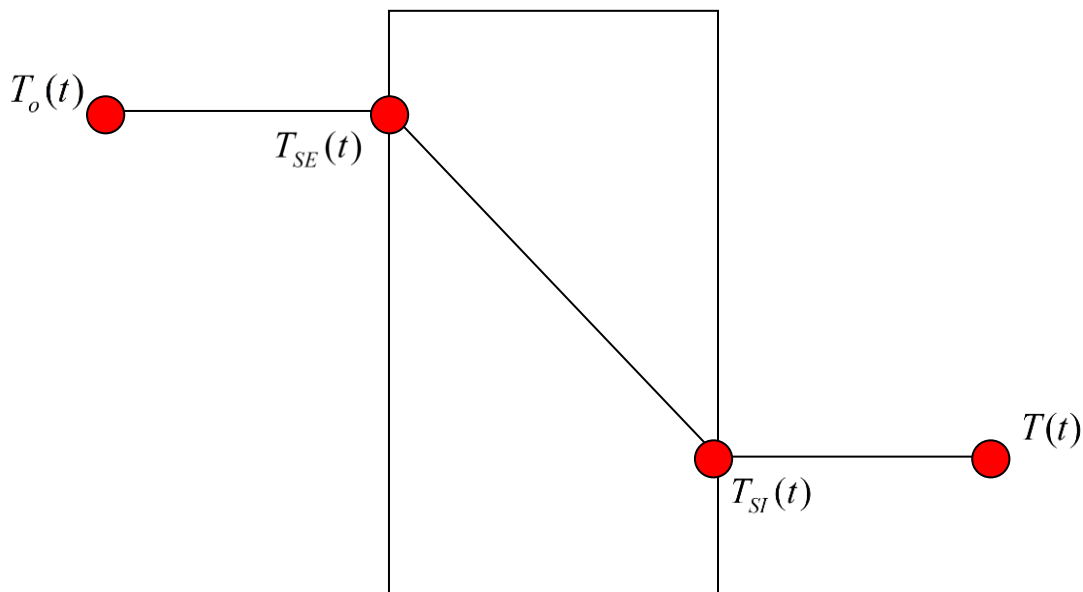
Figure 4. 16 – Two nodes now used for Structure, Tsi and Tse

In the 4ᵗʰ Order Model, the heat loss equations for the heat loss through the windows, floor, roof and furniture & internal mass remain consistent with those defined for the 3ʳᵈ order model (see chapter 4, section 2.2). Figure 4.17 below represents the whole 4ᵗʰ order model. The major difference between this model and the 3ʳᵈ order equivalent is that the single Ts term for structure is now

split into Tse (external structure component) and Tsi (internal structure component).
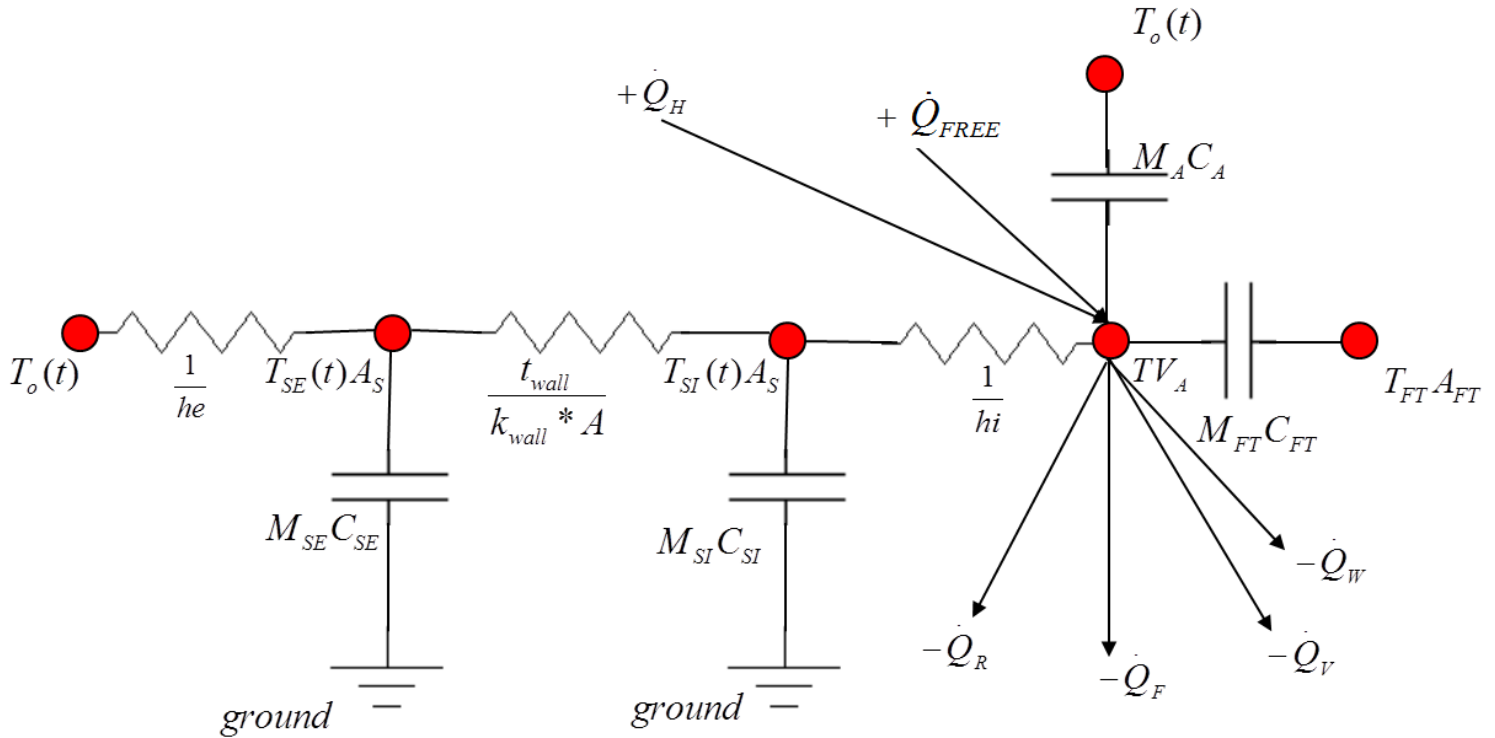
Figure 4.17 – A Resistor-Capacitor (RC Circuit) analogy of the 4th Order IDEAS Model

Figures 4.16 and 4.17 highlight the use of Tse and Tsi nodes to represent the structure of the dwelling. Calibration with SAP is still a prime focus of the model, and so SAP inputs are used wherever possible so that a comparison can be made. In the 3rd order version of IDEAS (equation (23)), the single U-Value taken from SAP was taken directly as the Ts value and used to calculate the matrices. Now that there are two nodes for the structure, the additional resistances of 1/he, 1/hi and tWall/kWall must be taken into account. It is very important for the SAP calibration that the 4th order IDEAS model uses the U-Value for the structure as taken from SAP to help to calculate the resistance terms hi and he, tWall and kWall. Where hi = internal convective heat transfer coefficient (W/m²K), he = external convective heat transfer coefficient (W/m²K), tWall = wall thickness (m), kWall = Thermal Conductivity of Wall (W/m.K).

For a given U-Value taken from SAP, an appropriate wall thickness

116

(tWall) and thermal conductivity (kWall) must be entered into IDEAS. For example, for a given U-Value of 2.1W/m²K, an appropriate tWall value would be 0.2286m (9inches), and a corresponding thermal conductivity of the structure would be 1.31W/(m.K). From the U-Value from SAP and the corresponding entered wall thickness and thermal conductivity, the terms hi and he can be calculated as follows (referring to figure 4.17).

$$Resistance_{total} = \frac{1}{U-Value * A} = \frac{1}{he * A} + \frac{tWall}{kWall * A} + \frac{1}{hi * A} \quad \text{(35)}$$

Where A (area) terms cancel out for steady heat flow:

$$\frac{1}{U-Value} = \frac{1}{he} + \frac{tWall}{kWall} + \frac{1}{hi} \quad \text{(36)}$$

The calculation stipulates that the steady state heat flow at UAΔT is equal to the steady state heat flow through the whole of the system. This highlights that the wall model in IDEAS is quasi steady state calibrated with SAP. This is important to ensure that SAP comparable results are produced from the 4th order ideas model.

4.7.2   Rate of Change of Stored Heat – 4th Order Model

The update in the 4th order model is that there are now two nodes used to define the structure of the dwelling. This allows for more flexibility in the IDEAS model and so various construction types can now be modelled. It is still assumed that thermal corner effects are ignored so that the internal and external wall areas are identical.

4.7.3   Rate of Change of Air Temperature – 4th Order Model

The air in the dwelling is described as:

$$M_A C_A \frac{dT(t)}{dt} = \dot{Q}_H(t) + \dot{Q}_{FREE}(t) - \dot{Q}_{SI}(t) - \dot{Q}_F(t) - \dot{Q}_R(t) - \dot{Q}_W(t) - \dot{Q}_V(t) - \dot{Q}_{FT}(t)$$

(37)

The difference between the rate of change of air temperature between the 3rd and 4th order models is due to the splitting of the model structure term into two. In the 3rd order model the $-\dot{Q}_S(t)$ term was used to denote the heat loss to the structure as a whole. In the 4th order model the $-\dot{Q}_{SI}(t)$ term denotes the heat loss to the inner node of the structure. In a model of a dwelling, the inner node would generally be warmer than the external node. This update will have an effect on the rate of change of air temperature as the $-\dot{Q}_{SI}(t)$ term will be generally of a warmer (and more realistic temperature which would affect internal comfort) than the $-\dot{Q}_S(t)$ term.

4.7.4 Controllability Analysis – 4th Order Model

As described for the 3rd order model, the differential equations are factorised and simplified for controllability analysis. The temperature of the dwelling furniture & internal mass constants remains consistent with the 3rd order model (chapter 4, section 2.5).

Temperature of internal dwelling air:

$$M_A C_A \frac{dT(t)}{dt} = \begin{bmatrix} \dot{Q}_H + \dot{Q}_{FREE} - \dot{M}_V C_A (T(t) - T_o(t)) - hiA_S (T(t) - T_{SI}(t)) - U_F A_F (T(t) - T_o(t)) \\ -U_R A_R (T(t) - T_o(t)) - U_w A_W (T(t) - T_o(t)) - U_{FT} A_{FT} (T(t) - T_{FT}(t)) \end{bmatrix}$$ (38)

Where the $-hiA_S$ term refers to the area of the structure which is multiplied by the heat transfer coefficient as defined for that particular dwelling.

Where he and hi calculated in Matlab as follows:

```
hratio = 1.09; %dimensionless - increase value to reduce
energy
hi = Usap*Kwall*(hratio + 1)/(hratio*(Kwall -
Usap*Twall));
```

```
        he = hratio*hi
```

Where:

- Usap = the U-Value as taken directly from SAP/BREDEM (e.g. 2.1W/m²K)

- tWall = thickness of the structure (e.g. 0.2286m / 9 inches)

- kWall = thermal conductivity of the structure (e.g. 1.31 W(mK) for solid brick)

- The hratio is a dimensionless parameter, a larger hratio term has the effect increasing the energy use of IDEAS, and reducing the annual MIT. The term he is larger than hi as there will be more resistance on the inside structure due to an air boundary layer. A smaller convective heat transfer coefficient (W/m²K) is more resistive so the external convective heat transfer coefficient will be numerically larger than the internal.

The equation used to calculate hi in IDEAS (as displayed in Matlab code above) is defined and detailed below. From SAP, it is known that in steady state for a wall, the overall heat loss:

$$\dot{Q}_{overall} = U_{wall} * A_{wall}(T - To) \tag{39}$$

So, for the 4th Order IDEAS model where the structure is represented by two nodes, it must satisfy the SAP criteria when in steady state:

$$hi * A_{wall}(T - T_{SI}) = (A_{wall} * \frac{tWall}{kWall})(T_{SI} - T_{SE}) = he * A_{wall}(T_{SE} - T_{SI}) = \dot{Q}_{overall}$$

$$\tag{40}$$

As detailed in figure 4.16, when there are three thermal resistances in series and in steady state in IDEAS (Tse (external wall temperature), Tsi (internal wall temperature), T(temperature inside the dwelling)), an electrical

analogy can be applied. From figure 4.17:

$$\frac{1}{UValue*A} = \frac{1}{he*A} + \frac{tWall}{kWall*A} + \frac{1}{hi*A}$$

(41)

Therefore, total thermal resistance is equal to U-Value resistance. N.B. Thermal resistance for convection from a surface to moving fluid:

$$R_{convective} = \frac{1}{hA}$$

(42)

And thermal resistance for conduction through a stationary fluid:

$$R_{conduction} = \frac{thickness}{kA}$$

(43)

So, if the thickness of the wall is known (tWall) and the walls overall thermal conductivity is known (kWall), then:

$$\frac{1}{U-Value \text{ from SAP}} = \frac{1}{hi} + \frac{tWall}{kWall} + \frac{1}{hratio*hi}$$

(44)

Where hratio is defined as :

$$hratio = \frac{he}{hi}$$

(45)

The terms hi and he do not have to be equal however as the thermal resistance will be greater inside the wall rather than the outside of the wall. Inside the dwelling, the air is more likely to be still and so a boundary layer will exist over the inside wall. Therefore, the inside wall is likely to have a greater thermal resistance than outside; i.e. a numerically smaller value in (W/m²K). A

120

term 'hratio' can be used to take the boundary later effect on the inside wall into account so:

$$he = hratio * hi \text{ where } hratio > 0 \qquad \textbf{(46)}$$

Equation (44) can be rearranged for hi as follows, where Usap is the U-Value from SAP:

$$\frac{1}{Usap} = \frac{1}{hi}\left(\frac{1}{hratio}+1\right) + \frac{twall}{kwall}$$

$$\frac{1}{hi}\left(\frac{1}{hratio}+1\right) = \frac{kwall - Usap * twall}{Usap * kwall}$$

$$\textbf{(47)}$$

$$h_i = \frac{\dfrac{1}{hratio}+1}{\dfrac{kwall-(Usap*twall)}{Usap*kwall}} = \frac{hratio+1}{\dfrac{hratio(kwall-(Usap*twall))}{Usap*kwall}}$$

Rearranging (47) again:

$$hi = \frac{Usap * kwall(hratio+1)}{hratio(kwall - Usap * twall)} \qquad \textbf{(48)}$$

Equation (48) is the equation computed in the Matlab m file:

```
hi = Usap*Kwall*(hratio + 1)/(hratio*(Kwall - Usap*Twall));
```

With hratio defined in the m file, a value 1.09 gives a good match with SAP results.

```
%dimensionless - increase value to reduce energy
hratio = 1.09;
```

The term factor he is defined as follows, based upon the calculation for

the terms hi and the value set for hratio :

```
he = hratio*hi
```

Therefore, he and hi are determined by the SAP / BREDEM U-Value and the entered thickness and k value for that construction. This is detailed in section 4.7.1 (Heat Flow through the Dwelling – 4th Order Model).

The terms he and hi are very important in the IDEAS model and are a core component of Equation (38) due to the use of he and hi in the definition of constants used in Equation (38). Equation (38) is factorised in terms of variables: $\dot{Q}_H(t)$, $\dot{Q}_{FREE}(t)$, $T(t)$, $T_{SI}(t)$, $T_{FT}(t)$ and $T_o(t)$:

$$\frac{dT(t)}{dt} = a_{11}T(t) + a_{12}T_{SI}(t) + a_{14}T_{FT}(t) + b_{11}\dot{Q}_H + d_{11}\dot{Q}_{FREE} + d_{12}T_o(t) \tag{49}$$

Where constants are defined as:

$$
\begin{aligned}
a_{11} &= \left[\frac{-\dot{M}_V C_A - heA_S - U_F A_F - U_R A_R - U_w A_W - U_{FT} A_{FT}}{M_A C_A} \right] \\
a_{12} &= \left[\frac{hiA_S}{M_A C_A} \right] \\
a_{14} &= \left[\frac{U_{FT} A_{FT}}{M_A C_A} \right] \\
b_{11} &= \left[\frac{1}{M_A C_A} \right] \\
d_{11} &= \left[\frac{1}{M_A C_A} \right] \\
d_{12} &= \left[\frac{M_V C_A + U_F A_F + U_R A_R + U_w A_W}{M_A C_A} \right]
\end{aligned}
\tag{50}
$$

The same procedure of simplification is carried out for temperature of

internal dwelling structure;

$$\frac{dT_{SI}(t)}{dt} = a_{21}T(t) + a_{22}T_{SI}(t) + a_{23}T_{SE}(t)$$ (51)

Where constants are defined as:

$$a_{21} = \left[\frac{heA_s}{M_{SI}C_{CS}} \right]$$

$$a_{22} = \left[\frac{-hiA_S - (A_S(Kwall / Twall))}{M_{SI}C_S} \right]$$ (52)

$$a_{23} = \left[\frac{(A_S(Kwall / Twall))}{M_{SI}C_S} \right]$$

The same procedure of simplification is carried out for temperature of external dwelling structure;

$$\frac{dT_{SE}(t)}{dt} = a_{32}T_{SI}(t) + a_{33}T_{SE}(t) + d_{32}T_O(t)$$ (53)

Where constants are defined as:

$$a_{32} = \left[\frac{(A_S(Kwall / Twall))}{M_{SE}C_S} \right]$$

$$a_{33} = \left[\frac{-(heA_S) - (A_S(Kwall / Twall))}{M_{SE}C_S} \right]$$ (54)

$$d_{32} = \left[\frac{(heA_S)}{M_{SE}C_S} \right]$$

The same procedure of simplification is carried out for temperature of

furniture & internal mass. Where the furniture & internal mass constants are the same as in the 3rd Order Model but they are now moved from the 3rd to the 4th row in the state space matrix.

$$\frac{dT_{FT}(t)}{dt} = a_{41}T(t) + a_{44}T_{FT}(t)$$

(55)

Where a_{41} and a_{14} are given by:

$$a_{41} = \left[\frac{U_{FT}A_{FT}}{M_{FT}C_{FT}} \right]$$

$$a_{44} = \left[-\frac{U_{FT}A_{FT}}{M_{FT}C_{FT}} \right]$$

(56)

4.7.5 State Space Model – 4th Order Model

The statespace equation for the 4th order model:

$$\begin{bmatrix} \dot{T}(t) \\ \dot{T}_{SI}(t) \\ \dot{T}_{SE}(t) \\ \dot{T}_{FT}(t) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 & a_{14} \\ a_{21} & a_{22} & a_{23} & 0 \\ 0 & a_{32} & a_{33} & 0 \\ a_{41} & 0 & 0 & a_{44} \end{bmatrix} \begin{bmatrix} \dot{T}(t) \\ \dot{T}_{SI}(t) \\ \dot{T}_{SE}(t) \\ \dot{T}_{FT}(t) \end{bmatrix} +$$

$$\begin{bmatrix} b_{11} \\ 0 \\ 0 \\ 0 \end{bmatrix} \left[\dot{Q}_H(t) \right] + \begin{bmatrix} d_{11} & d_{12} \\ 0 & 0 \\ 0 & d_{32} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{Q}_{FREE}(t) \\ T_o \end{bmatrix}$$

(57)

Equation (57) is the statespace of the 4th Order IDEAS model; other updates to the IDEAS model were required to update the 3rd Order to a 4th Order model, tracking comfort temperature and not air temperature

124

The temperature which is tracked is updated so that the comfort temperature is the system output, which is perfectly tracked. From the temperature research conducted using the 3rd Order IDEAS model, it is clear that the temperature tracked in SAP is comfort temperature (which is a ratio of air, furniture & internal mass and structure temperatures) and not air temperature alone. The output vector is updated to:

$$Y(t) = \begin{bmatrix} Ratio\_Ta & Ratio\_Tsi & 0 & Ratio\_Tft \end{bmatrix} \begin{bmatrix} T(t) \\ T_{SI}(t) \\ T_{SE}(t) \\ T_{FT}(t) \end{bmatrix} \quad \text{(58)}$$

It can be seen from equation (58) that the impact of the External Structure is always 0 with regards to its effect upon comfort temperature. The ratio of 0.33 Air Temperature, 0.33 Internal Structure, 0.33 Furniture and Internal Mass is based upon the Environment Temperature ratio as described in CIBSE Guide A, Environmental Design (CIBSE, 1999).

$$Y(t) = 0.33T(t) + 0.33T_{SI}(t) + 0 + 0.33T_{FT}(t) \quad \text{(59)}$$

The temperature tracked is now the comfort temperature, as defined in equation (59). The perfect inverse continuous control law is applied as described in equation (27). From equation (28), the measured output vector, Y(t), is the comfort temperature and the target room temperature, v(t), remains the same as in the 3rd Order Model and is defined by the SAP standard occupancy setpoint. The Simulink Model in Matlab was also updated as highlighted in figure 4.18.
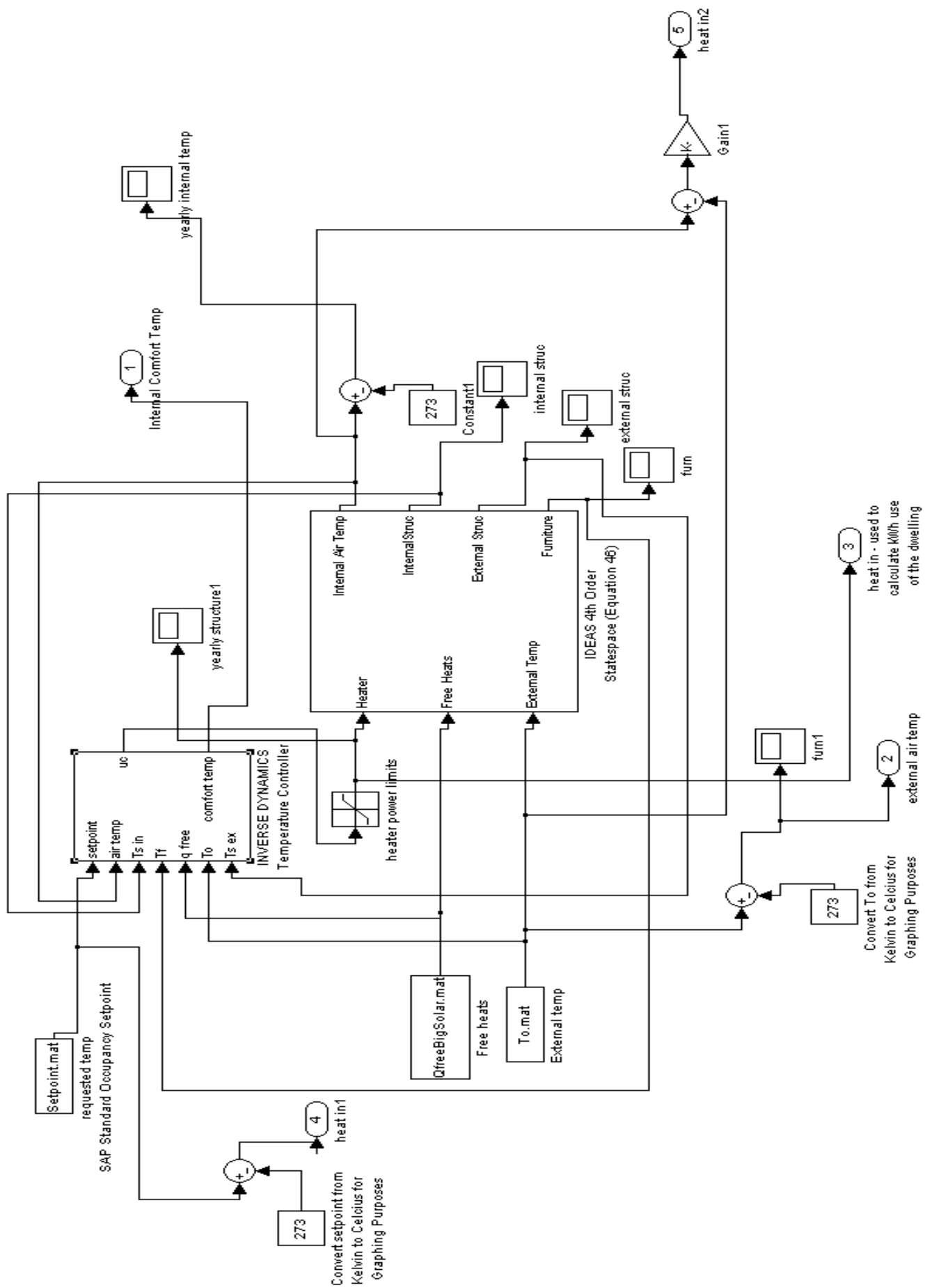
Figure 4. 18 – Simulink Model for 4th Order IDEAS Model

126

4.7.6   4th Order IDEAS model – poorly insulated house test case
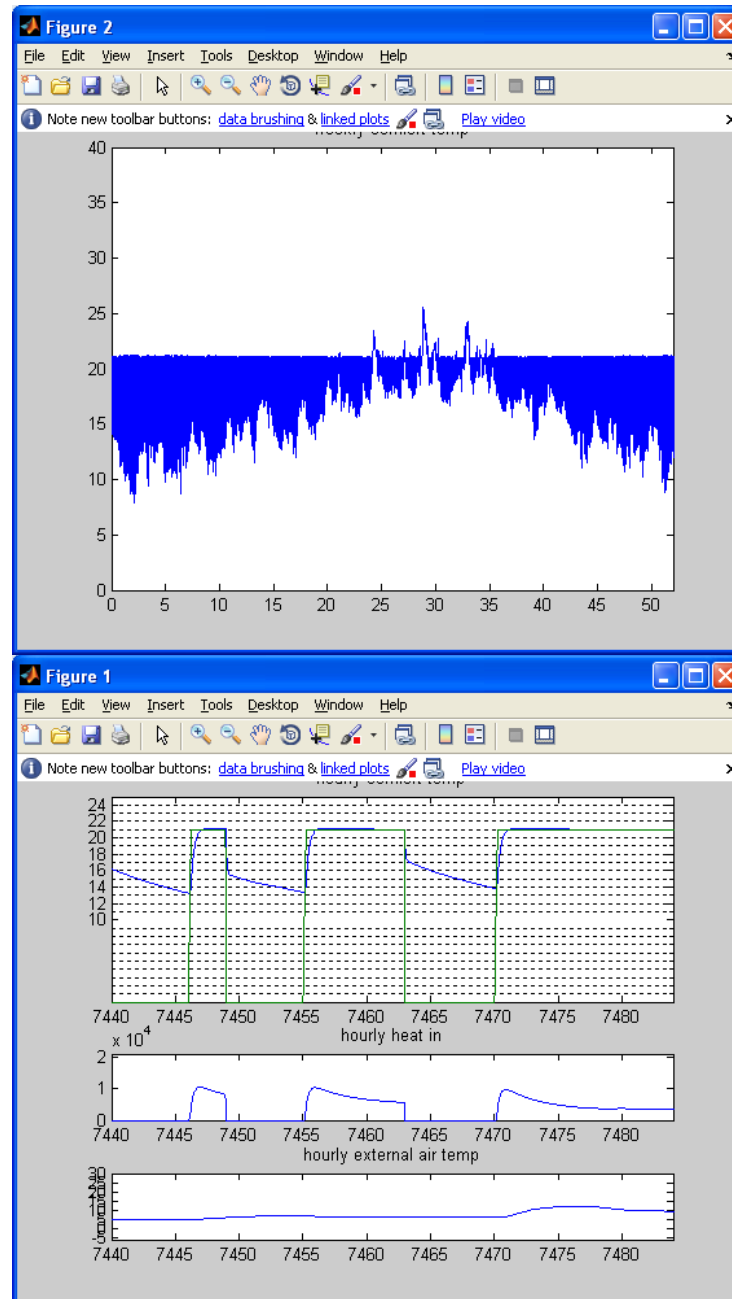
Figure 4.19 - IDEAS 4th Order Model in MATLAB for a poorly insulated home, yearly comfort temperature, transitory comfort temperature for a 36 hour period, heat input and external air temperature

The results for the poorly insulated house highlights that there is a large degree of fluctuation in comfort temperature over the year, with minimal overheating over summer.   The comfort temperature decay curves are steeper in the morning than in the evening due to the increased amount of heat stored in the structure and internal mass in the evening as opposed to the morning.

4.7.7   4th Order IDEAS model – highly insulated house
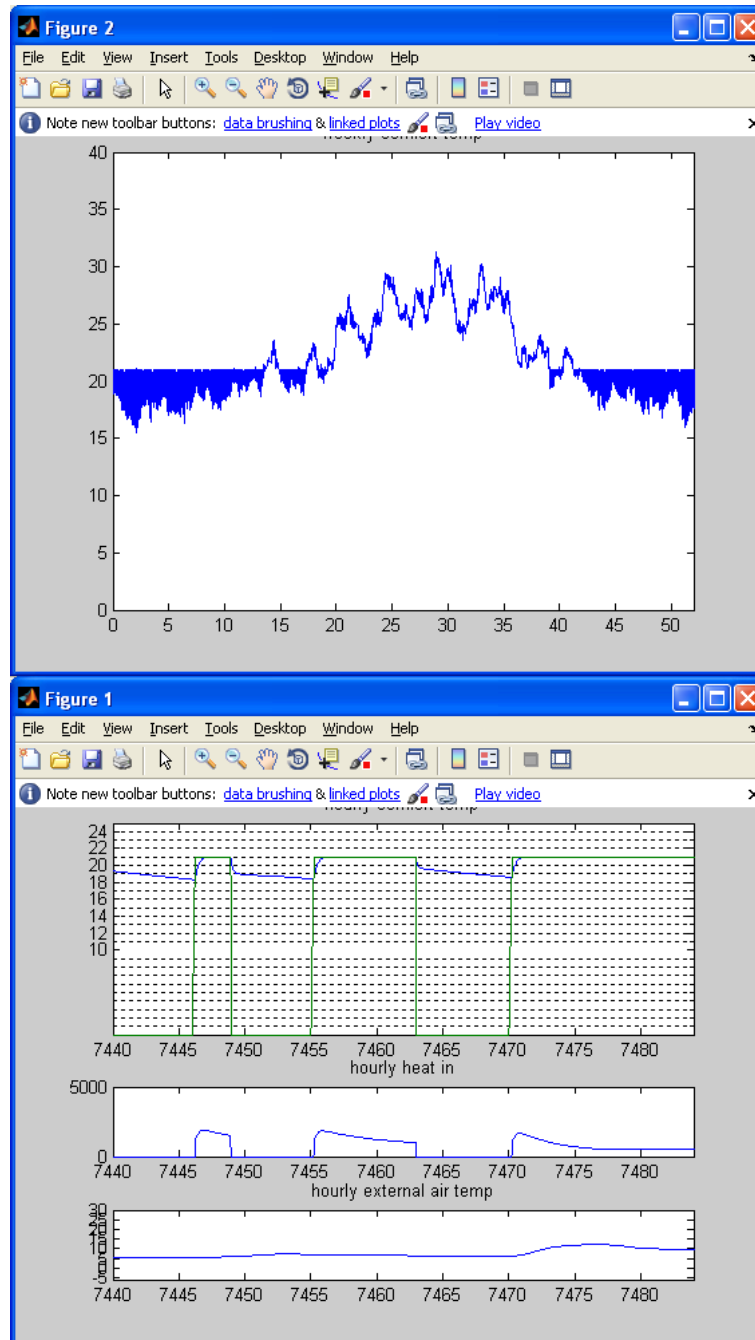
Figure 4.20 - IDEAS 4th Order Model in MATLAB for a well-insulated home, yearly comfort temperature, transitory comfort temperature for a 36hr period, heat input and external air temperature

The results from the well-insulated test case demonstrate the overheating can occur that significantly over the summer due to the improved fabric. BREDEM/SAP assumes that the upper limit of a dwelling is 21°C and so such overheats would not be shown. If it was desired to remove the overheats, then a window opening algorithm (Rijal et al., 2008) could be added to the IDEAS

model to predict the window opening habits of the occupants of such well insulated homes. The decay curves of the comfort temperature are very gradual due to the well-insulated building parameters. Also, the relative lack of heating required is highlighted when the heat input demanded by the well-insulated and poorly insulated dwellings are compared.

With a comfort temperature ratio of 0.33 Air Temperature, 0.33 Internal Structure, 0.33 Furniture and Internal Mass, the comfort temperature ratio fits well with CIBSE guidelines and also matches well with BREDEM. The results from the 4th Order Model are compared with BREDEM / SAP and discussed in greater depth in chapter 6.

4.7.8   Addition of Optimum Start to 4th Order Model

Also highlighted by the results from the 4th Order Model is that optimum start should be added to the IDEAS model so that the demand temperature is reached when required by the BREDEM setpoint. This should improve the comparative results of the 4th order IDEAS model with BREDEM and also allow systems of different responsiveness to integrate into the IDEAS method.

Figure 4.21 highlights the additional work which was carried out to add optimum start to the 4th order IDEAS model. Figure 4.21 highlights that the Optimum Start has been added to IDEAS in Matlab/Simulink as detailed in Section 4.3.2 (Optimum Start). Logic is required for the optimum start implementation to account for the differences between the weekday and weekend demand as defined by the SAP standard occupancy profile. From figure 4.21, two logic streams can be seen, with the top logic stream focusing on the creation of the optimum start setpoint for the weekdays and the bottom for the weekends. The top logic stream takes into account that there is an AM and PM optimum start required by SAP (7am->9am & 4pm->11pm). The 'AM1', 'PM' and the 'Setback_wkdays' blocks in the model define the logic as detailed in Section 4.3.2 (Optimum Start) for each weekday throughout the yearly

calculation. The file 'wkdys03.mat' is used to stipulate that the calculated setpoint should be used for only days which are defined as weekdays.

Similarly the bottom logic stream defines the optimum start for the weekends, where there is always only one period of standard occupancy per day (7am->11pm). The 'AMPM' and the 'Setback_wkends' blocks in this section model define the logic, (also as detailed in Section 4.3.2) for each weekend throughout the yearly calculation. The weekend calculated setpoint is only used for each day which is a weekend according to the file 'wkdys03.mat'. The setpoint outputs from the 'weekends' and 'weekdays' section of the optimum start calculation process are then added together to create 'optset.mat': this is the new setpoint which is tracked perfectly by IDEAS, taking into account the optimum start requirement of the heating system. The optimum start setpoint is dynamic and varies based upon the responsiveness and the maximum output of heating system.
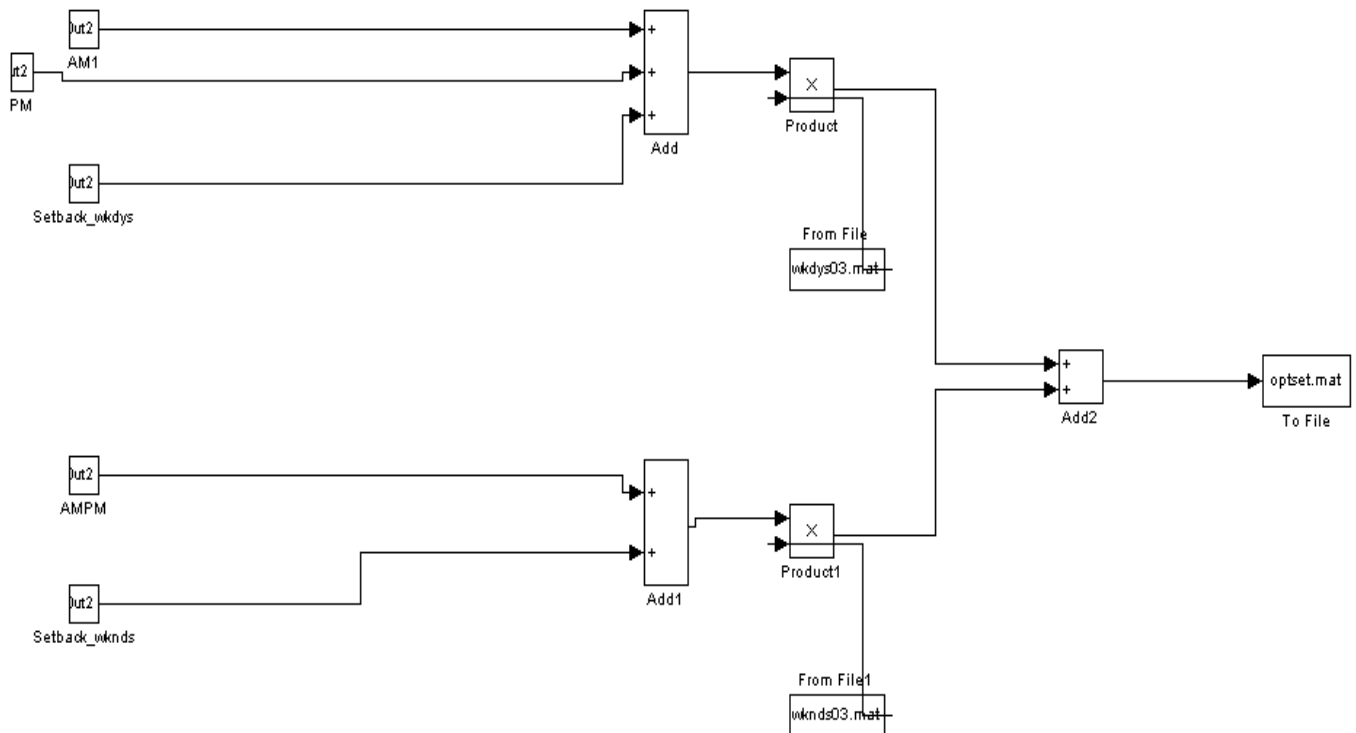
Figure 4. 21 – Addition of Optimum Start to 4th Order IDEAS Matlab model in Simulink

4.7.9   Optimum Start in 4th Order Model – Results

The addition of Optimum Start to the 4th Order Model is best demonstrated by the modelling of a slowly acting heating system such as underfloor heating. A heating system which responds quickly, defined by SAP as a direct acting electric heater or a gas wet system with radiators, is giving a controller time constant (g) of 1/(3*300). A heating system which responds slowly, such as an underfloor heating system, is given a g value of 1/((3*300)/5). The benefits of Optimum Start to the IDEAS model are highlighted when a slowly responding heating system is modelled.

4.7.9.1   Modelling of a poorly responsive heating system in IDEAS

Figure 4.22 highlights that without optimum start, the midweek AM heating demand profile is never met. The PM heating demand profile is met but this takes over two hours. Over the weekend, the demand temperature is similarly met approximatley 2 hours after being requested. **For an accurate comparison with SAP, the IDEAS model without optimum start can not be used as SAP assumes a degree of optimum start so that the demand temperature profiles are met when requested.** However, the IDEAS model without optimum start could be used to demonstate who heating systems with different power and responsivenesses could behave in different dwellings which do not have the benefit of optimum start. Figure 4.22 demonstrates that without the use of optimum start in IDEAS, the demand temperature is not met in time.
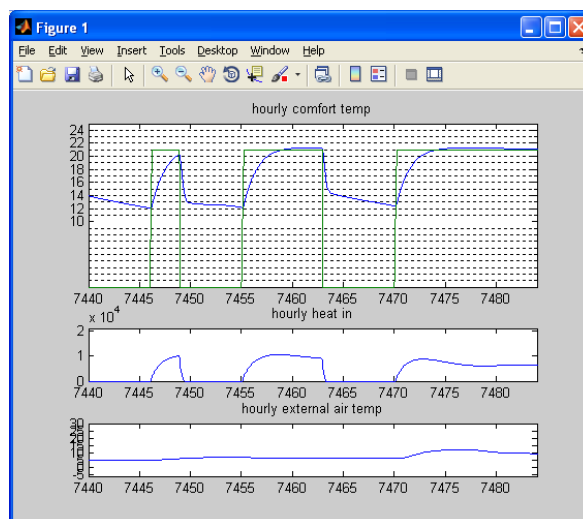
Figure 4.22 – A poorly responsive heating system modelled in the 4th Order IDEAS model, with NO optimum start algorithm employed
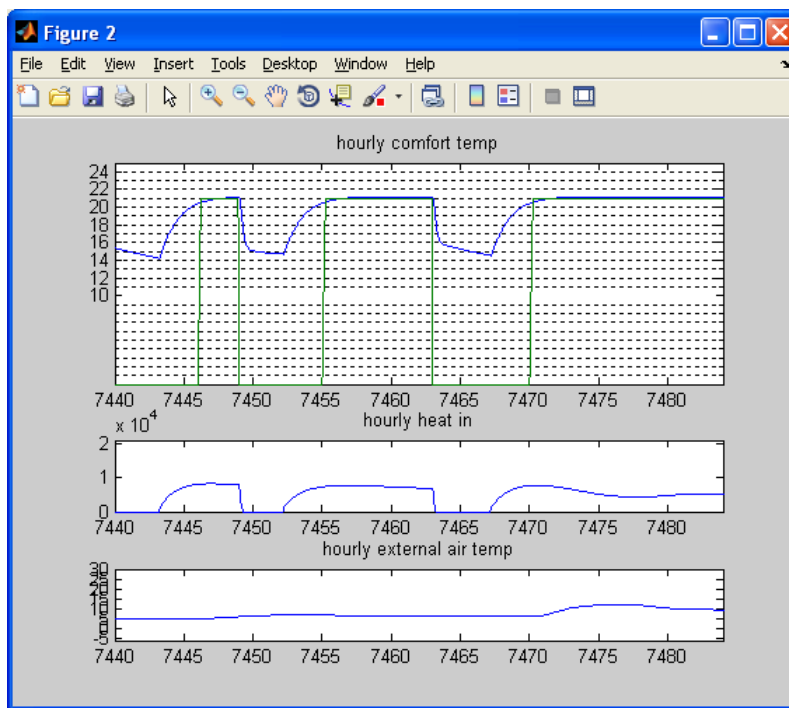
Figure 4.23 A poorly responsive heating system modelled in the 4th Order IDEAS model, with an optimum start algorithm employed

Figure 4.23 demonstrates the use of the optimum start algorithm in the IDEAS model, the demand temperature is met when requested due to the heating system switching on earlier. **Optimum start is required for IDEAS to produce SAP / BREDEM compliant results and is especially required for systems which respond slowly.**

4.7.10 Conclusion of 4th Order Model

There is now confidence that BREDEM / SAP compliant results are produced by the IDEAS method over a range of structure U-Values and dwelling types. Further results from the progression of the IDEAS model from its inception as a Microsoft Excel based tool to a 4th order dynamic Matlab / Simulink model with optimum start are presented in the 6th chapter. **With the addition of optimum start, the 4th order IDEAS model produces results which are comparable to BREDEM / SAP. IDEAS results are within 5% for yearly comfort temperature and energy consumption, for a range of dwelling types and heating systems, when compared to results produced by the BREDEM / SAP framework.** Full Matlab source code for the final 4th Order Model is situated in Appendix C: Matlab Source Code for final 4th Order Model with Optimum Start.

Corresponding Simulink Model files for the final 4th Order Model are located in Appendix B: Simulink Block Diagrams for final 4th Order Model.

4.8   Conclusions

This chapter presents the current SAP methodology and the BREDEM foundations with respect to the energy estimation of a heating system for a dwelling. From this a new methodology, named IDEAS, is presented based upon systems engineering analysis and control theory knowledge developed from the aerospace industry.

An energy estimation model for a single zone dwelling was presented; the methodology can be used to supplement the SAP Methodology. The methodology presented builds on the foundations set by BREDEM, by highlighting the importance of Responsivity, Efficiency and Controllability factors of a system. These factors are very important in the aerospace industry in addition to the buildings industry, and therefore it is felt that the correlation between the two sciences is appropriate.

The main benefits of this proposed addition to the SAP methodology are advantageous to both the dwelling occupier and the environment. A dwelling with good control is a home which has good occupant comfort, saves energy and therefore also saves the occupier money. The reduction in energy use from a well-controlled dwelling has a positive effect on both the dwellings SAP score and the environment. A dwelling with poor control wastes energy, can cause discomfort for the tenant and can increase dwelling CO_2 emissions.

The development of the following was described in detail in this chapter:

- Single Zone BREDEM 2009
- 3rd Order Continuous RIDE Excel IDEAS Model
- 3rd Order Digital Excel IDEAS Model

- 3rd Order Continuous Matlab IDEAS Model

- 4th Order Continuous Matlab IDEAS Model

- 4th Order Continuous Matlab IDEAS Model with Optimum Start Algorithm

With the presentation of comparative results of the 4th Order Continuous IDEAS Matlab Model, running at a time resolution of one minute, with BREDEM for a well and poorly insulated test case. This highlights that the IDEAS model produces comparable results to BREDEM/SAP over the range of U-Values; this validation is discussed more in the following results and discussion chapter. Additionally, the optimum start algorithm was implemented to the 4th order IDEAS model and results were produced for fast and slowly responsive systems.

The importance of comfort temperature was also highlighted. In the first incarnations of the IDEAS model, the air temperature was controlled and measured and it became clear that this was a major cause in the output of IDEAS being lower than BREDEM over the winter months. **BREDEM was measuring comfort temperature but it is unclear what exactly was measured. For a fair comparison with SAP, IDEAS has to track a comfort temperature based upon a ratio which matches that used in SAP calculations. As the ratio used to determine comfort criteria in SAP is not clear, research was carried out into what comfort ratio produces results which provided the best fit to SAP for both MIT and energy consumption.**

The ratio of 0.33 for Ta, Tsi and Tft was chosen due to its good fit with BREDEM and also as a close fit with the methods described in CIBSE Guide A was possible. Clarity is required on what exactly BREDEM / SAP measurements are based upon, although this may be difficult to achieve due to the length of time (decades in some cases) since measured test data was

recorded in dwellings for BREDEM / SAP. Also unclear is the temperature which people were controlling to – this is also information which is could be difficult to ascertain. These are issues for all simulation tools which wish to compare with BREDEM / SAP and assumptions must be therefore made in some cases as highlighted in the chapter.

Therefore, the major factors in the validation of IDEAS (and dynamic simulation tools) against BREDEM / SAP are:

- **Comfort Temperature – what is it?**
  - A ratio of 0.33 for Ta, Tsi and Tft tracked in IDEAS as comfort temperature has been found to produce the best results comparison with SAP

- **Effect of Furniture & Internal Mass in a Dwelling**
  - As the furniture and internal mass contributes one third of the comfort temperature requirement, its effect cannot be underestimated
- **Effect of structure component to comfort temperature**
  - When a 3rd order model was used, with one structure component, it was found that this structure node was very cold in comparison to the air temperature and furniture & internal mass temperature. This is due to the dominance of the external temperature over the structure. Therefore in the 3rd order IDEAS model the addition of the structure component to comfort temperature produced results which did not correlate well with SAP
  - In the 4th Order IDEAS model, with two nodes representing the structure of the building, the external wall does not have an effect upon comfort temperature. However, the internal structure component contributes one third of the comfort temperature requirement and is very important.
- **Requirement of an optimum start algorithm to IDEAS**
  - An optimum start algorithm is inherently built into SAP. Optimum start is impetrative in IDEAS for the accurate modelling of heating systems which respond slowly, is

SAP compliant

The major factors are in many cases:

- Uncertain

- Hard to Quantify

- Significant

The conclusion is that this body of work has contributed to the field by highlighting the importance of these major factors, leading to the development and calibration of a new dynamic simulation calculation method with SAP.

Additionally these areas could benefit from further research based upon real monitored data. Monitored test data is especially lacking for low energy homes of the future such as PassiveHouses – the 6th chapter of this thesis (Case Studies) will details an example of the monitoring which could be required to be carried out so that methods such as BREDEM and IDEAS can be enriched. Also presented in the Case Studies chapter is an example of the use of IDEAS Method to produce detailed dynamic results of heat pumps, so to enrich the BREDEM / SAP method.

Presented in the next chapter are results and discussion from the use of SAP and dynamic simulation tools (as detailed in chapter 3). Also presented in the 5th chapter are further results and discussion from the IDEAS method, as detailed in this chapter. The importance of comfort ratio and optimum start is presented and discussed.

CHAPTER FIVE

5   RESULTS AND DISCUSSION

5.1   Introduction

A selection of the results gained from the research detailed in prior chapters will be presented and discussed in this section of the thesis.   Discussion of Results for the following research areas will be presented:

- **Solar Energy Technologies**
  - PV in SAP and PVSyst
  - Solar Domestic Hot Water (SDHW) in SAP and TRNSYS

- **Inverse Dynamics Based Energy Assessment and Simulation (IDEAS)**
  - IDEAS implementation in Microsoft Excel – 3rd Order
    - Continuous vs. Digital RIDE
  - IDEAS Implementation – Matlab 3rd Order Model
    - Comfort Temperature
    - Poorly Insulated Test Case Example
    - Well Insulated Test Case Example
    - Effect of U-Value of Furniture and Internal Mass
  - IDEAS Implementation – Matlab 4th Order Model
    - Matlab vs. BREDEM results
      - Poorly Insulated House
        - Temperature
        - Energy
      - Well Insulated House
        - Temperature
        - Energy
    - Optimum Start in 4th Order Matlab Model

5.2 Solar Energy Technologies

5.2.1 PV Discussion of Results

For the calculation of PV data it was found that detailed simulation tools such as PVSyst record and differentiate between the recorded nominal power and Peak Maximum Power Point (PMPP), and in some cases there can be a discrepancy. This discrepancy is apparent in SAP results as only the nominal rating of a PV panel is recorded and used for results calculation. This can cause some error in results as, for example, a 200W nominal power PV panel can have a PMPP which is +/- 5% this figure. SAP does not record this difference and so all panels of a nominal rating are recorded identically in SAP. Analysis of the major factors which can affect the calculated kWh/year for PV determined that the inverter used to convert from DC to AC could have a dramatic effect on energy available from a PV system (Salas and Olías, 2009). The effect of the PV inverter upon the kWh/year output is analysed and discussed in the next section.

5.2.2 Effect of the inverter to a PV system

5.2.3 PV kWp Measurement

The kWp figure in SAP is that measured for the PV array in question under irradiation of 1 kW/m². Standard Test Conditions (STC) are 1,000Watts / m² solar irradiation with an air temperature of 25° (Blaesser and Rossi, 1988).

5.2.4 Suggestions for PV Inverter Inclusion in SAP

5.2.4.1 *Current SAP PV Equation:*

From SAP, the electricity produced per year by a PV Module is calculated as follows:

```
0.8 * kWp * S * Z_PV
```

Where:

0.80   –   SAP empirical factor for PV

S   –   Annual solar radiation

Z_{PV} –   Overshading factor

5.2.4.2 *Proposed SAP PV Equation:*

It is proposed that an Inverter Factor η_{EU} is added to the above equation as follows:

```
0.86 * η_EU * kWp * S * Z_PV
```

Where:

0.86   –   SAP empirical factor for PV

η_{EU} –   European Inverter Efficiency

S   –   Annual solar radiation

Z_{PV} –   Overshading factor

The electricity produced by the PV module in kWh/year would be amended to include the additional term, ' η_{EU} ' and would modify the existing SAP empirical factor of 0.8 to 0.86.

5.2.4.3 *SAP Empirical Factor for PV of 0.86:*

SAP utilises a factor 0.8 in the PV equation to account for all PV loses, including those of a PV Inverter. The 0.8 is derived from measurements of output achieved versus solar radiation. It is proposed that inverter loses are removed from the Empirical Factor, and that inverter loses are based directly upon the European Inverter Efficiency. The result of this step is to increase the SAP Empirical Factor from 0.8 to 0.86. The figure 0.86 is derived from the current Empirical Factor of 0.8 / the proposed SAP Typical Inverter Value of 0.93.

η_{EU} –   European Efficiency of Inverters[†]

The European Efficiency of Inverters has been in use throughout Europe since 1991 and is the function of the efficiency at defined percentage values of nominal AC power (Salas and Olías, 2009). The European Efficiency of Inverters Factor, **η_{EU}**, is a weighted average comprised of the addition of 6 multiplied terms which test an inverter under varying percentage loads. The weighted average is a useful tool and single term of reference for consumers and designers, as PV systems with Inverters are installed in a wide array of localities with varying solar resource (Bower et al., 2004). The European Efficiency of Inverters Factor, **η_{EU}**, is defined in the British Standard BS EN 50530 - Overall efficiency of photovoltaic inverters (Bründlinger et al., 2009).

The European Efficiency is defined as follows:

```
ηEU = (0.03 * η5%) + (0.06 * η10%) + (0.13 * η20%) +( 0.10
* η30%) + (0.48 * η50%) + (0.20 * η100%)
```

Where $\eta i\%$ is the conversion efficiency at i% of the inverter ouput rated power (Valentini et al., 2008).

The European Efficiency can be viewed in Figure 5.1 below:

Factor	Inverter Power Level	Weighting Factor	
		High-Insolation[1]	Low-Insolation[2]
F_1	5%	0.00	0.03
F_2	10%	0.04	0.06
F_3	20%	0.05	0.13
F_4	30%	0.12	0.10
F_5	50%	0.21	0.48
F_6	75%	0.53	0.00
F_7	100%	0.05	0.20
[1] – Based on irradiance and temperature data representative of Southwest US. [2] – Also known as European Efficiency.			

Figure 5.1 - Weighting factors for calculating Weighted Efficiency

---

[†] Comparable with the Californian Energy Commission (CEC) weighted factor for Inverter efficiency.

The European Efficiency utilses the Weighting Factors in the Low-Insolation column of Figure 5.1 with the corresponding Inverter Power Levels to calculate an efficiency figure for inverters based upon the irradiance distribution in North Western Germany (Salas and Olías, 2009).

Figure 5.1's High-Insolation Weighting Factors are not taken into account for the European Efficiency and are utilised exclusively for the California Energy Commission (CEC) Efficiency Rating – utilsed primarily in North America and based on upon irradiance distribution for Southwest, (Bower et al., 2004).
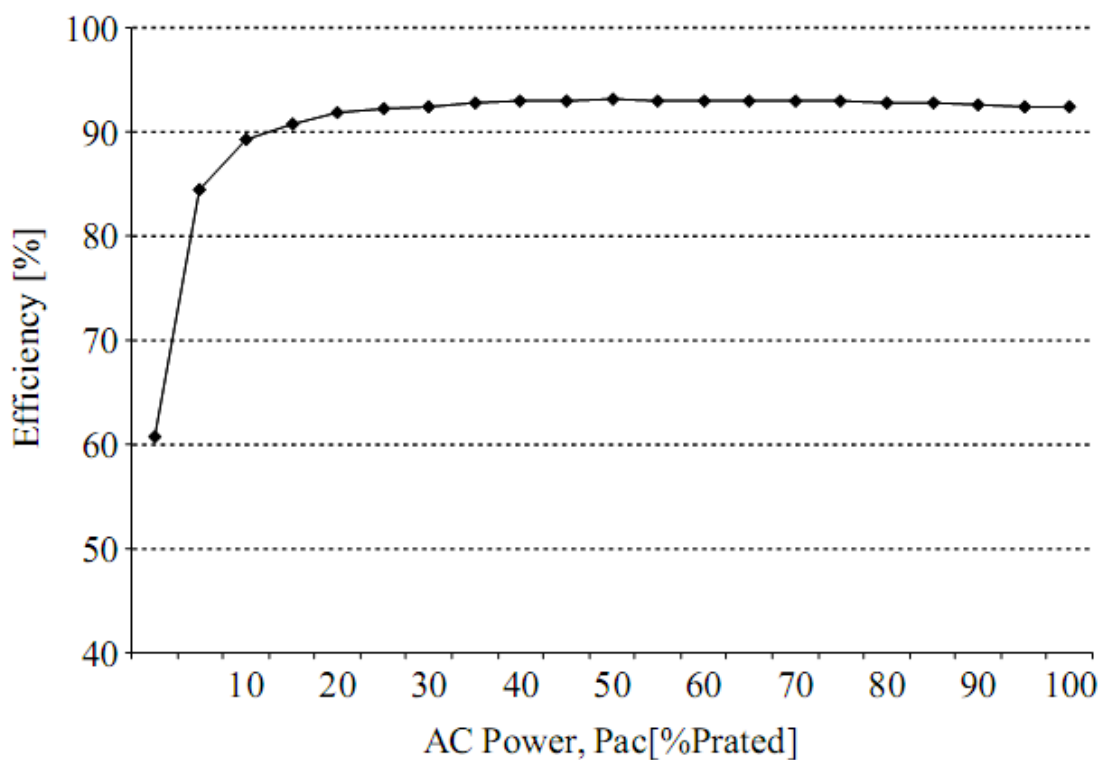
Figure 5.2 - Static Power Efficiency vs AC Power (Islam et al., 2006)

Figure 5.2 graphically represents a typical Inverter efficiency curve. It is

suggested that η_{EU} is utilised in the proposed SAP PV calculation to signify the European Efficiency of Inverters. The term η_{EU} would be filled by manufacturer supplied data. European Efficiency is readily available from manufacturer supplied data – such as SMA[‡].

5.2.5 Comparing European Normalised Average Efficiencies[§].
- Of all Inverters with a nominal power of 2kW:
  - Max European Efficiency: 95.7% (**Aixcon PT 2000**)
  - Min European Efficiency: 90.99% (**Exendis Gridfit 2000**)
- Of all Inverters with a nominal power between 1.8kW and 2.2kW:
  - Max European Efficiency: **96.9**% (**Sunways NT 2600**)
  - Min European Efficiency: 90.99% (**SMA PV-WR 86.57**)

Therefore the difference between the maximum and minimum euro efficiency is relatively close for all 2kW Inverters, but is in the region of 10% for Inverters in the 1.8kW – 2.2kW power range. The majority of PV systems installed domestically would require an inverter sized between 1.8 kW and 2.2 kW.

5.2.6 PV / Inverter Comparison
The output of three PV Array's (each rated at 2kW) was compared to each other with the use of two PV Inverters - Sunny Boy SB 2100TL and Suntechnics STW1900. For the purposes of SAP, efficiency of the PV construction material is not the concern as the PV arrays are calculated by kWp size of the system. To compare fairly with SAP, all kWh/year figures were calculated in PVSyst based upon weather data for Sheffield. Table 5.1 details the effect of different inverter upon PV Array output in kWh / year.

[‡] http://www.sma.de/en/products.html

[§] Inverter Data from PVSyst

143

Table 5. 1 - Effect of different Inverter upon PV Array output in kWh/year

PV Array (2kWp system)	PV Inverter	kWh/year (reduction in kWh output from best case in brackets if applicable %)	European Normalised Average Efficiencies (%) from PVSyst (efficiency reduction in brackets if applicable %)	PV Material	PVSyst PMPP (W)	PVSyst Inverter Nominal AC Power (kW)
Eurener PEPV 200	Sunny Boy SB 2100TL	1580	95.2	Polycrystalline	194.8	2
Eurener PEPV 200	Suntechnics - STW1900	1506 (4.7)	91.6 (3.6)	Polycrystalline	194.8	1.8
SCG 50-HV-F	Sunny Boy SB 2100TL	1808	95.2	CIS Thin Film	52.8	2
SCG 50-HV-F	Suntechnics - STW1900	1728 (4.4)	91.6 (3.6)	CIS Thin Film	52.8	1.8
Kyocera KC200GHT	Sunny Boy SB 2100TL	1632	95.2	Polycrystalline	200.3	2
Kyocera KC200GHT	Suntechnics - STW1900	1558 (4.6)	91.6 (3.6)	Polycrystalline	200.3	1.8
Eurener MEPV 220	Sunny Boy SB 2100TL	1644	95.2	Monocrystalline	221.5	2
Eurener MEPV 220	Suntechnics - STW1900	1571 (4.5)	91.6 (3.6)	Monocrystalline	221.5	1.8

The Sunny Boy SB 2100TL was found to have a Euro Efficiency of 95.2%, in comparison to the Suntechnics STW1900 with a Euro Efficiency of 91.6%. Table 5.1 highlights that for each of the PV Arrays; the reduction is in the region of 4.6%.

Another important finding was the difference in the manufactures Rated Power of a PV Panel as opposed to the PVSyst Peak Maximum Power Point. Table 5.1 highlights the following: The Eurener PEPV 200 has a PMPP of

194.8W, SCG 50-HV-F has a PMPP of 52.8W, Kyocera KC200GHT has a PMPP of 200.3W and Eurener MEPV 220 has a PMPP of 221.5W. Therefore, the primary reason why the results for the PEPV 200 are low in kWh/year terms is that the PV panels which are rated by the manufacturer at 200W have a PMPP which is 2.5% lower at 195W; Similarly, the results in kWh/year for the SCG 50-HV-F are high in Table 2 as the PV panels rated by the manufacturer at 50W have a PMPP which is 5% higher at 53W. In future research it is recommended that the PMPP of a panel is measured and used in calculations to compare kWp of a system. Manufacturer ratings can only be used as a guideline to the output of the panel.

It was also the case that the inverter with the lower nominal AC power, the Suntechnics model, happened to have the lower European normalised efficiency. This raised the question; does inverter nominal AC power have an effect on efficiency? All inverters in PVSyst with a nominal AC power of 1.8-2.2kW were selected and a chart plotting inverter efficiency vs. inverter power was created.
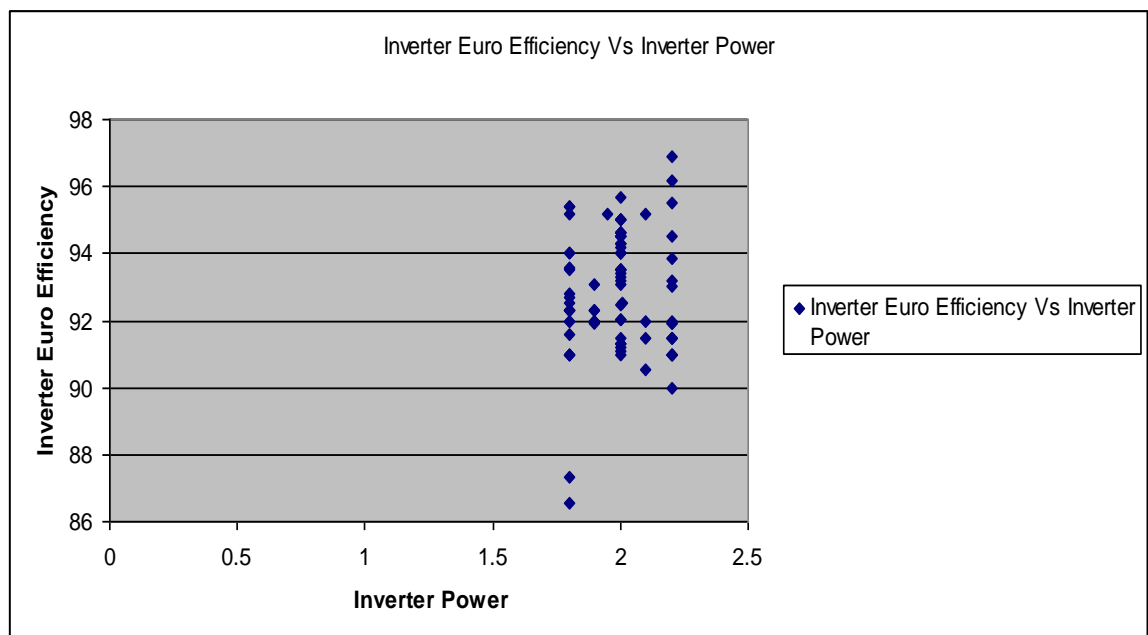
Figure 5.3 - Inverter Euro Efficiency Vs Inverter Power

Figure 5.3 highlights that there is an upwards trend in the increased Efficiency of an Inverter as the Power of the Inverter increases. Inverter Loses can therefore play a large part in determining the final kWh/year output of a PV System.

5.2.7 Differences between potential SAP typical and default values for inverters:

In the SAP PV equation, the 0.8 factor is a typical value which is fixed and cannot be altered. A SAP typical value is the best fair figure to be used. Default SAP values are deliberately low to encourage the use of real data in SAP. A comparison was made between all inverters sized between 1.8 and 2.2 kW to produce the mean, max and min inverter efficiencies.
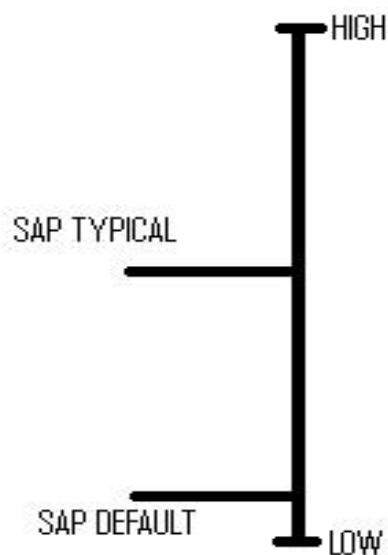
Figure 5.4 - SAP Default vs. SAP Typical Values

Figure 5.4 above details the differences between SAP Typical and SAP Default values as used in SAP calculations.

5.2.7.1 *Inverters of a nominal inverter power of 1.8 to 2.2 kW:*

- Of all Inverters with a nominal power between 1.8kW and 2kW:

    - Mean Inverter Efficiency: 93%

    - Max Inverter Efficiency: 97%

    - Min Inverter Efficiency: 87%

Therefore, based upon the data for Inverter Euro Efficiency for 1.8 - 2.2 kW inverters, a SAP typical efficiency of 93 would be given as opposed to a SAP Default efficiency of 0.87.

With the proposed revision of the SAP PV equation to: $0.86 * \eta_{EU} * kWp * S * Z_{PV}$, a default SAP figure of 0.87 could be provided to encourage the use of real European Efficiency figures. To maintain consistency with the current SAP PV equation, the proposed SAP empirical factor of $0.86 *$ the η_{EU} Typical figure of 0.93 equals the SAP V9.90 Empirical Factor:

```
η_EU Typical * SAP empirical factor for PV = 0.8
```

5.2.8 Effect of Inverter to the output of a PV Array:

Table 5.2 details the effect an inverter can have on the output in kWh/year of a PV Array (of significant size). Inverter Loses vary from 3.8% (4972kWh/year production) to 11.4% (4577kWh/year).

PV Panels / Array	Inverter	Model	kW	V	Inverter loss during operation (%)	Available energy at inverter output (kWh)
Kyocera KC200GHT - 3 Strings of 10	Mastervolt	QS6400	5.2	100-380	6.4	4839
Kyocera KC200GHT - 3 Strings of 10	Motech	5300 U	5.3	200-550	5.6	4881
Kyocera KC200GHT - 3 Strings of 10	Sharp	JHG 624	5.5	80-350	11.4	4577
Kyocera KC200GHT - 3 Strings of 10	Omron	KP 55F	5.5	100-370	6.7	4824
Kyocera KC200GHT - 3 Strings of 10	Aros	Sirio 6000P	6	180-550	5.6	4881
Kyocera KC200GHT - 3 Strings of 10	Power One	PVI-6000-OUTD	6	90-580	4	4964
Kyocera KC200GHT - 3 Strings of 10	Italcoel	SGM2-6	6.4	150-750	8.1	4752
Kyocera KC200GHT - 3 Strings of 10	Energetica	ENP 10	7	150-530	6.3	4768
Kyocera KC200GHT - 3 Strings of 10	Sunny Boy	4200 TL HC	4	125-600	4.6	4888
Kyocera KC200GHT - 3 Strings of 10	Aixon	PT 9000	7.2	125-420	7	4805
Kyocera KC200GHT - 3 Strings of 10	Power One	PVI-5000	4.6	90-580	3.8	4972

Table 5.2 - Available kWh at inverter output for one specified PV array

5.2.9 Inverter - Conclusion

SAP cannot add new data collection fields to the nth degree of detail to model systems as that would go against the low parameterised, easy to use design of SAP. However, when the addition of one field can make a substantial improvement to the quality of data produced via the SAP Methodology, this should be considered. **The addition of a field for the European Efficiency of Inverters to the SAP equation to calculate the energy produced by a PV array is an example of allowing manufacturer data to be inputted to allow SAP to produce more accurate results.** This discussion has highlighted the importance of the inverter to the setup of a domestic PV system. **The use of a SAP default figure for the European Efficiency of Inverters allows for consistency with the current equation used to calculate the electricity produced.** The use of manufacturer provided data for the European Efficiency of Inverters will allow for the generation of more accurate results from SAP.

5.2.10 SDHW Discussion of Results

The hot water draw off profile cannot be altered in SAP and this emphasises that the figures produced by SAP are representative only. This is a major difference between SAP and TRNSYS; TRNSYS results are specific to each particular case with exact details simulated and are not designed to be representative across a range of cases. Tank losses were found to be an area where SAP and TRNSYS compared poorly. A major factor in this was that SAP was found to ignore losses from the solar store section of a tank and deal with these in the collector performance factor ($f(a_1/ \eta 0)$). The collector performance factor has a similar purpose to the 0.8 factor in the SAP PV calculation – many factors which a DSM such as TRNSYS would record independently are accounted for by one simplified figure. The collector performance factor also underlines that SAP does not allow for the recording of an a_2 term (the second-order loss coefficient), corresponding to a_1.

The findings illustrate that SAP seems to systematically overestimate the performance of PV and SDHW systems for unfavourable orientations and that this could be caused by the impact of incidence angle not being taken into account in SAP. An additional SAP table detailing Transmitted Solar Radiation could be added to the SAP Methodology to improve SAP in this area. **The centralised weather location of Sheffield utilised by SAP allows for homes throughout the UK to be compared directly. However, this has the effect of overestimating PV and SDHW output in northerly areas of the UK whilst underestimating output in southerly areas of the UK.** Different system configurations and weather data locations were simulated and showed significant differences in performance, up to 35%. This seems to be even more the case for SDHW systems with high efficiency collectors; further work is required in this area. SAP ratings are typically affected by differences smaller than 1, but in some cases differences of 3 have been noted. As simplified methodologies such as SAP are sometimes used to rank energy saving measures, these differences can be significant.

5.2.11 Solar Energy Technologies - Conclusion

Simplified assessment methodologies such as SAP and DSMs such as PVSyst or TRNSYS all play a role in reducing the environmental impact of the built environment. The solar energy technologies work has shown that some of the discrepancies between SAP and detailed results could be resolved by increasing the modelling resolution of SAP in the following respects:

- **Considering different weather locations would allow renewable energy technologies to be ranked more fairly**, as illustrated by the differences between results in Efford and Eskdalemuir
- **For PV systems, including the Incidence Angle Modifier effects into incident radiation tables would give a fairer representation of non-optimal PV array orientations.**

- **For SDHW systems, increasing the time resolution of the modelling equation would allow to account for the (mis)match between solar heat availability and demand.** This would allow a better assessment of systems with a lower or higher solar fraction than the typical one. The time resolution of one year in SAP 2005 (and previous versions of SAP) has been increased to monthly values in SAP 2009. Work with the IDEAS model has shown the benefits that could be gained from moving the SAP methodology to a time resolution measured in minutes not months

5.3 IDEAS Implementation – Excel 3rd Order IDEAS

5.3.1 Digital vs. Continuous

As detailed in chapter 4, the IDEAS model was firstly created as a 3rd order model in Microsoft Excel, using the Continuous RIDE control algorithm. A time delay instability was found due to the 5 minute time resolution employed in the Microsoft Excel implementation. The 3rd order model was then updated to use the Digital RIDE Algorithm in Microsoft Excel. The results of the comparison between the two are detailed in Appendix T – Continuous to Digital Transformation using a Zero-Order Hold (ZOH).

5.3.1.1 *IDEAS in Excel: Digital vs. Continuous – Conclusion*

The graphs detailed in Appendix T highlight that the IDEAS models, using the continuous and digital RIDE algorithms, can produce comparable results for a highly insulated and a poorly insulated test case. The results from both incarnations of the IDEAS model are also compared to BREDEM to highlight that BREDEM comparable results are being produced. A comparison between Digital and Continuous IDEAS for a poorly insulated test case highlights that poorly insulated values in the Continuous RIDE version of IDEAS result in instabilities due to the time delay caused by the 5 minute sample period. The Digital RIDE version of IDEAS does not have a time-delay-instability with

poorly insulated U-Values.

Both the continuous and digital versions of the IDEAS model have an issue when compared with BREDEM as the curve fit for temperatures is very good but the IDEAS model results are constantly lower than that of BREDEM over the shoulder months.

The results from the continuous and digital versions of IDEAS are based upon the air temperature being tracked. It was hypothesised that the comfort temperature should in fact be tracked as this appears to be what was recorded in the original BRE SAP/BREDEM field trails. Additionally, it was hypothesised that some of the time delay issues suffered by the 5minute time resolution in the continuous RIDE IDEAS model could be overcome by the use of a time resolution of 1 minute. To update the tracking temperature from air temperature to comfort temperature is an onerous undertaking in Excel. Additionally, the update the a 5 minute time resolution to a 1 minute time resolution is very difficult due to amount of data this would create in Excel. Over 105,000 rows of data are required for the IDEAS model running at a 1 minute time resolution. Therefore the decision was taken to move the 3rd order model to Matlab where greater flexibility with regards to areas such as the tracking of comfort temperature and updating the resolution of the model is offered. The use of Microsoft Excel has been useful due to its flexibility, transparency and quick graphing capabilities.

Results from the 3rd Order Matlab IDEAS model are discussed in the next section.

5.4   IDEAS Implementation – Matlab 3rd Order

As detailed in the 4th chapter and in the previous section, the decision was made to move the excel model to Matlab due to concerns with the results from the Excel IDEAS 3rd order model. In addition to this, Matlab offers the same

transparency of design and greater flexibility than Microsoft Excel. The graphs for the Matlab 3rd Order model presented have been produced using Excel based upon Matlab produced results.

5.4.1 Comfort Temperature

The move to track comfort temperature was one of the main factors in the decision to move the IDEAS model to Matlab. This section details the effect that various comfort temperature ratios can have upon the comfort temperature and energy consumption produced by IDEAS. The result of each ratio combination in IDEAS is plotted against SAP/BREDEM.

5.4.2 Poor U-Value Test Case (structure 2.1W/m²K): compare with SAP/BREDEM

The following values were used as a test case between IDEAS and SAP/BREDEM, representing a poorly insulated home.

```
Mv  = 0.040156217; %FROM BREDEM    %(Kg/s)  Mass of the dwelling air
Ca = 1012;        %FROM BREDEM     %J/(kgK) Specific heat capacity of air
Us = 2.1;         %FROM BREDEM CELL AB47    %(W/m²K)    SAP Heat transfer coeff. of the
structure
As = 81.8;        %FROM BREDEM CELL AA47    %m^2       Surface area of structure
Ur = 2.3;         %FROM BREDEM CELL AB49    %(W/m²K)   Heat transfer coeff. of roof
Ar  = 44.4;        %FROM BREDEM CELL AA49    %(m²)      Area of Roof
Uw  = 4.167;      %FROM BREDEM CELL AB53    %(W/m²K)  Heat Transfer Co-Efficient of the
Windows
Aw  = 16.9;       %FROM BREDEM CELL AA53 %(m²)  Area of the Windows
Ma  = 249.795;    %FROM BREDEM    %kg       Mass of the air
Pa  = 1.22;       %FROM BREDEM    %kg/m3    Density of Air
Va  = 222;        %FROM BREDEM CELL AC6     %m3       Volume of Air
Ms  = 18203.73;   %FROM BREDEM (Total External Thermal Mass * 2/3)    %kg    Mass
of Structure
Cs  = 800;            %J/(kg.K)   Specific Heat Capacity of Structure
Uf  = 0.7;        %FROM BREDEM CELL AB48    %(W/m²K)   Heat Transfer Co-Efficient of the
Floor
Af  = 44.4;       %FROM BREDEM CELL AA48    %(m²)     Area of the Floor
Mft = 8828.8;         %kg       Mass of the Furniture
Cft = 900;        %J/(kg.K)   Specific Heat Capacity of Furniture
% Value for Wood, oak
% http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html
Uft = 1.2;          %(W/m²K)   Heat Transfer Co-Efficient of the Furniture
Aft = 120.7       %FROM BREDEM    %m2      Area of Internal Mass in a Dwelling
```

5.4.2.1 Ratio: Ta = 0.5 / Ts = 0.0 / Tft = 0.5

Ta_Ratio = 0.5; Ts_Ratio = 0.0; Tft_Ratio = 0.5;
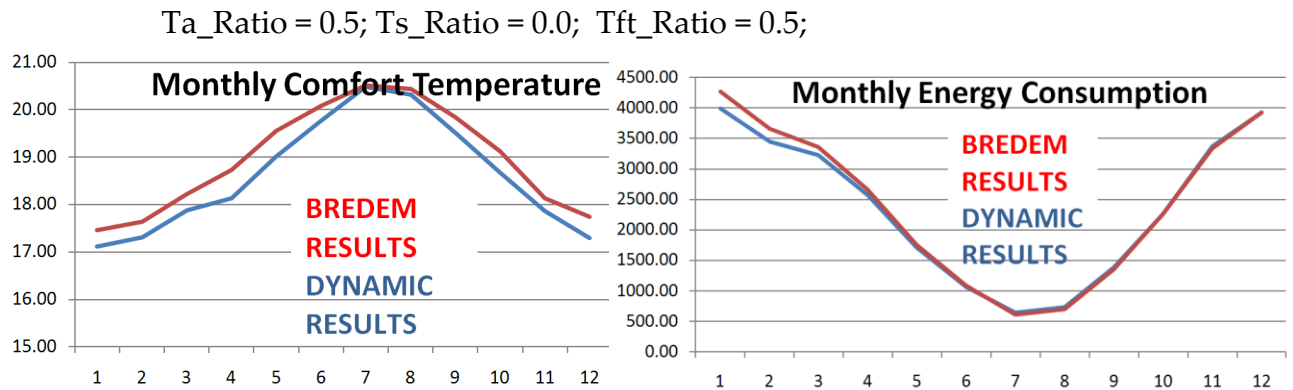
Figure 5.5 - Comfort Temperature Ratio: Ta = 0.5 / Ts = 0.0 / Tft = 0.5; Comfort Temperature and Energy Consumption

The above figure highlights that with a ratio of Ta = 0.5 / Ts = 0.0 / Tft = 0.5, the Comfort Temperature is a very good fit between the 3rd Order Continuous RIDE IDEAS Model and BREDEM 2009. The Monthly Energy Consumption and Monthly Comfort Temperature are shown to both be within a 3% match over the year with BREDEM results.

5.4.2.2 Ratio: Ta = 0.6 / Ts = 0.0 / Tft = 0.4, Uft = 2W/m^2K

Ta_Ratio = 0.6; Ts_Ratio = 0.0; Tft_Ratio = 0.4;
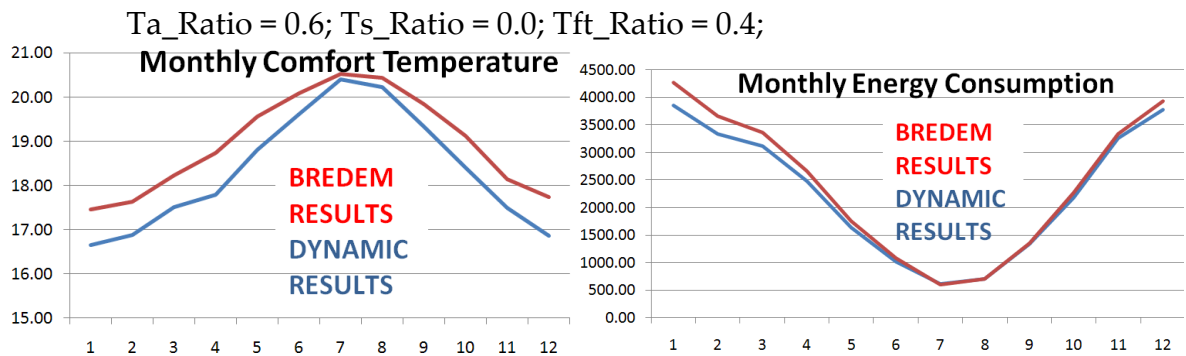
Figure 5.6 - Comfort Temperature Ratio: Ta = 0.6 / Ts = 0.0 / Tft = 0.4; Comfort Temperature and Energy Consumption. Uft = 2W/m²K

The above figure highlights that with a ratio of Ta = 0.6 / Ts = 0.0 / Tft = 0.4, the Comfort Temperature is a good fit between the 3rd Order Continuous RIDE IDEAS Model and BREDEM 2009. The Monthly Energy Consumption is shown to be comparable in the 3rd Order Continuous RIDE IDEAS Model, with a 7% deviation in results over the year. The comfort temperature is lower in the

154

IDEAS model over the heating season with a 5% deviation of results.

5.4.2.3   U-Value of Furniture & Internal Mass Model Sensitivity

The U-Value for Furniture and Internal Mass was then updated to gauge the effect on temperature and Energy Consumption. In the following example, the U-Value of the furniture and Internal Mass was updated from 2 to 1W/m²K.

Ta_Ratio = 0.4; Ts_Ratio = 0.0; Tft_Ratio = 0.6;
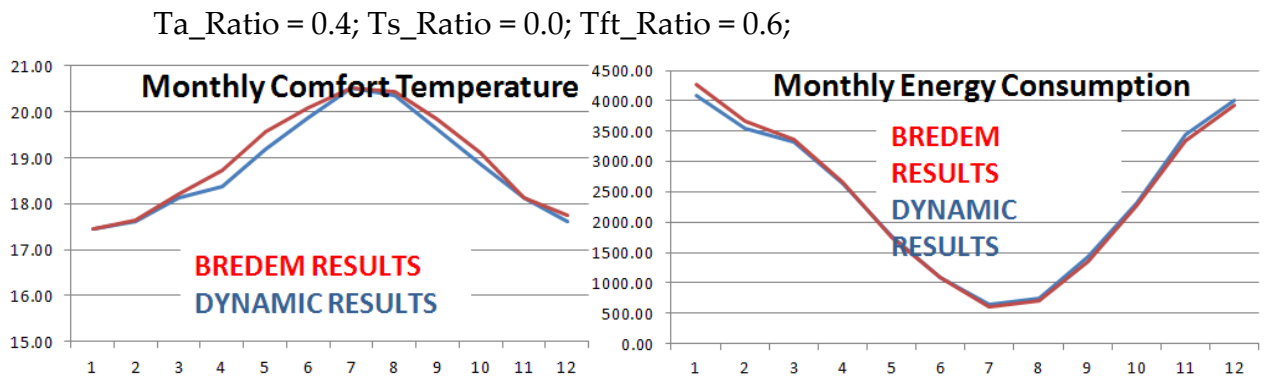
Figure 5.7 - Comfort Temperature Ratio: Ta = 0.4 / Ts = 0.0 / Tft = 0.6; Comfort Temperature and Energy Consumption, U-Value of Furniture and Internal Mass updated to 1W/m²K

Figure 4.15 highlighted that with a ratio of Ta = 0.4 / Ts = 0.0 / Tft = 0.6 and a U-Value for the furniture and Internal Mass of 2W/m²K, the Comfort Temperature is a very good fit between the 3rd Order Continuous RIDE IDEAS Model and BREDEM 2009 (99.8% for comfort, 101.67% for energy). Figure 5.7 above demonstrates that there is still a very good match between BREDEM and IDEAS when the U-Value of the furniture and internal mass is updated to 1W/m²K, the match is now 99.25% for Comfort Temperature and 100.33% for Energy Consumption over the year.

5.4.2.4   Mass of Furniture & Internal Mass Model Sensitivity

The Mass value for Furniture & Internal Mass was then updated to gauge the effect on temperature and Energy Consumption. In the following example, the mass of the furniture and internal mass was halved from 8828.8Kg to 4414.4Kg. A 1W/m²K was used as in figure 4.27.   The ratio remains as:

Ta_Ratio = 0.4; Ts_Ratio = 0.0; Tft_Ratio = 0.6;
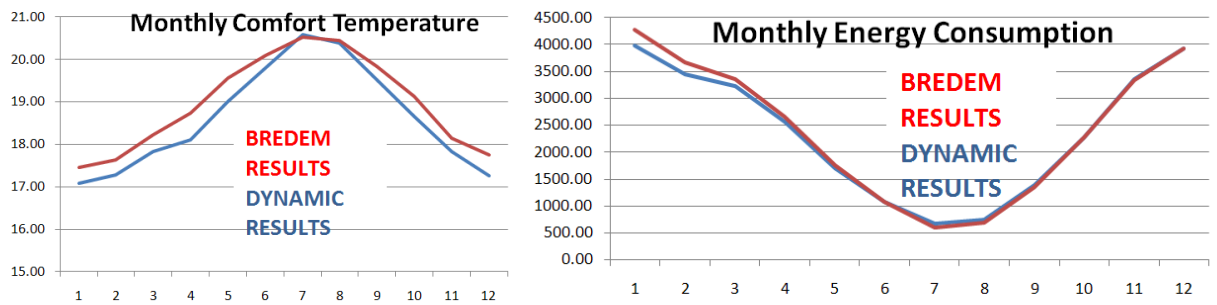
Figure 5.8 - Comfort Temperature Ratio: Ta = 0.4 / Ts = 0.0 / Tft = 0.6; Comfort Temperature and Energy Consumption, Mass of Furniture and Internal Mass halved to 4414Kg

Figure 4.27 highlighted that with a ratio of Ta = 0.4 / Ts = 0.0 / Tft = 0.6 and a Mass Value for the furniture and Internal Mass of 8828.8Kg, the Comfort Temperature is a very good fit between the 3rd Order Continuous RIDE IDEAS Model and BREDEM 2009. Figure 5.8 demonstrates that there is still a very good match between BREDEM and IDEAS when the Mass of the furniture and internal mass is halved to 4414Kg, the match is now 98.17% for Comfort Temperature and 97.84% for Energy Consumption over the year. Therefore, lowering the mass of the Furniture and Internal Mass has had the effect of slightly reducing the Comfort Temperature and Energy Consumption match of the IDEAS model with SAP/BREDEM.

5.4.3 Improved U-Values Test Case (structure 1W/m²K); compare with BREDEM

To gain another test case representative of a newer dwelling, the U-Values were updated as follows:

```
Mv  = 0.040156217; %FROM BREDEM    %(Kg/s)  Mass of the dwelling air
Ca = 1012;        %FROM BREDEM      %J/(kgK) Specific heat capacity of air
Us = 1;       %FROM BREDEM CELL AB47    %(W/m²K)    SAP Heat transfer coeff. of the
structure
As = 81.8;        %FROM BREDEM CELL AA47   %m^2        Surface area of structure
Ur = 1;        %FROM BREDEM CELL AB49    %(W/m²K)    Heat transfer coeff. of roof
Ar  = 44.4;        %FROM BREDEM CELL AA49    %(m²)       Area of Roof
Uw  = 1.852;       %FROM BREDEM CELL AB53    %(W/m²K)   Heat Transfer Co-Efficient of the
Windows
Aw = 16.9;        %FROM BREDEM CELL AA53 %(m²)   Area of the Windows
Ma  = 249.795;     %FROM BREDEM     %kg         Mass of the air
Pa  = 1.22;       %FROM BREDEM      %kg/m3      Density of Air
Va  = 222;        %FROM BREDEM CELL AC6      %m3         Volume of Air
Ms  = 18203.73;    %FROM BREDEM (Total External Thermal Mass * 2/3)      %kg       Mass
of Structure
```

```
Cs  = 800;          %J/(kg.K)   Specific Heat Capacity of Structure
Uf  = 0.7;          %FROM BREDEM CELL AB48    %(W/m²K)   Heat Transfer Co-Efficient of the
Floor
Af  = 44.4;         %FROM BREDEM CELL AA48    %(m²)      Area of the Floor
Mft = 8828.8;           %kg         Mass of the Furniture
Cft = 900;              %J/(kg.K)   Specific Heat Capacity of Furniture
% Value for Wood, oak
% http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html
Uft = 1;                %(W/m²K)    Heat Transfer Co-Efficient of the Furniture
Aft = 120.7         %FROM BREDEM    %m2        Area of Internal Mass in a Dwelling
```

The values above are indicative of an early 1980's dwelling. From the parameters in section 5.4.2 (Poor U-Value test case), updates have been made to the dwelling structure (2.1 -> 1 W/m²K), glazing (4.167 -> 1.852 W/m²K) and roof (2.3 -> 1 W/m²K). The improvements in fabric and glazing have produced a dwelling which requires less energy to heat. The comfort ratio which was tracked remained at $Ta = 0.4 / Ts = 0.0 / Tft = 0.6$.
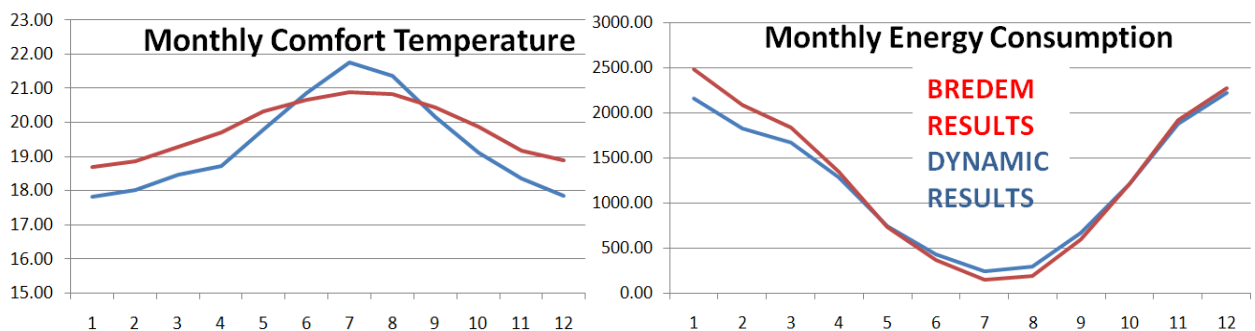
Figure 5.9 - Monthly Comfort Temperature and Monthly Energy Consumption comparison between IDEAS and BREDEM for updated based upon the values in section 5.4.4 (Improve Test Case U-Values and compare with BREDEM)

Figure 5.9 above highlights that with improved test case U-Values entered into IDEAS and BREDEM there is a good match for energy consumption. The curve fit for comfort temperature is good but there is still almost one degree of difference between the comfort temperature produced by IDEAS and BREDEM.

5.4.4   3rd Order IDEAS Model in Matlab – Conclusion

The main issues which were resolved by the move to a Matlab version of the 3rd order IDEAS model is the ability to now run the model at a 1 minute time resolution, and the ability to modify the comfort temperature ratio which is

157

tracked.

With the model now running at a 1 minute timestep, there is a penalty of a few seconds in model run time speed. However, this update of timestep now gives a greater accuracy of results and allows for the continuous RIDE algorithm to be employed to perfectly track the desired setpoint.

The tracking of comfort ratio was also a major step forward in the development of the model. A comfort temperature ratio is not provided by BREDEM and so a series of differing ratios were used and these results compared against BREDEM. For the 3rd Order Model with a single node for the structure, the best fit comfort ratio was found to be Ta = 0.4 / Ts = 0.0 / Tft = 0.6. With this comfort ratio tracked by IDEAS, the match in results between IDEAS and BREDEM for both a poorly and well insulated test case was very good. This highlights the importance of defining the correct comfort ratio in building simulation. Although the results were very good using a comfort ratio of Ta = 0.4 / Ts = 0.0 / Tft = 0.6, there was a concern over the use of this ratio: the comfort ratio will be affected to an extent by the temperature of the structure. However, using this comfort ratio the temperature of the structure was not directly taken into account in contributing to comfort.

It was found that updating the U-Value of the Furniture & Internal Mass has a negligible effect upon the Comfort Temperature and a slightly greater effect upon the Energy Consumption of the IDEAS model, with a comfort ratio of Ta_Ratio = 0.4; Ts_Ratio = 0.0; Tft_Ratio = 0.6; employed.

5.5   IDEAS Implementation – Matlab 4th Order

5.5.1   Introduction

Based upon the prior results and discussion it was decided to move the 3rd order continuous RIDE model to a 4th order model by splitting the structure to inner and outer sections.

There had been concerns regarding the comfort ratio used with the 3rd order model to achieve the best fit with BRDEM results. Now that the structure had been split to have two nodes, with only the inner (warmer) node, Tsi, having an effect upon the comfort temperature, it was possible to adjust the comfort ratios from those used with the 3rd order model. **It was found that the most appropriate comfort ratio was Ta_Ratio = 0.33; Tsi_Ratio = 0.33; Tft_Ratio = 0.33; an equal distribution between the temperature of the air, temperature of the inner structure node and the temperature of the furniture & internal mass. This definition of comfort criteria fits with the CIBSE environmental temperature definition as detailed in chapter 4.**

Following are a series of results presented for the 4th order model, for poorly and better insulated test cases with a variety of comfort ratios.

5.5.2   Poor U-Values Test Case (structure 2.1W/m²K): compare with BREDEM

The following values were used as a test case between IDEAS 4th Order and BREDEM, representing a poorly insulated home.

```
Mv  = 0.040156217;      %FROM BREDEM     %(Kg/s) Mass of the dwelling air
Ca = 1012;              %FROM BREDEM     %J/(kgK) Specific heat capacity of air
Us = 2.1;               %FROM BREDEM CELL AB47 %(W/m²K) structure
As = 81.8;                      %FROM BREDEM CELL AA47   %m^2  Surface
area of structure
Ur = 2.3;               %FROM BREDEM CELL AB49   %(W/m²K)   Roof
Ar = 44.4;              %FROM BREDEM CELL AA49   %(m²)      Area of Roof
Uw  = 4.167;            %FROM BREDEM CELL AB53   %(W/m²K)  Windows
Aw  = 16.9;                     %FROM BREDEM CELL AA53 %(m²)   Area of the
Windows
Ma  = 249.795;          %FROM BREDEM     %kg        Mass of the air
Pa  = 1.22;                     %FROM BREDEM     %kg/m3     Density of Air
```

Va = 222;	%FROM BREDEM CELL AC6	%m3	Volume of Air
Msi = 16062.12/2;	% kg		Mass of Structure Internal
Mse = 16062.12/2;	% kg		Mass of Structure External
Cs = 800;	%J/(kg.K)		Specific Heat Capacity of Structure
Uf = 0.7;	%FROM BREDEM CELL AB48	%(W/m²K)	Floor
Af = 44.4;	%FROM BREDEM CELL AA48	%(m²)	Area of the Floor
Mft = 8828.8;	%kg		Mass of the Furniture
Cft = 900;	%J/(kg.K)		Specific Heat Capacity of Furniture
Uft = 1.2;	%(W/m²K)		Heat Transfer Co-Efficient of the Furniture
Aft = 120.7	%FROM BREDEM	%m2	Area of Internal Mass in a Dwelling

5.5.2.1 Comfort Ratio: Ta = 0.33 / Tsi = 0.33 / Tft = 0.33 Results:

5.5.2.1.1 Comfort Temperature:

Monthly Comfort Temperature Comparison				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	16.99	17.46	-0.47			
February	17.22	17.64	-0.42			
March	17.74	18.22	-0.49			
April	17.97	18.73	-0.76			
May	18.76	19.56	-0.80			
June	19.36	20.09	-0.72			
July	19.81	20.52	-0.71			
August	19.78	20.44	-0.66			
September	19.15	19.85	-0.69			
October	18.41	19.12	-0.71			
November	17.69	18.14	-0.45			
December	17.15	17.75	-0.59			
AVERAGE	18.34	18.96	96.72%	17.53	18.06	97.10%

Figure 5.10 - Comfort Ratio: Ta = 0.33 / Ts = 0.33 / Tft = 0.33 Results: Comfort Temperature

5.5.2.1.2 Energy Consumption:

Monthly Energy Consumption				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	3593.20	4272.98	-679.78			
February	3126.20	3664.62	-538.42			
March	3008.80	3355.88	-347.08			
April	2436.10	2657.48	-221.38			
May	1789.10	1751.85	37.25			
June	1203.30	1086.51	116.79			
July	858.05	606.65	251.40			
August	963.61	698.34	265.28			
September	1510.80	1354.93	155.87			
October	2256.00	2268.46	-12.46			
November	3138.10	3339.96	-201.86			
December	3584.60	3929.84	-345.24			
TOTAL:	27468	28987.50	94.76%	18706.90	20831.74	89.80%

Figure 5.11 - Comfort Ratio: Ta = 0.33 / Tsi = 0.33 / Tft = 0.33 Results: Energy Consumption

With a comfort ratio of 0.33 for Ta, Tsi and Tft, it can be seen that there is a match within 5% for MIT and Energy Consumption when IDEAS and SAP/BREDEM are compared. Based upon the parameters detailed in 5.5.2 (Poor U-Values Test Case (structure 2.1W/m2K), the match between IDEAS and SAP/BREDEM is within 5% over a modelled year for comfort temperature with

160

a match of 96.72%.   Similarly the comparison between IDEAS and SAP/BREDEM for energy consumption over a modelled year is within 5% with a energy consumption match of 94.76%.

Based upon this test case, modelling a dwelling which is poorly insulated, a good match is seen between IDEAS and SAP/BREDEM for both comfort temperature and energy consumption. The use of the comfort ratio which evenly weights the impact of air, furniture & internal mass and internal structure is found to produce results which match well with SAP.

5.5.2.2 *Comfort Ratio: Ta = 0.5 / Tsi = 0.0 / Tft = 0.5 Results:*

5.5.2.2.1 Comfort Temperature:

Monthly Comfort Temperature Comparison				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	17.03	17.46	-0.43			
February	17.24	17.64	-0.40			
March	17.84	18.22	-0.38			
April	18.13	18.73	-0.60			
May	19.23	19.56	-0.33			
June	20.18	20.09	0.09			
July	21.06	20.52	0.54			
August	20.79	20.44	0.36			
September	19.70	19.85	-0.14			
October	18.64	19.12	-0.49			
November	17.72	18.14	-0.42			
December	17.11	17.75	-0.64			
AVERAGE	18.72	18.96	98.76%	17.60	18.06	97.46%

Figure 5.12 - Comfort Ratio: Ta = 0.5 / Tsi = 0.0 / Tft = 0.5 Results: Comfort Temperature

5.5.2.2.2 Energy Consumption:

Monthly Energy Consumption			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	2370.00	4272.98	-1902.98			
February	2043.90	3664.62	-1620.72			
March	1888.20	3355.88	-1467.68			
April	1446.00	2657.48	-1211.48			
May	879.85	1751.85	-872.01			
June	484.09	1086.51	-602.42			
July	264.80	606.65	-341.85			
August	321.74	698.34	-376.59			
September	752.05	1354.93	-602.88			
October	1336.00	2268.46	-932.46			
November	2069.90	3339.96	-1270.06			
December	2419.90	3929.84	-1509.94			
TOTAL:	16276	28987.50	56.15%	12127.90	20831.74	58.22%

Figure 5.13 - Comfort Ratio: Ta = 0.5 / Tsi = 0.0 / Tft = 0.5 Results: Energy Consumption

The results from the IDEAS comparison with SAP/ BREDEM based upon the parameters detailed in 5.5.2, for a comfort ratio of 0.5 Air, 0.0 Internal Structure, 0.5 Furniture & Internal Mass is displayed in figure 5.12 and 5.13 above. It can

be seen from these results that a good agreement is found between IDEAS and SAP/BREDEM for comfort temperature. This match is within 5%. The temperatures produced by IDEAS are slightly higher in figure 5.12 as opposed to figure 5.10 (when a comfort ratio of 0.33 for Ta, Tsi and Tft was employed). This is to be expected as the relative coldness of the internal structure is not taken into account in figure 5.12. The energy consumption produced by IDEAS in this test case is almost 50% lower than that of SAP/BREDEM. Therefore, this ratio produced a good match for comfort temperature but a very poor match for energy consumption. The comfort ratio of Ta = 0.5 / Tsi = 0.0 / Tft = 0.5 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.2.3   Comfort Ratio: Ta = 0.5 / Tsi = 0.25 / Tft = 0.25 Results:

5.5.2.3.1   Comfort Temperature:

Monthly Comfort Temperature Compariso				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	16.66	17.46	-0.80			
February	16.87	17.64	-0.77			
March	17.52	18.22	-0.70			
April	17.87	18.73	-0.86			
May	18.95	19.56	-0.61			
June	19.88	20.09	-0.20			
July	20.71	20.52	0.20			
August	20.52	20.44	0.08			
Septembe	19.50	19.85	-0.34			
October	18.44	19.12	-0.69			
Novembe	17.44	18.14	-0.70			
Decembe	16.77	17.75	-0.98			
AVERAGE○	18.43 ●	18.96	97.20%	17.28	18.06	95.72%

Figure 5.14 - Comfort Ratio: Ta = 0.5 / Tsi = 0.25 / Tft = 0.25 Results: Comfort Temperature

5.5.2.3.2   Energy Consumption:

Monthly Energy Consumption				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	2645.60	4272.98	-1627.38			
February	2303.90	3664.62	-1360.72			
March	2146.70	3355.88	-1209.18			
April	1644.70	2657.48	-1012.78			
May	1055.70	1751.85	-696.15			
June	588.97	1086.51	-497.54			
July	332.35	606.65	-274.30			
August	390.50	698.34	-307.83			
Septembe	857.39	1354.93	-497.53			
October	1490.30	2268.46	-778.16			
Novembe	2298.50	3339.96	-1041.46			
Decembe	2678.70	3929.84	-1251.14			
TOTAL: ○	18433 ●	28987.50	63.59%	13563.70	20831.74	65.11%

Figure 5.15 - Comfort Ratio: Ta = 0.5 / Tsi = 0.25 / Tft = 0.25 Results: Energy Consumption

The results from the IDEAS comparison with SAP/ BREDEM based upon the

162

parameters detailed in 5.5.2, for a comfort ratio of 0.5 Air, 0.25 Internal Structure, 0.25 Furniture & Internal Mass is displayed in figure 5.14 and 5.15 above. This ratio takes into account each of the components which can make up comfort temperature. The air is highly weighted in this test case.

The results highlight that there is a good match between IDEAS and SAP/BREDEM for comfort temperature over the year. Results for comfort temperature are within 5%. For energy consumption, there is a poor match of 63.59% between IDEAS and SAP/BREDEM with IDEAS energy consumption continually lower for each month compared. The comfort ratio of Ta = 0.5 / Tsi = 0.25 / Tft = 0.25 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.2.4 Comfort Ratio: Ta = 0.4 / Tsi = 0.0 / Tft = 0.6 Results:

5.5.2.4.1 Comfort Temperature:

Monthly Comfort Temperature Comparison			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	17.59	17.46	0.13			
February	17.77	17.64	0.13			
March	18.29	18.22	0.06			
April	18.53	18.73	-0.20			
May	19.47	19.56	-0.09			
June	20.32	20.09	0.23			
July	21.12	20.52	0.60			
August	20.86	20.44	0.42			
September	19.90	19.85	0.05			
October	18.96	19.12	-0.16			
November	18.18	18.14	0.04			
December	17.66	17.75	-0.09			
AVERAGE ●	19.05 ○	18.96	100.50%	18.08	18.06	100.11%

Figure 5.16 - Comfort Ratio: Ta = 0.4 / Tsi = 0.0 / Tft = 0.6 Results: Comfort Temperature

5.5.2.4.2 Energy Consumption:

Monthly Energy Consumption			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	2482.90	4272.98	-1790.08			
February	2137.90	3664.62	-1526.72			
March	1974.10	3355.88	-1381.78			
April	1522.40	2657.48	-1135.08			
May	924.38	1751.85	-827.48			
June	509.82	1086.51	-576.68			
July	276.66	606.65	-329.99			
August	335.14	698.34	-363.20			
September	789.78	1354.93	-565.15			
October	1401.80	2268.46	-866.66			
November	2158.20	3339.96	-1181.76			
December	2529.90	3929.84	-1399.94			
TOTAL: ○	17043 ●	28987.50	58.79%	12684.80	20831.74	60.89%

Figure 5.17 - Comfort Ratio: Ta = 0.4 / Tsi = 0.0 / Tft = 0.6 Results: Energy Consumption

The results from the IDEAS comparison with SAP/ BREDEM based upon the

parameters detailed in 5.5.2, for a comfort ratio of 0.4 Air, 0.0 Internal Structure, 0.6 Furniture & Internal Mass is displayed in figure 5.16 and 5.17. This ratio takes into account each of the components which can make up comfort temperature. The air is highly weighted in this test case.

Interestingly there is a 100% match between IDEAS and SAP/BREDEM over the course of the year with this comfort ratio. There is very little deviation between IDEAS and SAP/BREDEM results when each of the monthly values are compared. The same cannot be said for the energy consumption comparison however with a match found of only 58.79%. IDEAS produced energy consumption is constantly less than that of SAP/BREDEM with this comfort ratio. The comfort ratio of Ta = 0.4 / Tsi = 0.0 / Tft = 0.6 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.2.5 Comfort Ratio: Ta = 0.6 / Tsi = 0.0 / Tft = 0.4 Results:

5.5.2.5.1 Comfort Temperature:

Monthly Comfort Temperature Compariso			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	16.52	17.46	-0.94			
February	16.75	17.64	-0.89			
March	17.44	18.22	-0.79			
April	17.77	18.73	-0.96			
May	19.02	19.56	-0.54			
June	20.06	20.09	-0.02			
July	21.02	20.52	0.50			
August	20.74	20.44	0.30			
Septembe	19.53	19.85	-0.32			
October	18.34	19.12	-0.79			
Novembe	17.29	18.14	-0.85			
Decembe	16.60	17.75	-1.15			
AVERAGE○	18.42 ●	18.96	97.17%	17.16	18.06	95.02%

Figure 5.18 - Comfort Ratio: Ta = 0.6 / Tsi = 0.0 / Tft = 0.4 Results: Comfort Temperature

5.5.2.5.2 Energy Consumption:

Monthly Energy Consumption			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	2266.90	4272.98	-2006.08			
February	1957.40	3664.62	-1707.22			
March	1808.70	3355.88	-1547.18			
April	1376.10	2657.48	-1281.38			
May	839.12	1751.85	-912.73			
June	461.56	1086.51	-624.95			
July	255.62	606.65	-351.04			
August	311.26	698.34	-387.08			
Septembe	718.13	1354.93	-636.79			
October	1276.00	2268.46	-992.46			
Novembe	1987.90	3339.96	-1352.06			
Decembe	2319.50	3929.84	-1610.34			
TOTAL: ○	15578 ●	28987.50	53.74%	11616.40	20831.74	55.76%

Figure 5.19 - Comfort Ratio: Ta = 0.6 / Tsi = 0.0 / Tft = 0.4 Results: Comfort Temperature

Figures 5.18 and 5.19 highlight the comparison between IDEAS and SAP/BREDEM for a comfort ratio of 0.6 Air, 0.0 Internal Structure, 0.4 Furniture & Internal Mass based upon the parameters detailed in 5.5.2. A match within 5% for comfort temperature is found between IDEAS and SAP/BREDEM. A poor match of 53.74% is found between IDEAS and SAP/BREDEM for energy consumption with IDEAS results being constantly lower. Therefore an element of internal structure must be taken into account in the comfort ratio used if a closeness is results produced is to be found for energy consumption when IDEAS and SAP/BREDEM are compared. The comfort ratio of Ta = 0.6 / Tsi = 0.0 / Tft = 0.4 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.2.6 Comfort Ratio: Ta = 0.4 / Tsi = 0.2 / Tft = 0.4 Results:

5.5.2.6.1 Comfort Temperature:

Monthly Comfort Temperature Comparison	DYNAMIC	BREDEM	DIFF.	COLDEST 6 MONTHS DYNAMIC	BREDEM	DIFF.
January	17.34	17.46	-0.12			
February	17.52	17.64	-0.12			
March	18.07	18.22	-0.15			
April	18.35	18.73	-0.38			
May	19.28	19.56	-0.28			
June	20.10	20.09	0.01			
July	20.85	20.52	0.34			
August	20.65	20.44	0.21			
September	19.76	19.85	-0.09			
October	18.83	19.12	-0.29			
November	18.00	18.14	-0.14			
December	17.43	17.75	-0.31			
AVERAGE	18.85 ●	18.96	99.42%	17.87	18.06	98.95%

Figure 5.20 - Comfort Ratio: Ta = 0.4 / Tsi = 0.2 / Tft = 0.4 Results: Comfort Temperature

5.5.2.6.2 Energy Consumption:

Monthly Energy Consumption	DYNAMIC	BREDEM	DIFF.	COLDEST 6 MONTHS DYNAMIC	BREDEM	DIFF.
January	2721.00	4272.98	-1551.98			
February	2359.90	3664.62	-1304.72			
March	2193.70	3355.88	-1162.18			
April	1693.20	2657.48	-964.28			
May	1073.30	1751.85	-678.55			
June	598.36	1086.51	-488.15			
July	332.47	606.65	-274.19			
August	392.10	698.34	-306.23			
September	880.09	1354.93	-474.84			
October	1535.30	2268.46	-733.16			
November	2354.30	3339.96	-985.66			
December	2752.40	3929.84	-1177.44			
TOTAL:	○ 18886 ●	28987.50	65.15%	13916.60	20831.74	66.80%

Figure 5.21 - Comfort Ratio: Ta = 0.4 / Tsi = 0.2 / Tft = 0.4 Results: Energy Consumption

With a comfort ratio of 0.4 Air, 0.2 Internal Structure, 0.4 Furniture & Internal Mass, figures 5.20 and 5.21 detail the comparison between IDEAS and SAP/BREDEM results; based upon the parameters detailed in 5.5.2. There is a near perfect match when comfort temperature is compared. In each test case the comfort temperature has been within 5%, therefore the comfort ratio selected has little bearing on the temperature produced by IDEAS. For energy consumption, the match is 65.15% with IDEAS results constantly lower. This again highlights that the energy consumption produced by the IDEAS model is highly sensitive to the comfort ratio selected. The comfort ratio of Ta = 0.4 / Tsi = 0.2 / Tft = 0.4 should not be used as SAP compliant results are not produced for both MIT and energy consumption. The most appropriate comfort ratio to use was found to be that of Ta = 0.33 / Tsi = 0.33 / Tft = 0.33 for the poorly

insulated dwelling test case. With a ratio of Ta = 0.33 / Tsi = 0.33 / Tft = 0.33, results from IDEAS for temperature and energy consumption are within 5% when they are compared with SAP/BREDEM.

5.5.3   Improved U-Values Test Case (structure 1W/m²K): compare with SAP/BREDEM: 4th Order Model

The following values were used as a test case between IDEAS 4th Order and SAP/BREDEM, representing a better insulated home.

```
Mv  = 0.040156217;        %FROM BREDEM    %(Kg/s) Mass of the dwelling air
Ca = 1012;                %FROM BREDEM    %J/(kgK) Specific heat capacity of air
Us = 1.0;                 %FROM BREDEM CELL AB47 %(W/m²K) structure
As = 81.8;                %FROM BREDEM CELL AA47   %m^2  Surface area of
structure
Ur = 2.3;                 %FROM BREDEM CELL AB49   %(W/m²K)   Roof
Ar  = 44.4;               %FROM BREDEM CELL AA49   %(m²)     Area of Roof
Uw  = 4.167;              %FROM BREDEM CELL AB53   %(W/m²K)   Windows
Aw  = 16.9;               %FROM BREDEM CELL AA53 %(m²)   Area of the Windows
Ma  = 249.795;            %FROM BREDEM    %kg        Mass of the air
Pa  = 1.22;                    %FROM BREDEM    %kg/m3    Density of Air
Va  = 222;                %FROM BREDEM CELL AC6    %m3        Volume of Air
Msi = 16062.12/2;         % kg        Mass of Structure Internal
Mse = 16062.12/2;         % kg        Mass of Structure External
Cs  = 800;                     %J/(kg.K)   Specific Heat Capacity of Structure
Uf  = 0.7;                %FROM BREDEM CELL AB48    %(W/m²K)   Floor
Af  = 44.4;               %FROM BREDEM CELL AA48    %(m²)      Area of the Floor
Mft = 8828.8;             %kg        Mass of the Furniture
Cft = 900;                %J/(kg.K)  Specific Heat Capacity of Furniture
Uft = 1.2;                %(W/m²K)   Heat Transfer Co-Efficient of the Furniture
Aft = 120.7               %FROM BREDEM    %m2        Area of Internal Mass in a
Dwelling
```

5.5.3.1 Comfort Ratio: Ta = 0.3 / Tsi = 0.33 / Tft = 0.33 Results:

5.5.3.1.1 Comfort Temperature:

Monthly Comfort Temperature Compariso	DYNAMIC	BREDEM	DIFF.	COLDEST 6 MONTHS DYNAMIC	BREDEM	DIFF.
January	17.89	18.73	-0.83			
February	18.07	18.88	-0.81			
March	18.44	19.32	-0.88			
April	18.62	19.73	-1.11			
May	19.39	20.35	-0.96			
June	20.03	20.67	-0.64			
July	20.59	20.88	-0.29			
August	20.49	20.84	-0.34			
Septembe	19.80	20.45	-0.65			
October	19.03	19.90	-0.87			
Novembe	18.39	19.19	-0.79			
Decembe	17.91	18.91	-1.00			
AVERAGE	19.06 ●	19.82	96.15%	18.29	19.15	95.49%

Figure 5.22 - Comfort Ratio (structure 1W/m2K): Ta = 0.33 / Tsi = 0.33 / Tft = 0.33 Results: Comfort Temperature

5.5.3.1.2 Energy Consumption:

Monthly Energy Consumption	DYNAMIC	BREDEM	DIFF.	COLDEST 6 MONTHS DYNAMIC	BREDEM	DIFF.
January	1919.60	2442.86	-523.26			
February	1671.10	2056.49	-385.39			
March	1614.30	1805.82	-191.52			
April	1274.10	1322.75	-48.65			
May	837.07	713.31	123.75			
June	518.49	356.55	161.94			
July	336.21	137.91	198.30			
August	378.75	187.27	191.48			
Septembe	708.48	579.91	128.57			
October	1182.10	1185.07	-2.97			
Novembe	1718.10	1885.47	-167.37			
Decembe	2011.70	2241.17	-229.47			
TOTAL:	○ 14170 ●	14914.58	95.01%	10116.90	11616.88	87.09%

Figure 5.23 - Comfort Ratio(structure 1W/m2K): Ta = 0.33 / Tsi = 0.33 / Tft = 0.33 Results: Energy Consumption

With a comfort ratio of 0.33 for Ta, Tsi and Tft, it can be seen that there is a match within 5% when IDEAS and SAP/BREDEM are compared. **Based upon the parameters detailed in 5.5.3 (Improved U-Values Test Case (structure 1.0W/m2K), the match between IDEAS and SAP/BREDEM is within 5% over a modelled year for comfort temperature with a match of 96.15%. Similarly the comparison between IDEAS and SAP/BREDEM for energy consumption over a modelled year is within 5% with an energy consumption match of 95.01%.**

5.5.3.2   Comfort Ratio: Ta = 0.5 / Tsi = 0.0 / Tft = 0.5 Results:

5.5.3.2.1   Comfort Temperature:

Monthly Comfort Temperature Compariso			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	17.91	18.73	-0.81			
February	18.14	18.88	-0.74			
March	18.64	19.32	-0.68			
April	18.98	19.73	-0.75			
May	20.53	20.35	0.18			
June	22.04	20.67	1.37			
July	23.10	20.88	2.22			
August	22.43	20.84	1.60			
Septembe	20.68	20.45	0.23			
October	19.19	19.90	-0.71			
Novembe	18.31	19.19	-0.87			
Decembe	17.77	18.91	-1.14			
AVERAGE○	19.81 ●	19.82	99.96%	18.33	19.15	95.69%

Figure 5.24 - Comfort Ratio (structure 1W/m2K): Ta = 0.5 / Tsi = 0.0 / Tft = 0.5 Results: Comfort Temperature

5.5.3.2.2   Energy Consumption:

Monthly Energy Consumption			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	1262.10	2442.86	-1180.76			
February	1053.60	2056.49	-1002.89			
March	937.42	1805.82	-868.40			
April	678.82	1322.75	-643.94			
May	314.06	713.31	-399.25			
June	142.60	356.55	-213.94			
July	59.60	137.91	-78.31			
August	76.66	187.27	-110.61			
Septembe	334.18	579.91	-245.73			
October	702.75	1185.07	-482.32			
Novembe	1169.20	1885.47	-716.27			
Decembe	1391.30	2241.17	-849.87			
TOTAL:	○ 8122.3 ●	14914.58	54.46%	6516.37	11616.88	56.09%

Figure 5.25 - Comfort Ratio (structure 1W/m2K): Ta = 0.5 / Tsi = 0.0 / Tft = 0.5 Results: Energy Consumption

The comparison between IDEAS and SAP/BREDEM are shown above for a comfort ratio of Ta = 0.5 / Tsi = 0.0 / Tft = 0.5. A match within 5% can be seen for temperature. The match between IDEAS and SAP/BREDEM for energy consumption is poor at only 54.45%.

Based upon these results, the comfort ratio of Ta = 0.5 / Tsi = 0.0 / Tft = 0.5 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.3.3 Comfort Ratio: Ta = 0.5 / Tsi = 0.25 / Tft = 0.25 Results:

5.5.3.3.1 Comfort Temperature:

Monthly Comfort Temperature Compariso				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	17.73	18.73	-1.00			
February	17.85	18.88	-1.03			
March	18.32	19.32	-1.00			
April	18.61	19.73	-1.12			
May	19.89	20.35	-0.46			
June	21.06	20.67	0.39			
July	22.06	20.88	1.18			
August	21.76	20.84	0.92			
Septembe	20.41	20.45	-0.04			
October	19.10	19.90	-0.80			
Novembe	18.18	19.19	-1.01			
Decembe	17.57	18.91	-1.34			
AVERAGE	19.38 ●	19.82	97.78%	18.13	19.15	94.64%

Figure 5.26 - Comfort Ratio (structure 1W/m2K): Ta = 0.5 / Tsi = 0.25 / Tft = 0.25 Results: Comfort Temperature

5.5.3.3.2 Energy Consumption:

Monthly Energy Consumption				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	1366.00	2442.86	-1076.86			
February	1196.20	2056.49	-860.29			
March	1113.90	1805.82	-691.92			
April	822.31	1322.75	-500.44			
May	445.75	713.31	-267.57			
June	215.07	356.55	-141.47			
July	100.01	137.91	-37.90			
August	112.21	187.27	-75.06			
Septembe	367.59	579.91	-212.32			
October	758.41	1185.07	-426.66			
Novembe	1258.10	1885.47	-627.37			
Decembe	1511.20	2241.17	-729.97			
TOTAL:	○ 9266.7	● 14914.58	62.13%	7203.81	11616.88	62.01%

Figure 5.27 - Comfort Ratio (structure 1W/m2K): Ta = 0.5 / Tsi = 0.25 / Tft = 0.25 Results: Energy Consumption

The comparison between IDEAS and SAP/BREDEM are shown above for a comfort ratio of Ta = 0.5 / Tsi = 0.25 / Tft = 0.25. A match within 5% can be seen for temperature. The match between IDEAS and SAP/BREDEM for energy consumption is poor at only 62.13%.

Based upon these results, the comfort ratio of Ta = 0.5 / Tsi = 0.25 / Tft = 0.25 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.3.4 Comfort Ratio: Ta = 0.4 / Tsi = 0.0 / Tft = 0.6 Results:

5.5.3.4.1 Comfort Temperature:

Monthly Comfort Temperature Comparison			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	18.36	18.73	-0.36			
February	18.56	18.88	-0.32			
March	18.98	19.32	-0.34			
April	19.26	19.73	-0.47			
May	20.63	20.35	0.29			
June	22.09	20.67	1.42			
July	23.09	20.88	2.21			
August	22.44	20.84	1.60			
September	20.80	20.45	0.35			
October	19.45	19.90	-0.45			
November	18.71	19.19	-0.48			
December	18.25	18.91	-0.66			
AVERAGE●	20.05 ○	19.82	101.17%	18.72	19.15	97.72%

Figure 5.28 - Comfort Ratio(structure 1W/m2K): Ta = 0.4 / Tsi = 0.0 / Tft = 0.6 Results: Comfort Temperature

5.5.3.4.2 Energy Consumption:

Monthly Energy Consumption			COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	1313.90	2442.86	-1128.96			
February	1095.40	2056.49	-961.09			
March	974.17	1805.82	-831.65			
April	709.86	1322.75	-612.90			
May	324.49	713.31	-388.83			
June	146.90	356.55	-209.64			
July	60.21	137.91	-77.71			
August	76.40	187.27	-110.87			
September	346.82	579.91	-233.09			
October	732.13	1185.07	-452.94			
November	1211.40	1885.47	-674.07			
December	1444.90	2241.17	-796.27			
TOTAL:	○ 8436.6	● 14914.58	56.57%	6771.90	11616.88	58.29%

Figure 5.29 - Comfort Ratio(structure 1W/m2K): Ta = 0.4 / Tsi = 0.0 / Tft = 0.6 Results: Energy Consumption

The comparison between IDEAS and SAP/BREDEM are shown above for a comfort ratio of Ta = 0.4 / Tsi = 0.0 / Tft = 0.6. A match within 5% can be seen for temperature. The match between IDEAS and SAP/BREDEM for energy consumption is poor at only 56.57%.

Based upon these results, the comfort ratio of Ta = 0.4 / Tsi = 0.0 / Tft = 0.6 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.3.5 Comfort Ratio: Ta = 0.6 / Tsi = 0.0 / Tft = 0.4 Results:
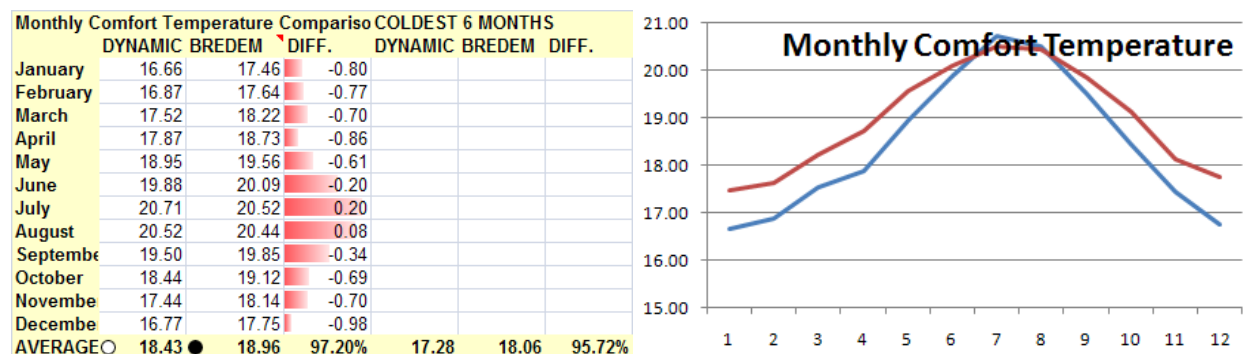
5.5.3.5.1 Comfort Temperature:

Monthly Comfort Temperature Compariso				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	17.49	18.73	-1.23			
February	17.75	18.88	-1.13			
March	18.33	19.32	-0.99			
April	18.72	19.73	-1.01			
May	20.45	20.35	0.10			
June	22.01	20.67	1.34			
July	23.11	20.88	2.23			
August	22.44	20.84	1.61			
Septembe	20.58	20.45	0.13			
October	18.95	19.90	-0.94			
Novembe	17.94	19.19	-1.24			
Decembe	17.33	18.91	-1.58			
AVERAGE ○	19.59 ●	19.82	98.85%	17.97	19.15	93.79%

Figure 5.30 - Comfort Ratio (structure 1W/m2K): Ta = 0.6 / Tsi = 0.0 / Tft = 0.4 Results: Comfort Temperature

5.5.3.5.2 Energy Consumption:

Monthly Energy Consumption				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	1214.20	2442.86	-1228.66			
February	1014.70	2056.49	-1041.79			
March	902.97	1805.82	-902.85			
April	650.69	1322.75	-672.07			
May	305.57	713.31	-407.74			
June	139.67	356.55	-216.87			
July	60.03	137.91	-77.88			
August	78.27	187.27	-109.00			
Septembe	323.24	579.91	-256.67			
October	675.70	1185.07	-509.37			
Novembe	1129.50	1885.47	-755.97			
Decembe	1341.70	2241.17	-899.47			
TOTAL: ○	7836.2 ●	14914.58	52.54%	6278.76	11616.88	54.05%

Figure 5.31 - Comfort Ratio(structure 1W/m2K): Ta = 0.6 / Tsi = 0.0 / Tft = 0.4 Results: Energy Consumption

The comparison between IDEAS and SAP/BREDEM are shown above for a comfort ratio of Ta = 0.6 / Tsi = 0.0 / Tft = 0.4. A match within 5% can be seen for temperature. The match between IDEAS and SAP/BREDEM for energy consumption is poor at only 52.54%.

Based upon these results, the comfort ratio of Ta = 0.6 / Tsi = 0.0 / Tft = 0.4 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.3.6 Comfort Ratio: Ta = 0.4 / Tsi = 0.2 / Tft = 0.4 Results:

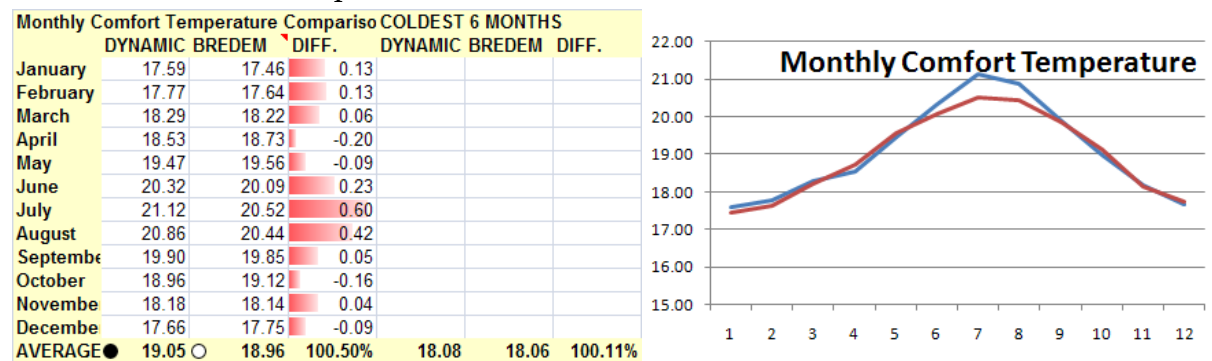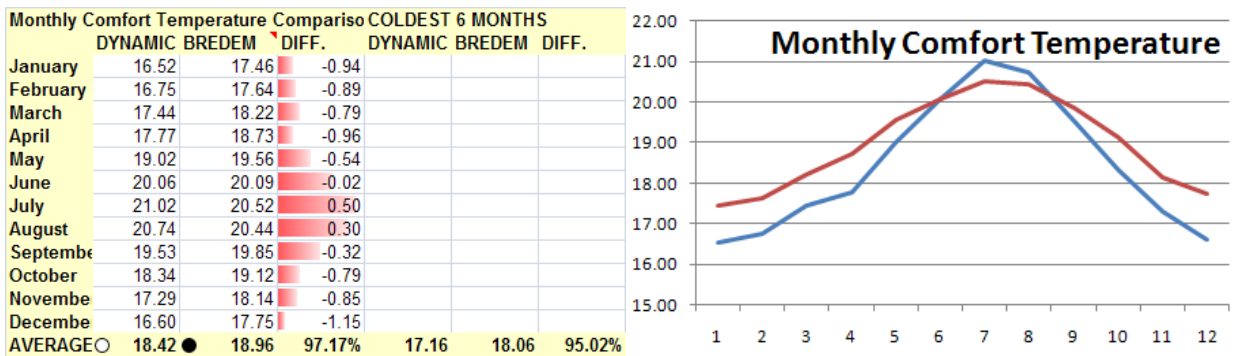#### 5.5.3.6.1 Comfort Temperature:

Monthly Comfort Temperature Compariso				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	18.24	18.73	-0.48			
February	18.37	18.88	-0.51			
March	18.78	19.32	-0.54			
April	19.02	19.73	-0.71			
May	20.16	20.35	-0.19			
June	21.30	20.67	0.63			
July	22.25	20.88	1.37			
August	21.88	20.84	1.04			
Septembe	20.58	20.45	0.13			
October	19.39	19.90	-0.51			
Novembe	18.62	19.19	-0.56			
Decembe	18.12	18.91	-0.79			
AVERAGE○	19.73 ●	19.82	99.53%	18.59	19.15	97.04%

Figure 5.32 - Comfort Ratio(structure 1W/m2K): Ta = 0.4 / Tsi = 0.2 / Tft = 0.4 Results: Comfort Temperature
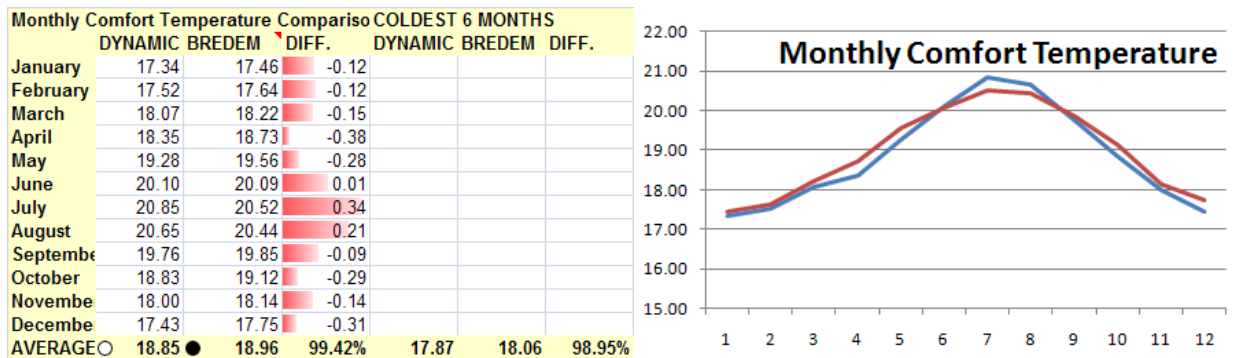
5.5.3.6.2 Energy Consumption:

Monthly Energy Consumption				COLDEST 6 MONTHS		
	DYNAMIC	BREDEM	DIFF.	DYNAMIC	BREDEM	DIFF.
January	1406.60	2442.86	-1036.26			
February	1215.80	2056.49	-840.69			
March	1120.70	1805.82	-685.12			
April	830.09	1322.75	-492.67			
May	430.75	713.31	-282.56			
June	203.19	356.55	-153.36			
July	89.56	137.91	-48.36			
August	102.12	187.27	-85.15			
Septembe	375.69	579.91	-204.21			
October	782.13	1185.07	-402.93			
Novembe	1289.60	1885.47	-595.87			
Decembe	1548.60	2241.17	-692.57			
TOTAL: ○	9394.8 ●	14914.58	62.99%	7363.43	11616.88	63.39%

Figure 5.33 - Comfort Ratio(structure 1W/m2K): Ta = 0.4 / Tsi = 0.2 / Tft = 0.4 Results: Energy Consumption

The comparison between IDEAS and SAP/BREDEM are shown above for a comfort ratio of Ta = 0.4 / Tsi = 0.2 / Tft = 0.4. A match within 5% can be seen for temperature.   The match between IDEAS and SAP/BREDEM for energy consumption is poor at 62.99%.

Based upon these results, the comfort ratio of Ta = 0.4 / Tsi = 0.2 / Tft = 0.4 should not be used as SAP compliant results are not produced for both MIT and energy consumption.

5.5.4   4th Order Comfort Criteria Conclusion

The most appropriate comfort ratio to use was found to be that of Ta = 0.33 / Tsi = 0.33 / Tft = 0.33 for the dwelling test case with improved insulation. This matches with the findings from the test case studies for the poorly insulated dwelling. **With a ratio of Ta = 0.33 / Tsi = 0.33 / Tft = 0.33, results from IDEAS for temperature and energy consumption are within 5% when they are compared with SAP/BREDEM.**

The research detailing the different comfort ratios highlights that the comfort ratio has a greater effect upon the energy consumption than the comfort temperature. **The results from the ratio where the internal structure, air temperature and internal mass are equally weighted (Ta = 0.33 / Tsi = 0.33 / Tft = 0.33) give the best fit results for the 4th order model with BREDEM over a range of U-Values.** This comparison could be improved by the implementation of optimum start in the IDEAS 4th order Matlab model.

5.5.5   4th Order Results – Optimum Start

The decision was taken to add optimum start capability to the IDEAS 4th order model so that systems of different responsiveness can be modelled. In addition the application of an optimum start algorithm in the IDEAS model may help the temperature and energy consumption match between IDEAS and BREDEM. To highlight the impact of the optimum start algorithm on results, four test cases are presented based upon the poorly insulated test case dwelling (as defined in section 5.5.2).

5.5.5.1 Optimum Start Off - A Heating System which responds quickly

Monthly Comfort Temperature Comparison			
	DYNAMIC	BREDEM	DIFF.
January	16.99	17.46	-0.47
February	17.22	17.64	-0.42
March	17.74	18.22	-0.49
April	17.97	18.73	-0.76
May	18.76	19.56	-0.80
June	19.36	20.09	-0.72
July	19.81	20.52	-0.71
August	19.78	20.44	-0.66
September	19.15	19.85	-0.69
October	18.41	19.12	-0.71
November	17.69	18.14	-0.45
December	17.15	17.75	-0.59
AVERAGE	18.34	18.96	96.72%

Monthly Energy Consumption			
	DYNAMIC	BREDEM	DIFF.
January	3593.20	4272.98	-679.78
February	3126.20	3664.62	-538.42
March	3008.80	3355.88	-347.08
April	2436.10	2657.48	-221.38
May	1789.10	1751.85	37.25
June	1203.30	1086.51	116.79
July	858.05	606.65	251.40
August	963.61	698.34	265.28
September	1510.80	1354.93	155.87
October	2256.00	2268.46	-12.46
November	3138.10	3339.96	-201.86
December	3584.60	3929.84	-345.24
TOTAL:	27468	28987.50	94.76%

Figure 5.34 - Optimum Start Off - A Heating System which responds quickly

The above figure highlights that without optimum start, there is still a close match between IDEAS and BREDEM for a poorly insulated dwelling (U–Value = 2.1W/m2K) with a fast heating system.

5.5.5.2 Optimum Start On – A Heating System which responds quickly

Monthly Comfort Temperature Comparison			
	DYNAMIC	BREDEM	DIFF.
January	17.04	17.46	-0.42
February	17.25	17.64	-0.39
March	17.77	18.22	-0.45
April	18.01	18.73	-0.72
May	18.80	19.56	-0.76
June	19.39	20.09	-0.70
July	19.83	20.52	-0.68
August	19.80	20.44	-0.64
Septembe	19.18	19.85	-0.67
October	18.44	19.12	-0.68
November	17.72	18.14	-0.42
December	17.15	17.75	-0.59
AVERAGE ○	18.37 ●	18.96	96.87%

Monthly Energy Consumption			
	DYNAMIC	BREDEM	DIFF.
January	3606.80	4272.98	-666.18
February	3133.00	3664.62	-531.62
March	3016.40	3355.88	-339.48
April	2444.10	2657.48	-213.38
May	1796.10	1751.85	44.25
June	1209.30	1086.51	122.79
July	863.30	606.65	256.65
August	968.73	698.34	270.39
Septembe	1517.50	1354.93	162.57
October	2263.90	2268.46	-4.56
November	3145.00	3339.96	-194.96
December	3580.50	3929.84	-349.34
TOTAL: ○	27545 ●	28987.50	95.02%

Figure 5.35 - Optimum Start On - A Heating System which responds quickly

The above figure highlights that with optimum start, there is slight improvement in the close match between IDEAS and BREDEM for a poorly insulated dwelling (U–Value = 2.1W/m2K) with a fast heating system. The IDEAS calculated figures are slightly higher with optimum start. Therefore with Optimum Start, the match between IDEAS and BREDEM is improved slightly for a heating system which is highly responsive.

176

5.5.5.3 Optimum Start Off - A Heating System which responds slowly

Monthly Comfort Temperature Comparison

	DYNAMIC	BREDEM	DIFF.
January	16.99	19.02	-2.03
February	17.22	19.11	-1.89
March	17.74	19.40	-1.66
April	17.97	19.65	-1.68
May	18.76	20.07	-1.31
June	19.36	20.33	-0.97
July	19.81	20.55	-0.74
August	19.78	20.51	-0.73
Septembe	19.15	20.21	-1.06
October	18.41	19.85	-1.44
November	17.69	19.36	-1.67
December	17.15	19.16	-2.01
AVERAGE	18.34	19.77	92.75%

Monthly Energy Consumption

	DYNAMIC	BREDEM	DIFF.
January	3593.20	4774.58	-1181.38
February	3126.20	4091.35	-965.15
March	3008.80	3734.17	-725.37
April	2436.10	2942.86	-506.76
May	1789.10	1909.52	-120.42
June	1203.30	1156.71	46.59
July	858.05	614.77	243.28
August	963.61	717.88	245.73
Septembe	1510.80	1465.54	45.26
October	2256.00	2501.62	-245.62
November	3138.10	3718.97	-580.87
December	3584.60	4385.52	-800.92
TOTAL:	27468	32013.49	85.80%

Figure 5.36 - Optimum Start Off - A Heating System which responds slowly

The above figure highlights that for a poorly insulated dwelling with a slowly responding heating system, there is a larger discrepancy between the results produced by IDEAS and those produced by BREDEM. Due to the slowly responding nature of the heating system, in this example, when a temperature is demanded from the setpoint this will be slowly reached. The implications of this are that the dwelling would be colder for longer and that less energy would be used as a result.

5.5.5.4 Optimum Start On – A Heating System which responds slowly

Monthly Comfort Temperature Comparison			
	DYNAMIC	BREDEM	DIFF.
January	18.77	19.02	-0.25
February	18.88	19.11	-0.23
March	19.15	19.40	-0.25
April	19.28	19.65	-0.38
May	19.71	20.07	-0.37
June	20.08	20.33	-0.25
July	20.40	20.55	-0.14
August	20.35	20.51	-0.16
Septembe	19.97	20.21	-0.24
October	19.53	19.85	-0.32
November	19.15	19.36	-0.22
December	18.84	19.16	-0.32
AVERAGE ○	19.51 ●	19.77	98.68%

Monthly Energy Consumption			
	DYNAMIC	BREDEM	DIFF.
January	4034.40	4774.58	-740.18
February	3480.60	4091.35	-610.75
March	3337.10	3734.17	-397.07
April	2741.10	2942.86	-201.76
May	2000.50	1909.52	90.98
June	1369.70	1156.71	212.99
July	996.05	614.77	381.28
August	1097.50	717.88	379.62
Septembe	1703.20	1465.54	237.66
October	2529.00	2501.62	27.38
November	3465.40	3718.97	-253.57
December	3990.90	4385.52	-394.62
TOTAL: ○	30745 ●	32013.49	96.04%

Figure 5.37 - Optimum Start On - A Heating System which responds slowly

The above figure highlights the power and necessity of having an optimum start algorithm in the IDEAS model. **Without optimum start employed on a poorly insulated test case with a heating system which responds slowly, the results from IDEAS do not compare favourably with BREDEM.** However, once the optimum start algorithm is implemented in IDEAS, the match between IDEAS and BREDEM is very good, both for temperature and energy consumption.

5.5.6 4th Order Results – Conclusions

The most appropriate comfort ratio was defined as Ta_Ratio = 0.33; Tsi_Ratio = 0.33; Tft_Ratio = 0.33. Over a range of U-Values, using this ratio, a close match was found between IDEAS and BREDEM for MIT and energy consumption.

178

The addition of an optimum start algorithm was found to be very useful, especially for systems which respond slowly. The optimum start algorithm has, as expected, a lesser effect on heating systems which respond quickly as these systems do not need a great deal of setback to meet the desired temperature.

5.6 Conclusion

This chapter has presented results and discussion from the PV and SDHW work comparing SAP with DSMs. Highlighted in this research are issues where SAP could be improved by allowing different weather profiles and additional parameters such as inverter efficiency to be directly recorded. This chapter has also highlighted the transition of the IDEAS model to its final version. The final version is defined to be the 4th Order IDEAS model in Matlab and Simulink. 4th Order IDEAS implements a continuous RIDE controller so that IDEAS can PERFECTLY track a sap standard occupancy setpoint. 4th Order IDEAS has then been calibrated with BREDEM / SAP across a range of U-Values. The addition of optimum start allows IDEAS calibration with SAP for slowly responsive systems.

Now that there is confidence that the IDEAS model can produce comparable results to those produced by BREDEM / SAP, the IDEAS tool can be used for a variety of purposes.

The following chapter will highlight and building upon the use of the IDEAS model with case studies highlighting the 3rd party use of IDEAS. The use of IDEAS as basis for genetic algorithm assessment and the addition of heat pump models to IDEAS are detailed. The case studies will highlight that IDEAS is a usable, flexible tool which can be employed by those who have had little training in either the IDEAS model or with Matlab & Simulink. The case studies chapter will also highlight different applications where the IDEAS model has been used as a foundation. The importance of gathering real

monitored test data has been also highlighted throughout this thesis. Detail regarding practical work conducted to monitor the first PassiveHouse constructed in Scotland will also be provided in the next chapter.

CHAPTER SIX

6 CASE STUDIES

6.1 Introduction

There are three main aspects to this chapter:

- o Third Party Development work with IDEAS (6.2)
- o Case Study: Addition of a Heat Pump model with Optimum Start using the IDEAS method (6.3)
- o Case Study: (Practical Work) Monitoring the first PassiveHouse in the UK (6.4)

During the development of the IDEAS model, a priority was placed upon the model being usable, adaptable and malleable. To highlight that the model produced meets this criteria, three third party examples of the use of IDEAS are presented in this chapter. The first example is the work of PhD student focusing on the advantages of advanced optimisation techniques; for this work a building model was required and IDEAS was selected. The second and third examples highlight the development of heat pump models in IDEAS. The second example has been development by EA Technology and a Nuffield Scholarship award student. The third example has been developed by an MSc student at the University of Strathclyde. Each example demonstrates the ease of use inherent in the IDEAS model and its wide range of applications. The direct relationship between the use of the IDEAS, or IDEAS based, model and the case studies will be highlighted in this chapter.

The second aspect of this chapter (6.3) presents the development of a new heat pump model with optimum start as an example of the addition of a new heating source to IDEAS.

The third aspect of this chapter (6.4) will detail practical work carried out during this research, presenting initial results from a monitoring project focusing on the first PassiveHouse constructed in Scotland.

6.2   Third Party development with IDEAS

6.2.1   Robust Control of Room Temperature and Relative Humidity using Advanced Nonlinear Inverse Dynamics and Evolutionary Optimisation

In this work (Zaher et al., 2011) a robust controller is developed for room temperature control. The control method used in this work makes use of the RIDE algorithm as a foundation for the controller design employed. A Genetic Algorithm (GA) is employed to find the optimal gains for a given uncertainty range.   The IDEAS model and a comparable model focusing on the controllability aspects of buildings (Khalid, 2011) were used as the basis of the building model used to evaluate the performance of the controller.   The building model in this example is extended to include zone humidity and relative humidity. This highlights the robustness of low level symbolic models and the wide applicability of their use.

It was also found in this work that the most appropriate temperature to track is the comfort temperature, consisting of 0.33 Air, 0.33 Internal Structure, 0.33 Furniture & Internal Mass. This assertion matches that made by the 4th order IDEAS model and the CIBSE Environmental Temperature declaration. The use of an IDEAS based modelling environment was critical to this work. This work built upon the IDEAS framework by carrying out further comparisons between the controllability of RIDE based perfect controllers tracking a comfort temperature based upon a defined varying occupancy profile. Figures 6.1 and 6.2 below highlight outputs from this work when the U–Value for the Furniture & Internal Mass is updated in the IDEAS based building model. Figure 6.1 and 6.2 use an IDEAS based modelling environment to assess the impact of using a Proportional-Integral (PI) or RIDE based controllers to tracking a comfort temperature. Figure 6.1 highlights that with a PI controller there is some overshoot in comparison to the RIDE methods.
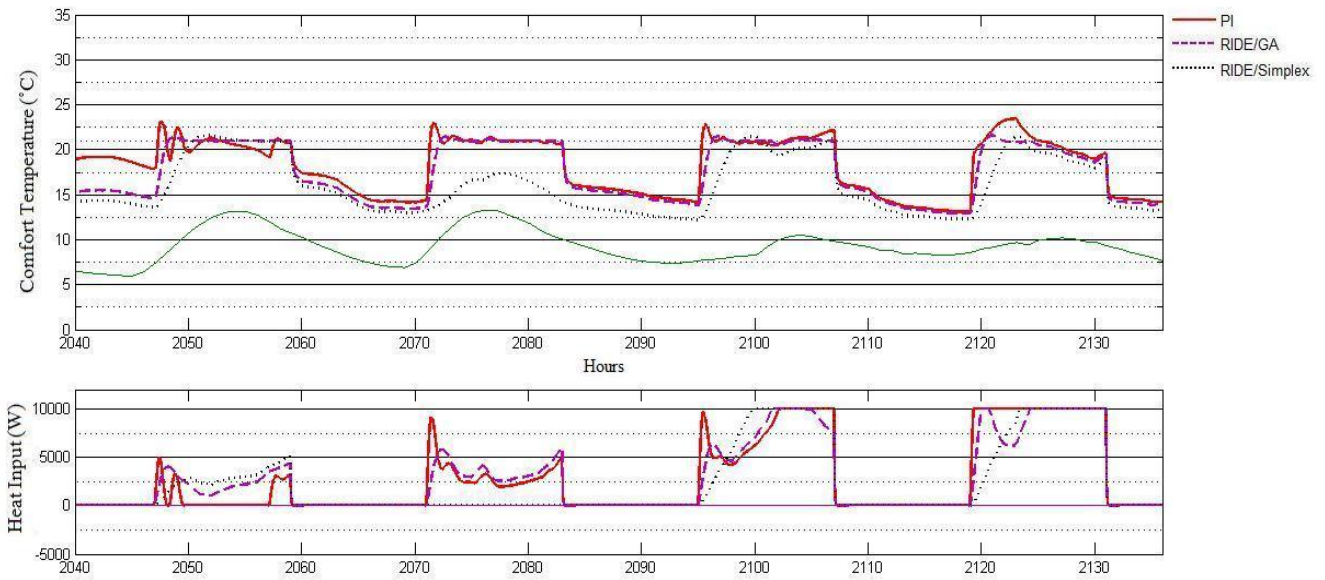
Figure 6.1 – Use of an IDEAS based modelling environment to compare the behaviour of a Proportional-Integral (PI) Controller with two RIDE Perfect Controller variants. Uft = 0.8W/m²K (Zaher et al., 2011)

Figure 6.2 highlights that with the U–Value of Furniture & Internal Mass increased to 3.2 W/m²K from 0.8W/m²K that there is now a dramatic effect on the controllability and track-ability of the setpoint in the IDEAS based model. Figure 6.2 demonstrates that with a very poor U–Value for the Furniture and & Internal Mass component when a comfort temperature is tracked, that a PI controller tracks the setpoint very poorly and there is significant overshoot. The RIDE based controllers perform better and track the setpoint well, even with a very poor U-Value for Furniture & Internal Mass.
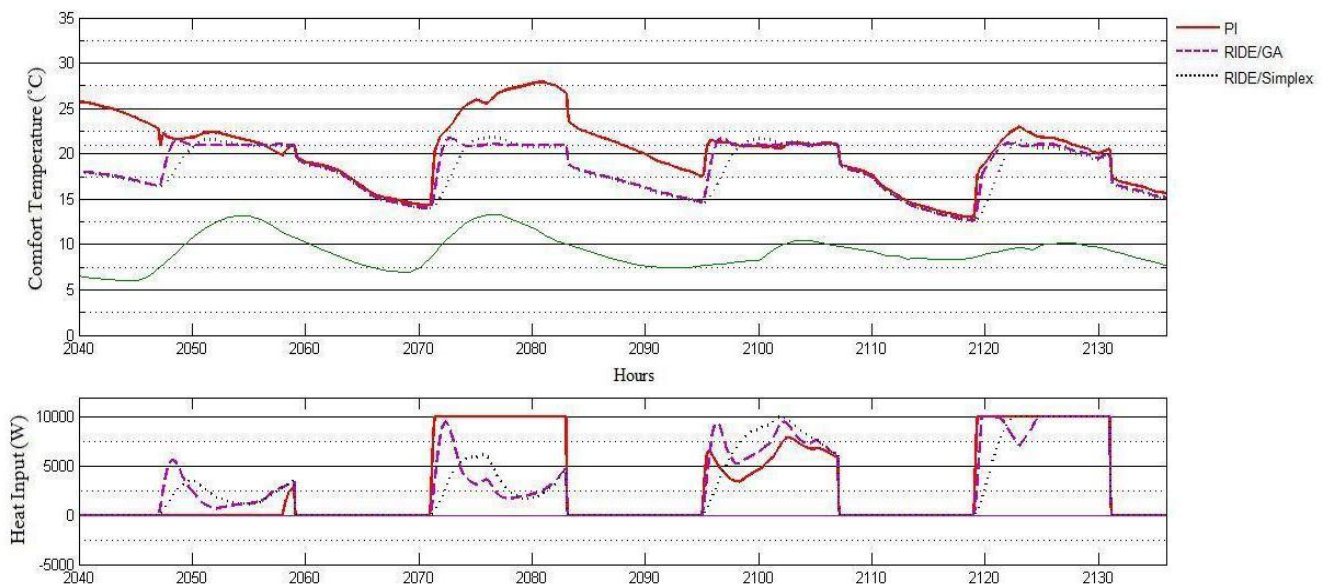
Figure 6.2 – Use of an IDEAS based modelling environment to compare the behaviour of a Proportional-Integral (PI) Controller with two RIDE Perfect Controller variants. Uft = 3.2W/m²K (Zaher et al., 2011)

184

The results from this study highlights that the RIDE control method with GA optimisation gives superior performance than the other methods measured. The results from this study also confirm that IDEAS and an IDEAS based building model can be used as the basis for complex control systems analysis, in case demonstrated by the use of Genetic Algorithm informed controllers versus Proportional-Integral (PI) control. Therefore, the use of Perfect Control Philosophy in IDEAS has also been vindicated as this has been highlighted to provide very good results over a range of values expected for components such as the U-Value of Furniture & Internal Mass in a dwelling. This study highlights that for parameter values which are outwith the expected range for a dwelling, such as Uft = 3.2W/m²K, then an improvement to the RIDE controller can be seen by the addition of a Genetic Algorithm. A Genetic Algorithm based perfect RIDE controller could be built into the main IDEAS model if IDEAS was to be adopted to cope with values commonly not seen in dwellings; for example if IDEAS was to be adopted to be used to model large complex commercial buildings where the building parameters could be outwith the range of expected values in IDEAS.

This study has highlighted another use for the IDEAS building model, by providing an environment which can be utilised independently by researchers to make an assessment of complex controllability issues in a reliable, malleable, stable, calibrated environment. Emphasised by this study is the unique contribution to the field and to the research community provided by the IDEAS framework.

6.2.2   Third Party Heat Pump Development

6.2.2.1   *Energy Performance of Heat Pumps in Domestic Buildings*

Developed by a Nuffield Scholarship student (at EA Technology in Chester, England), the purpose of this work was to make use of an advanced dynamic method to carry out a series of investigations to assess the performance of heat

pump under varying conditions (Counsell, 2011). The report highlights that there is a perception that heat pumps could be installed in large numbers throughout the UK, but that evidence to support the performance of heat pumps under varying conditions is lacking. The research poses the main problem as being "there is no clear cut evidence to show that a heat pump will provide the same heating power output as a gas boiler (or any other current heating system)." Additionally the research answers the question "whether or not it is more efficient to run the heat pump at a constant output or by supplying maximum capacity when needed". To attempt to fill the defined knowledge gaps, the IDEAS tool was selected, due to its close linkage and results correlation with SAP. Additionally, the IDEAS tool was selected as it allows an assessment to be made on heat pump efficiency, delivered heat and energy consumption based upon the simple update of selected parameters such as dwelling U value. The IDEAS methodology is transparent and allows for the addition of newly developed subsystems to be added and integrated. Throughout this project a new heat pump subsystem was added to IDEAS to calculate heat pump specific variables for a range of modelled heat pump systems under a range of differing conditions.

The main conclusions which were drawn from this work are as follows:

- The IDEAS method can be used to almost perfectly control the thermal output of Heat Pumps

    o The IDEAS method can be used successfully by a third party and an external company both not involved in its development

- The major factor in the performance of a heat pump is the heat loss parameters of the dwelling

- Tracking a fixed setpoint of 21° (**again based upon a comfort**

temperature determined by the ratio: 0.33 Air, 0.33 Internal Structure, 0.33 Furniture & Internal Mass) is slightly more efficient than tracking the intermittent SAP standard occupancy profile

- o However it is noted that tracking a fixed setpoint of 21° is more energy intensive across the year

- The effects of auxiliary heating were investigated

- o Bivalent systems (a system where the heat pump cannot meet the maximum heating requirements of the dwelling, and this heating discrepancy is met by auxiliary heating) were researched and found to a viable heat pump solution in the UK only if the dwelling is insulated sufficiently.

- o This assertion matches the earlier work in this thesis with regards to the addition of renewables to a dwelling; insulation of the dwelling should always be the priority

- Optimum Start is required to allow a modelled heat pump to produce heat in advance of a required 21° demand period when an intermittent SAP standard occupancy profile is tracked

- Heat pumps do not perform well at low ambient temperatures due to increase electricity demand of the compressor

- The larger the heat pump, the larger the maximum COP at smaller temperature differences.

- The heat pump model produced in IDEAS controls the output of the heat pump successfully

- o From this it is concluded that the major losses when downsizing the total area of a radiator in heat pump system are efficiency and

energy consumption

- A study was carried out between heat pumps and gas boilers with the conclusion given that a heat pump can compete financially with a gas boiler

  - It can be extrapolated from this that due to the added complexity of heat pumps there is greater degree of error in sizing and installation and so an up-skilling of the industry is required for heat pumps to be sized installed correctly

6.2.2.2 *Modelling the performance of Air Source Heat Pump Systems*

Independent to the previous heat pump study using IDEAS, this research was created by an MSc student as partial fulfilment for the requirement of his degree (Baster, 2011). The objective stated at the outset of this project was "the development of an air source heat pump-based heating system model which can be used to assess the impact of different methods of providing heating on heat pump performance." It was decided that the IDEAS methodology would be used as the dynamic modelling environment for this research due to the following reasons cited in the text:

- The calibration of IDEAS against SAP

- The incorporation of inverse dynamics-based perfect control to allow heat pump performance to be assessed independently from the effect of a particular control method

- The Matlab version of IDEAS, linking with the Simulink graphical interface, provides flexibility which enables different heat pump configurations to be examined

The major contribution to the field of this work is the development of an inverse model of a radiator distribution system which integrates into the IDEAS

methodology. A well-researched overview detailing the major factors affecting heat pump performance (and the effect of these upon important elements such as Coefficient of Performance [COP], Seasonal Performance Factors [SPF], system efficiency, heat pump frosting and the vapour compression cycle) is provided in the work.

The focus of the research is the use of IDEAS and the newly developed heat pump and radiator modules to simulate the performance of retrofit air source heat pumps (ASHPs) in homes which are typical of the UK dwelling stock. From this main focus, a sub-goal is the modelling and hence the comparison of integrated and separate supplementary heating systems for ASHPs. A comparison is made between a heat pump tracking a continuous demand temperature of 21° and a heat pump tracking the SAP determined intermittent standard occupancy profile. An interesting highlight of the research here was the importance of electricity tariffs employed and the variation in off peak times between Scotland and the rest of the UK on an economy 10 tariff. The results suggest that, in Scotland, the most favourable heating demand profile to track is the SAP standard occupancy heating pattern. For the rest of the UK, the heating pattern tracked makes little difference. This compares with the previous work of (Counsell, 2011) which highlighted that controlling to a fixed set point used more electrical energy.

The following main conclusions can be made from 'Modelling the performance of Air Source Heat Pump Systems' is:

- A new IDEAS compatible generalised ASHP (with supplementary heating) and radiator model has been developed

    o The use of these models in IDEAS has been shown to allow the ASHP performance under different distribution and heating

system configurations to be assessed

  o The key parameters in the performance of the radiator model are the heat transfer coefficient of the radiator and the area of the radiator

- The heat pump model has been designed to match SAP assumptions where possible

  o For example, the power draw of the pump has been set to 32.1W to match the SAP annual consumption figure

- Differing weather profiles were used in the simulations highlighting the flexibility of the IDEAS model in this respect

- The IDEAS heat pump simulations highlighted the importance of the sizing of heating systems

  o This is another aspect of IDEAS where SAP is extended to allow more flexibility and functionality; the sizing of heating systems is not possible in SAP

- A comparison of integrated supplementary heating and separate supplementary heating was made

  o Separate supplementary heating allows the heat pump to keep its return temperatures within its assumed maximum operating range

  o ASHPs with separate supplementary heating have the potential to provide the best performance

- Comfort temperature was tracked using the same ratio of 0.33 for air, internal structure and furniture & internal mass as seen in (Zaher et al.,

2011).   Therefore the importance of comfort temperature is again highlighted.

The further work section (Baster, 2011) highlights the importance of relative humidity (RH) to the defrost cycle. This is especially important in humid and cold weather climates such as Scotland. An additional area for future work could also be the simulation of the models again but with the IDEAS optimum start algorithm employed, to gauge the effect of an optimum start across the range of heat pumps studied.

6.2.3   Third Party Heat Pump Development – Conclusions

The work detailed in section 6.2.2 (Third Party Heat Pump Development) demonstrates the third party use of the IDEAS model and highlights the results which can be produced (and extended) from the 4th order IDEAS model with a relatively short amount of development time. Both projects referenced here highlighted that there were three major reasons why the IDEAS methodology was chosen as the dynamic simulation tool of choice: the calibration of IDEAS with SAP, the importance of the inverse dynamics controllability foundation of IDEAS to allow the perfect control of heating systems such as ASHPs and the flexibility of IDEAS given from its implementation in Matlab / Simulink.

This work detailed in section 6.2.2 was used as the foundation of the development of a new Heat Pump model in IDEAS as detailed in section 6.3. This highlights one of the core benefits of the IDEAS methodology: individual work packages and projects can be flexibly built upon to enhance prior results and to provide sufficient detail for analysis: "the system efficiencies achieved by the model correspond well to those reported in field trials and the results of other simulation exercises. It is the author's view that the model is sufficiently realistic to offer an insight into the impact of supplementary heating system configuration on system performance" (Baster, 2011). Additionally the Perfect

Control Philosophy of IDEAS is highlighted to be one of the main reasons why IDEAS was chosen as the developmental framework for the two 3rd party heat pump projects highlighted. The Perfect Control Philosophy in IDEAS was able to provide the developers of the 3rd party heat pump work an environment where, based upon specific external and internal factors, the best possible behaviour of a heating system in a dwelling can be simulated. From this, it is then possible to degrade this best case theoretical maximum so that a more realistic performance is given. This is the same process as that employed by SAP.

The benefit of using the IDEAS model as opposed to SAP has been highlighted by the heat pump case study examples. For example by using IDEAS, there are no hidden assumptions made as is the case in SAP. Additionally IDEAS has been highlighted to provide a flexible developmental environment which is calibrated with SAP but which allows the addition of heating system in a more flexible manner than in SAP. In SAP it would not have been possible to assess the effect of a heat pump system with various radiator areas (Baster, 2011), nor what it have been possible in SAP to investigate dynamically the effects of auxiliary heating to a heat pump set up (Counsell, 2011). SAP would also not allow the tracking of different setpoints (SAP occupancy intermittent profile vs. constant 21°C profile) or the use of different weather profiles. The value of the unique contribution of the IDEAS modelling environment and its flexibility over SAP has been confirmed.

6.3   Extension of Heat Pump Modelling and Analysis using the IDEAS Method

Building on the work described in section 6.2.2 (Heat Pump Development), a new heat pump model was added to the IDEAS model. The work of (Baster, 2011) was enhanced by the implementation of an optimum start algorithm. Additionally the IDEAS based heat pump work of (Counsell, 2011) was

extended by more advanced comparisons between the cost of running a heat pump vs. an efficient and an inefficient gas boiler.

6.3.1 Addition of an Optimum Start algorithm to an Air Source Heat Pump Model in IDEAS
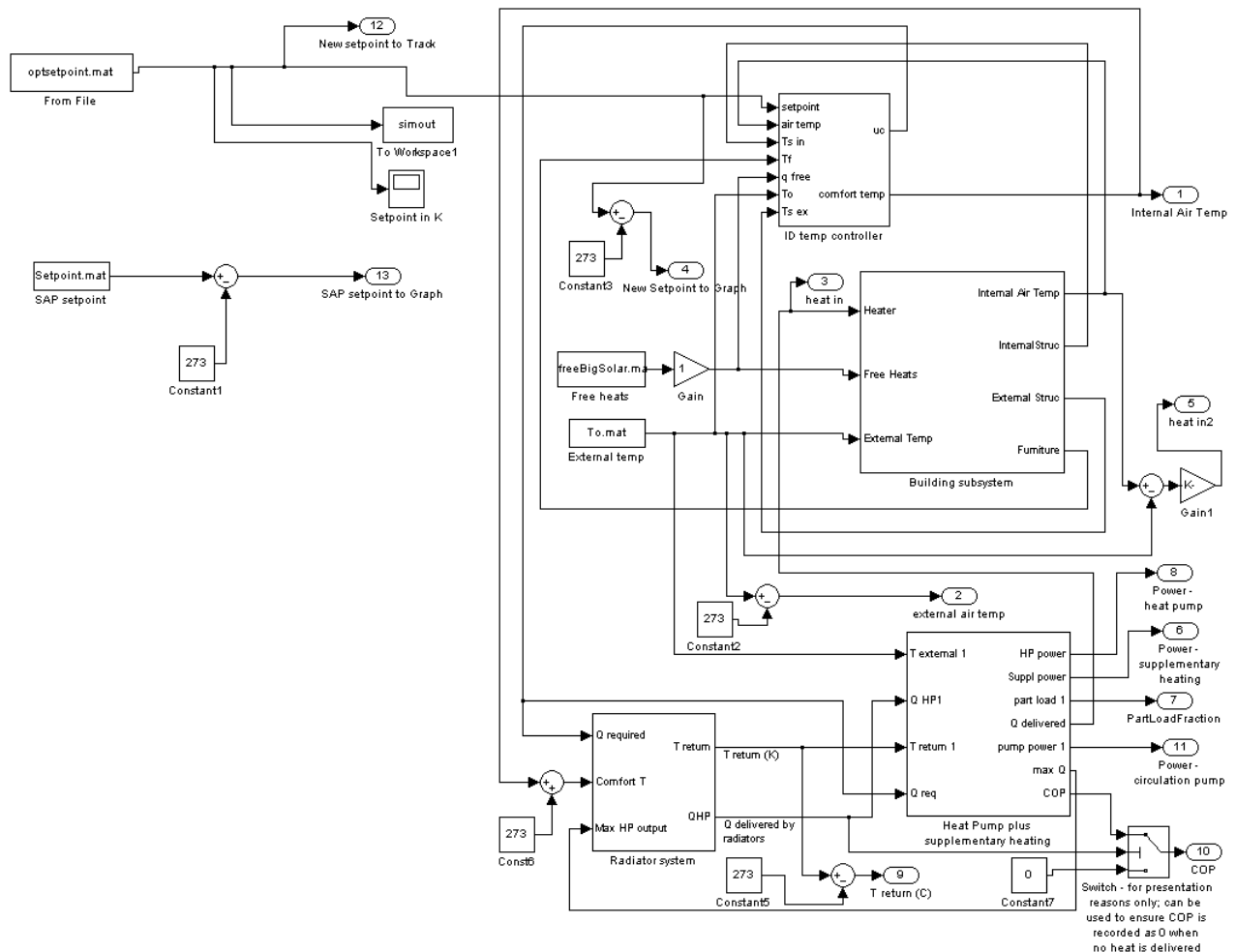
Figure 6.3 – Addition of Optimum Start to (Baster, 2011) heat pump model

The major addition to the prior heat pump work is the additional of an optimum start algorithm as highlighted in the figure above. With the optimum start algorithm implemented, the responsiveness of the heating system can be taken into account so that the demand times in an intermittent demand profile are met when requested; i.e. if 21° is demanded at 7am then the optimum start algorithm will determine when the heating system has to be switched on for this to be achieved. Highlighting the ease of the use and modular design of the

IDEAS model in Matlab / Simulink, the optimum start work is called in the Matlab m file as follows:

```
% call setpoint model
[t,x]=sim('optimum_start_setmodel');
load('optset.mat')
```

Optimum start is therefore self-contained in an additional model as shown in the figure below. Optimum Start was added based upon the method described in section 4.7.8 (Addition of Optimum Start to 4th Order Model)
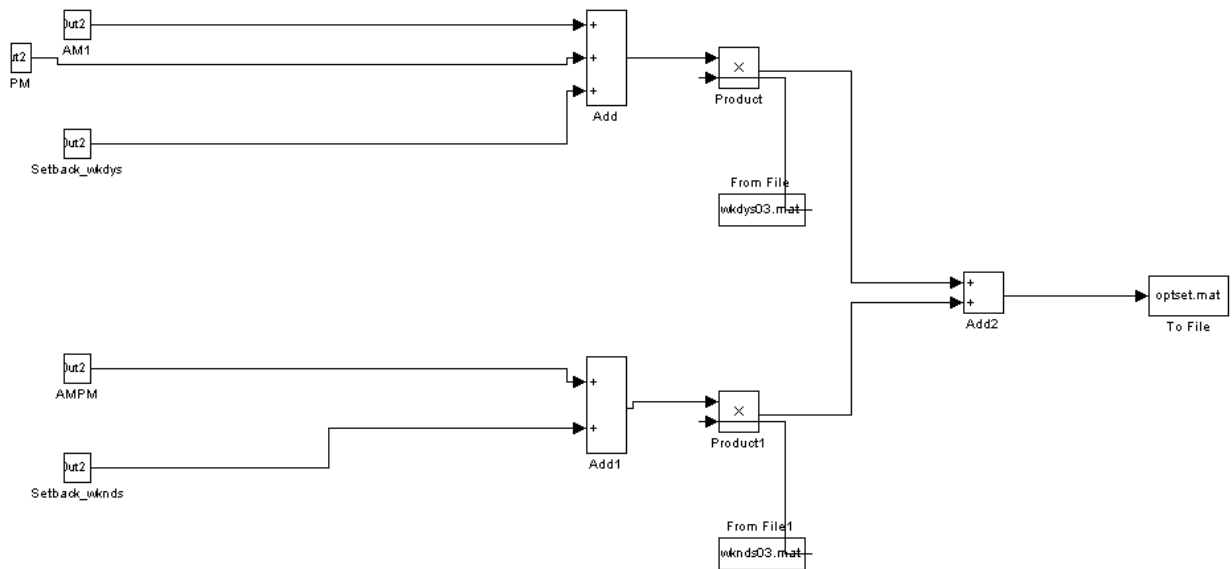
Figure 6.4 – Optimum Start setpoint addition to heat pump model

6.3.1.1   Results – addition of Optimum Start to Heat Pump Model

Two heat pump scenarios were run to determine the impact of optimum start to the energy consumption and mean internal temperature of a typical dwelling, (structure U-Value 1W/m²K).

1. A highly responsive heat pump system with and without optimum start
2. A slowly responsive heat pump system with and without optimum start

6.3.1.1.1 Highly responsive heat pump system without and with optimum start
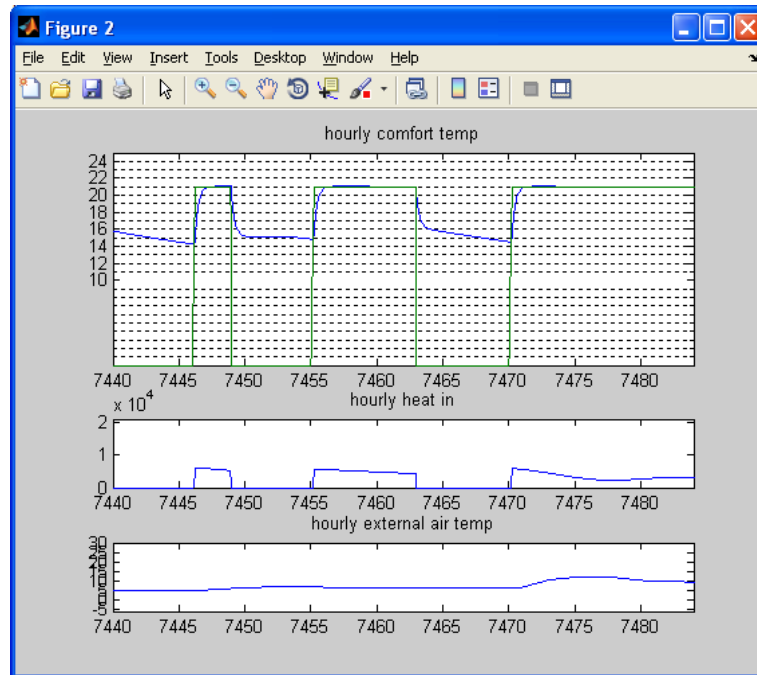
Figure 6.5 – Highly responsive heat pump system WITHOUT Optimum Start;

Average MIT = 19.06, Total Energy Consumption = 14170kWh
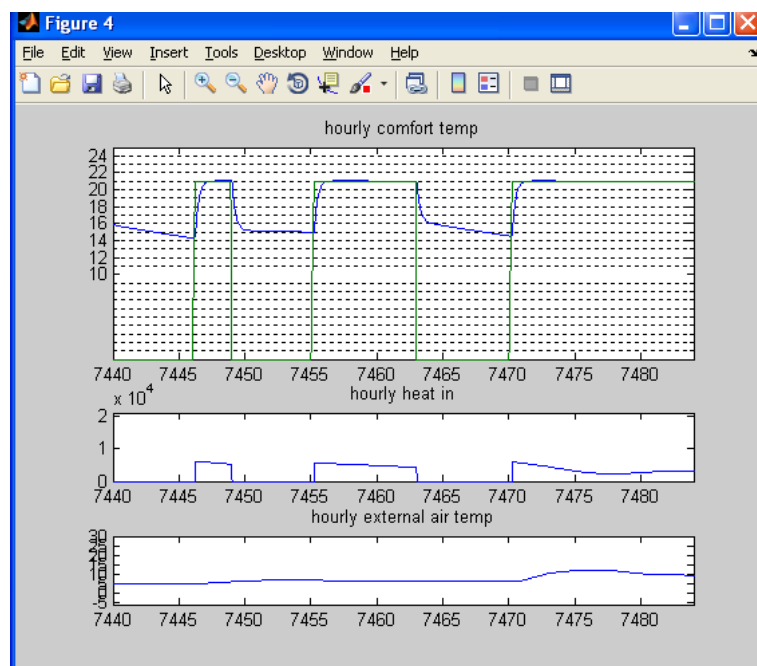
Figure 6.6 – Highly responsive heat pump system WITH Optimum Start;

Average MIT = 19.08, Total Energy Consumption = 14212kWh

As highlighted by the similarity of the two figures above (highly responsive heat pump system with and highly responsive heat pump system without optimum start), there is little difference in results for a highly responsive heat

pump system if optimum start is applied or not. As expected, when optimum start is employed there is an increase in overall MIT and energy consumption. This increase is minimal.

6.3.1.1.2 Slowly responsive heat pump system without and with optimum start
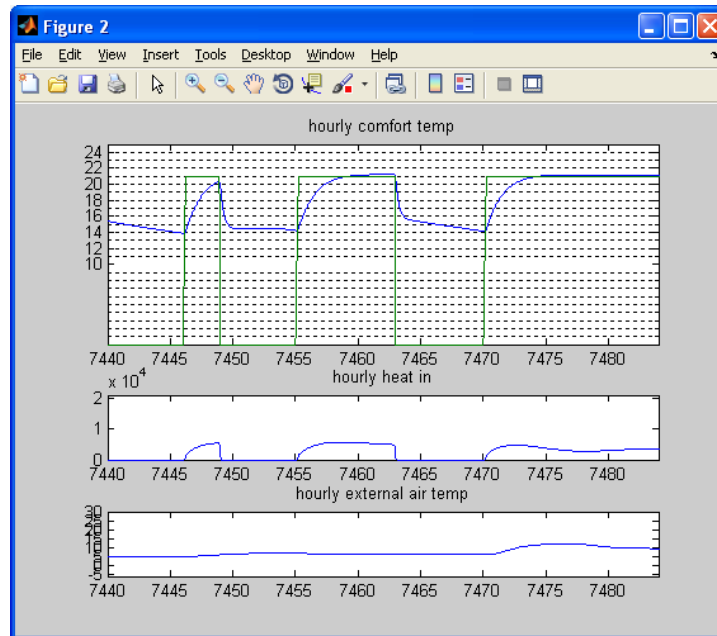
Figure 6.7 – Slowly responsive heat pump system WITHOUT Optimum Start, Average MIT = 18.63,

Total Energy Consumption = 13477kWh
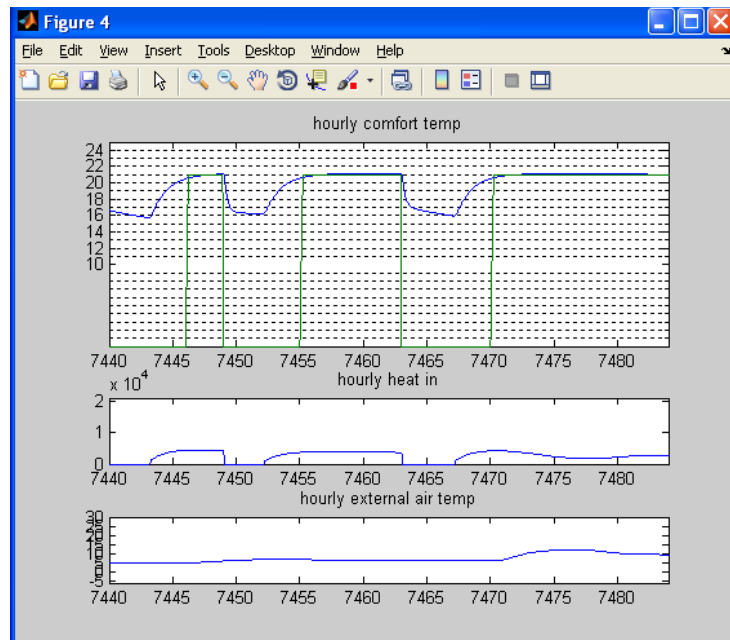
Figure 6.8 – Slowly responsive heat pump system WITH Optimum Start, Average MIT = 19.98, Total

Energy Consumption = 15663kWh

With optimum start applied to a slowly responsive heat pump, the average MIT is seen to increase by over 1° over the course of a year (in comparison with a slowly responsive heat pump system with optimum start), enhancing the comfort of the occupants. There is an energy penalty of 14% over the course of the year for the average MIT increase.

Without the implementation of an optimum start algorithm, a poorly responsive heat pump will never be able to meet the set point in time. As highlighted in Figure 6.8. The AM setpoint start time of 7am is never reached and the PM setpoint start time of 4PM is not reached until approximately 5.30PM. Figure 6.7 demonstrates that a slowly responsive heat pump system modelled in IDEAS with the addition of optimum start will reach the setpoint times as required.

The addition of optimum start to the heat pump model has therefore been a success and has been highlighted as being imperative for heat pump systems which respond slowly.

6.3.2 Annual Energy Costs (Heat Pump vs. Gas)

Following on from the work of (Counsell, 2011) it is important to further compare the annual energy costs of heat pump systems in with gas boiler systems. (Counsell, 2011) used the IDEAS tool to create a series of results used to calculate the kWh per year from a heat pump based upon a dwelling with a series of heat loss factors. The heat loss factors for the dwelling decrease from 490W/K to 115W/K based upon a fixed ventilation heat loss of 39.9W/k combined with a decreasing fabric heat loss factor. The fabric heat loss factor is calculated based upon U-Values ranging from very poor (structure U-Value 2.52W/m²K) to highly insulated (structure U-Value 0.42W/m²K). A series of kWh/year results for a heat pump were calculated and total cost derived per year based upon a unit cost of electricity being taken as £0.15.

To build upon this work, a comparison was then made between a highly efficient and an inefficient boiler. Based upon the same criteria applied against the heat pump, the kWh / per year was calculated SEDBUK band A rated boiler (Keston Qudos: 28s Regular Condensing 28.4kW 90.3% efficient) and a SEDBUK band G rated boiler (Glowworm 45/2 BBU 9.5kW 68.4% efficient). The total cost was then calculated for each boiler based upon a unit price of gas of £0.036. The details for the energy efficient and inefficient boilers are displayed in Figures 6.9 and 6.10. Where column:

o 'Total HLF' = is the total heat loss factor (W/K) for a number of dwellings; where 490.4W/K relates to a dwelling with a structure U–Value of 2.52W/m²K. 115W/K relates to a dwelling with a structure U–Value of 0.42W/m²K.

o 'kWh from Gas Boiler' = kWh Heat Demand required for that HLF, calculated using IDEAS

o 'Cost of Gas / kWh' = indicative cost per kWh of gas. 3.6p per kWh[**]

o 'Total Cost' = (kWh from Gas Boiler / Boiler Efficiency) * Cost of Gas / kWh to give an indicative cost for gas based upon a dwelling

Annual Enery Costs - Gas - Efficiency Band A Boiler			
Keston Qudos: 28s Regular Condensing			
Total HLF	kWh Heat Demand	Cost of Gas kWh	Total Cost
490.4	31842	£0.04	£1,258.30
452.8	29562	£0.04	£1,168.20
415.3	27287	£0.04	£1,078.30
377.8	24977	£0.04	£987.02
340.2	22646	£0.04	£894.90
302.7	20310	£0.04	£802.59
265.1	17926	£0.04	£708.38
227.6	15503	£0.04	£612.63
190.1	13049	£0.04	£515.66
152.5	10500	£0.04	£414.93
115.0	7836	£0.04	£309.66

Figure 6.9 – Annual Energy Costs for SEDBUK band A boiler (28.4kW 90.3% efficient where HLF factors of 490 and 115W/K relate to structure U-Values of 2.52 and 0.42W/m²K). kWh Heat Demand is calculated in IDEAS

[**] http://www.britishgas.co.uk/pdf/Fixed%20Price%202011%20Gas%20Prices.pdf

198

Annual Enery Costs - Gas - Efficiency Band E Boiler			
Glowworm 45/2 BBU 9.5kW 68.4%			
Total HLF	kWh Heat Demand	Cost of Gas kWh	Total Cost
490.4	31842	£0.04	£1,675.89
452.8	29562	£0.04	£1,555.89
415.3	27287	£0.04	£1,436.16
377.8	24977	£0.04	£1,314.58
340.2	22646	£0.04	£1,191.89
302.7	20310	£0.04	£1,068.95
265.1	17926	£0.04	£943.47
227.6	15503	£0.04	£815.95
190.1	13049	£0.04	£686.79
152.5	10500	£0.04	£552.63
115.0	7836	£0.04	£412.42

Figure 6.10 – Annual Energy Costs for SEDBUK band G boiler

Figures 6.11 and 6.12 detail the Annual Energy Costs for a HeatKing Bwarm 1200 Air Source Heat Pump[††] for a series of dwellings based upon varying Heat Loss Factors (based upon varying U-Values used for the structure components). Figure 6.11 details the cost of the ASHP when a SAP standard occupancy profile is tracked.

Annual Enery Costs - Heat Pump - SAP Standard Occupancy Profile (Comfort Temperature of 21°)			
HeatKing Bwarm 1200 ASHP			
Total HLF	kWh Heat Demand	Cost of Electricty kWh	Total Cost
490.4	10198	£0.15	£1,529.70
452.8	9440	£0.15	£1,416.00
415.3	8614	£0.15	£1,292.10
377.8	7739	£0.15	£1,160.85
340.2	6615	£0.15	£992.25
302.7	5972	£0.15	£895.80
265.1	5222	£0.15	£783.30
227.6	4619	£0.15	£692.85
190.1	3889	£0.15	£583.35
152.5	3074	£0.15	£461.10
115.0	2238	£0.15	£335.70

Figure 6.11 – Annual Energy Costs for HeatKing Bwarm 1200 ASHP, tracking a SAP Standard Occupancy Profile

---

[††] http://www.heatking.co.uk/pdfs/General_Brochure_09.pdf

199

Figure 6.12 details the cost of the ASHP when a fixed comfort temperature (ratio of 0.33 for air, internal structure and furniture & internal mass) of 21° is tracked.

Annual Enery Costs - Heat Pump - Fixed Set Point (Fixed Comfort Temperature of 21°)
HeatKing Bwarm 1200 ASHP

Total HLF	kWh Heat Demand	Cost of Electricty kWh	Total Cost
490.4	11223	£0.15	£1,683.45
452.8	10218	£0.15	£1,532.70
415.3	9247	£0.15	£1,387.05
377.8	8301	£0.15	£1,245.15
340.2	7553	£0.15	£1,132.95
302.7	6639	£0.15	£995.85
265.1	6187	£0.15	£928.05
227.6	5243	£0.15	£786.45
190.1	4319	£0.15	£647.85
152.5	3399	£0.15	£509.85
115.0	2476	£0.15	£371.40

Figure 6.12 – Annual Energy Costs for HeatKing Bwarm 1200 ASHP, tracking a fixed comfort temperature of 21°

From the data in tables 6.9 -> 6.12, a comparison can be made between the IDEAS based heat pump figures and the SEDBUK informed gas boilers with regards to the costs. This is detailed in Figure 6.13
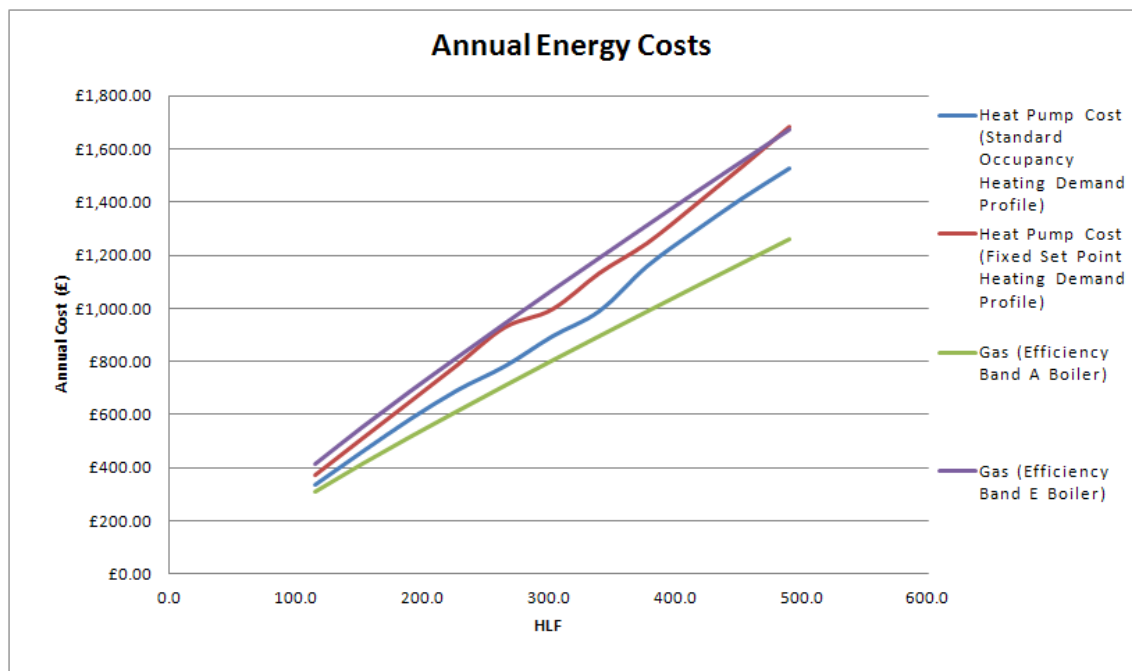
Figure 6.13 – Annual Energy Costs – Heat Pump vs. Gas Boiler

From figure 6.13 it can be seen that the efficiency of the gas boiler can have a major bearing on the cost. Overall, an A rated gas boiler can be seen to always offer the lowest annual energy costs over a variety of dwellings with varying Heat Loss Factors. Conversely, the band E rated boiler generally offers the highest annual cost for across the dwelling modelled. This again highlights the importance of installing energy efficiency heating systems wherever possible. Interestingly the heat pump energy costs can be seen to be very similar to that of the band E boiler (i.e. very high); in fact when the heat pump is tracking a fixed set point temperature for a dwelling with a very high Heat Loss Factor (a very poorly insulated dwelling) then the annual energy cost is actually higher with the heat pump than with the band E rated boiler. The annual energy costs are all relatively similar for a very highly insulated dwelling (low HLF) as little heat is required for such dwellings. However a far greater divergence of annual energy costs for the heating systems can be seen in a very well insulated dwelling (high HLF). This is to be expected as a dwelling of this type would have a far greater heat demand. This highlights the need for the retrofitting of dwellings with a high HLF to improve the thermal performance and so reduce the heating demand. **For all dwellings the most efficient method of heating the home is by the use of a Band A gas boiler, this is especially true for dwellings with poorer U-Values.**

Additionally, the Annual Energy Costs – Heat Pump vs. Gas Boiler figure highlights that for heat pumps there can be a large discrepancy between results depending on whether a SAP standard occupancy heating profile or a fixed set point profile of 21° comfort temperature is tracked. For all dwellings it was found that when the heat pump tracks a SAP standard occupancy heating profile, lower annual energy costs are given. The temperatures tracked (and PERFECTLY met) in all of the test cases is a comfort temperature (ratio of 0.33 for air, internal structure and furniture & internal mass) based upon work

detailed earlier in this thesis; this allows for results to be consistent with those produced by SAP. **The IDEAS tool can therefore be used a tool to help suggest to owners what the potential cost of installing a specific heating system or improving the thermal performance of the dwelling will have upon their annual energy costs.**

6.3.3 Conclusion - extension of Heat Pump Modelling and Analysis using the IDEAS Method

This case study has highlighted the extension of two specific examples of the use of the IDEAS model to analyse the performance of heat pumps in a UK domestic scenario. The modular and open design of the IDEAS method has been demonstrated by the extension of the two example projects.

In the first example, an optimum start algorithm was added to the heat pump work created previously (Baster, 2011). This demonstrated the modular approach taken in the development of IDEAS. The results highlight that the addition of optimum start can be important to heat pump systems which respond slowly. In the second example, the heat pump modelling and analysis work of (Counsell, 2011) was updated. This extension highlighted the importance of efficiencies of heating systems and the cost of fuel in the comparison made between a gas boiler and air source heat pump as the main heating source. **This work also highlighted the importance of the method employed in IDEAS: once perfect control is achieved the theoretical maximum performance of a heating system is given. From this theoretical maximum, it is then possible to degrade the performance by the use of factors such as boiler efficiency as provided by the SEDBUK database. This methodology is a good fit with that employed by SAP.**

6.4 Monitoring the first PassiveHouse in the UK

6.4.1 Introduction

Created by the PassiveHouse Institute, PassiveHouse is a low energy building standard that can reduce the energy use of a building. PassiveHouses have been built in many parts of the world; with the first PassiveHouse in Scotland completed in 2010. The importance of monitoring advances in building design and technology can be useful to improve future constructions and technology applications. This section of the case studies chapter describes the monitoring of three dwellings in Dunoon, Scotland; one PassiveHouse, one highly insulated house and one 1980's house. Results suggest that the PassiveHouse approach is applicable in a Scottish climate and could be valuable to reduce carbon emissions and improve energy efficiency in dwellings.

Passive House Criteria is detailed in Table 2.2.

An exciting development of low energy homes, including the first certified PassiveHouse in Scotland, has been recently completed by Fyne Homes in Dunoon. The homes were officially opened by Alex Neil, Scottish Government Minister for Housing and Communities in October 2010 with the properties detailed as follows: "The 15 terraced properties, located 1 mile south of Dunoon and overlooking the beautiful Firth of Clyde, boasts the First Passivhaus for Scotland, the First affordable Passivhaus for the UK, a Scottish Saltire Housing Design Awards 2010 commendation and demonstrates that low energy homes can also be affordable." (Fyne Homes, 2010)

An initiative was taken forward by the University of Strathclyde and Fyne Homes to carry out detailed monitoring on a number of homes in the development and locality. The monitoring will be used to assess the applicability of PassiveHouse design in a Scottish climate.

6.4.2 Objective

The objective of this study is to monitor 3 dwellings in Dunoon, Scotland for a period of one year. This will allow detailed analysis to be undertaken into the performance of each dwelling. The objective presented in this section is to detail the monitoring of the first PassiveHouse in Scotland along with a highly insulated dwelling and a home built in the 1980's. All three dwellings are located within a 100 metre radius. The monitored information will be used to assess the impact of new design methods and materials to energy utilisation and occupant satisfaction (Tuohy and Murphy, 2011).

Figure 6. 14 - Fyne Homes Tigh-Na-Cladach Development

Source: © G.B.MURPHY www.flickr.com/murphygb

6.4.3   MONITORING IMPLEMENTATION

6.4.3.1   *Location of Monitoring Project*

Location of the project was dictated to a large degree by the location of Scotland's first PassiveHouse and the other test case dwellings. Situated on the Cowal Peninsula in Argyll Scotland, Dunoon enjoys a climate which rarely drops below 0° and rarely exceeds 20° (Weather 2 Ltd, 2011).

Figure 6.15 – Monitoring Project Location: Dunoon, Scotland

Non-invasive monitoring was a primary focus of the project to reduce the impact on the families living in each home. Telemetry monitoring was selected as the best method of conducting the monitoring. The telemetry monitoring placed a restriction upon the monitoring as each transmitter must be placed with 100meters of the main receiver. As highlighted below, repeaters could be used to boost the signal for more than 100meters but this would have added another layer of complexity to the monitoring process.
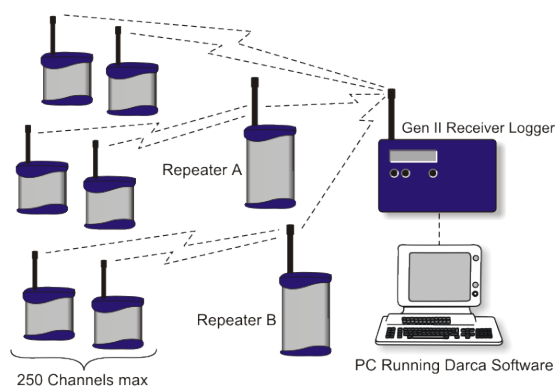
Figure 6.16 - Telemetry Monitoring Setup (Eltek, 2011)

6.4.4 Description of Monitored Dwellings

A selection of three homes to monitor was made to represent the broad spectrum of housing types in Scotland. As can be seen from Figure 6.15, all homes are within a close proximity to each other; therefore all of the homes will experience very similar external conditions. All home are of a semi-detached design. Collated detail on each dwelling is provided in Table 6.1 below.

Table 6.1 – Summary of Monitored Dwellings

		TFA‡	U-Values W / (m² K)		Heating	
#	Name	m²	Wall	Glazing	Space	Water
1	Passive House	88	0.095	0.8	Eco Air Split Type Air Conditioner; Model ECOO701S	4.6m² Velux M08 Collectors (6 collectors with a specified aperture of 0.9m² each); 200l TFF 200 Tank
2	Highly Insulated Home	120	1.0	1.2	Storage Heaters + Direct Acting Electric Heating	Immersion Boiler
3	1980's Home	72	1.6	1.8	Storage Heaters + Direct Acting Electric Heating	Immersion Boiler

6.4.5 PassiveHouse (Dwelling 1)

The figure below highlights the location of dwelling1; located on the Firth of Clyde to ensure a perfect view (important in PHPP) and additional source of humidity. However the location can be seen to be shaded by local trees and also not have the benefit of southerly facing windows. Solar heat gain is therefore minimised in this location.

---

‡ Total Floor Area

Figure 6.17 - Dunoon PassiveHouse – Note Solar Thermal Panel Installation

Source: © G.B.MURPHY www.flickr.com/murphygb
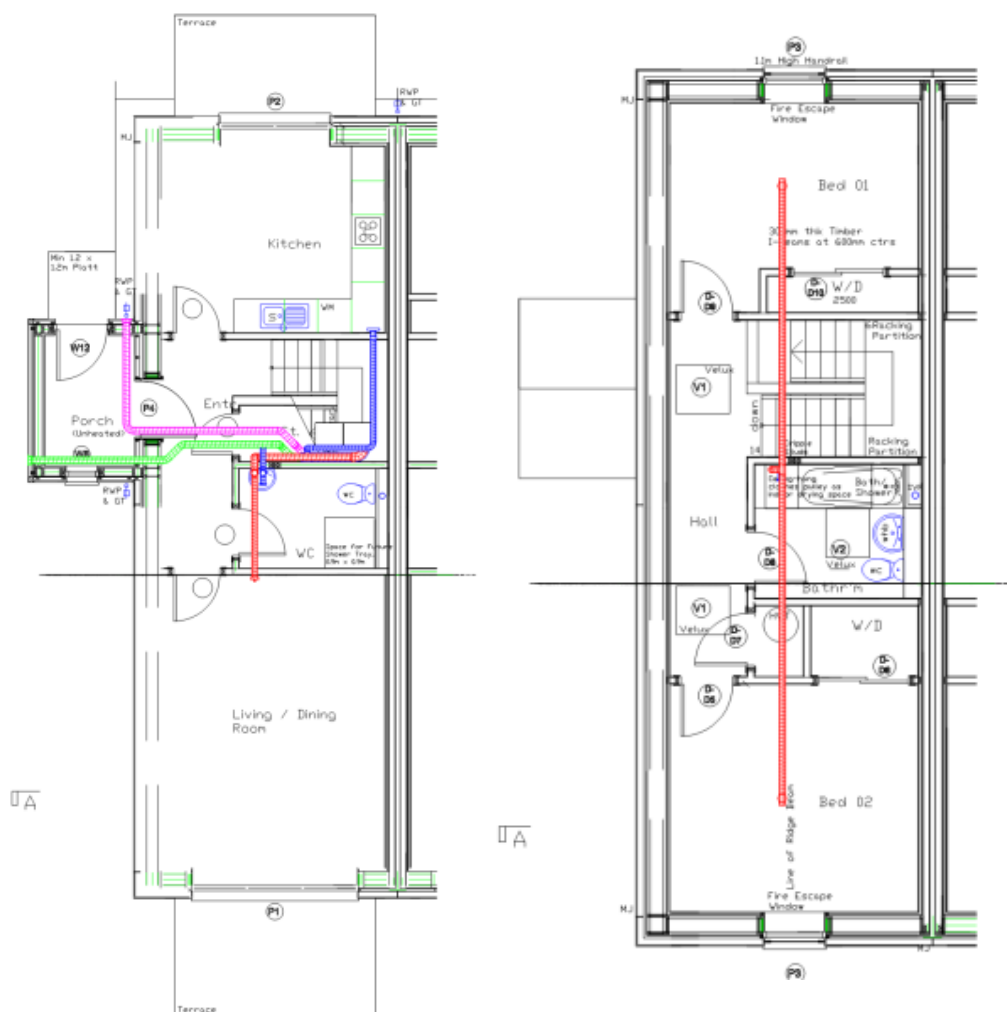
Figure 6.18 – PassiveHouse Floor Plans ((Divici, 2011))

207

The figure above details the floor plans for dwelling 1. Noted on the diagram is the location of the supply air ductwork and supply air intake (western side of porch), the supply air inlets are placed appropriately in the living and sleeping areas of the home. Also highlighted is the extract air outlet (northern side of porch), the extract air outlets are placed in the kitchen and bathroom to recover the heat from these areas.

Table 6.2 – PassiveHouse: installed Monitoring Equipment details

Location	To Measure	ID
Lounge	Relative Humidity + Temperature + CO2	GD 47 (http://www.eltekdataloggers.co.uk/pdf/GD47_product_preview.pdf)
Kitchen	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Coldest Room	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Bathroom	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Electric Meter	Current	Eltek M2D
MVHR	Current	Eltek M2D / GS 42 Transmitter (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Space Heat (Duct)	Current	Eltek M2D / GS 42
Heat Pump - Outside	Current	Eltek M2D / Eltek GS 42 Transmitter (http://www.eltekdataloggers.co.uk/transmitter.shtml)

SDHW	Tank Temperature / Cold Water Intake Temperature / Solar Heated Water Intake / Hot Water Extract	Eltek GS32 Transmitter (http://www.eltekdataloggers.co.uk/transmitter.shtml)
SDHW	Immersion Curent / Pump Current	Two * Clamp Meter + 1 * GS42

6.4.6 Energy Efficient House (Dwelling 2)

Figure 6.19 details the energy efficient home during build. Energy efficient materials were utilised to ensure that the home is broadly in line with the Code for Sustainable Homes level 4.

Figure 6.19 – Energy Efficient Home during build, part of the Tigh-Na-Cladach development

Table 6.3 – Energy Efficient Home: installed Monitoring Equipment details

Location	To Measure	ID
Lounge	Relative Humidity + Temperature + CO2	GD47 (http://www.eltekdataloggers.co.uk/pdf/GD47_product_preview.pdf)
Kitchen	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Coldest Room	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Bathroom	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Electric Meter	Current	M2D / Eltek GS42 Transmitter (http://www.eltekdataloggers.co.uk/transmitter.shtml)
HW Immersion Heater	Current	M2D / Eltek GS 42 Transmitter (http://www.eltekdataloggers.co.uk/transmitter.shtml)
HW Tank	HW tank temp	1 Thermistor + 1 GS32
Hot Water - Cold Water Intake Feed	Cold Water Inlet Pipe	1 Thermistor (GS32 not required as one Gs32 / 2 Thermistor)
Hot Water - Hot Water Pipe Leaving Tank	Hot Water Outlet Pipe	1 Thermistor + 1 GS32

6.4.7   1980s House (Dwelling 3)

Constructed in the 1980's dwelling 3 is an example of the type of dwelling which is commonplace throughout Scotland.

Figure 6.20 – 1980′s Test Case Dwelling

Table 6.4 – 1980′s House: installed Monitoring Equipment details

Location	To Measure	Monitoring Equipment Reference
Lounge	RH + Temperature + CO2	GD47 (http://www.eltekdataloggers.co.uk/pdf/GD47_product_preview.pdf)
Kitchen	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Coldest Room	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Bathroom	Temperature	GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)
Electric Meter	Current	M2D / GS42 (M2D Clamp Meter – Sense Heat Pump and House Electric Consumption)
HW Immersion Heater	Current	M2D / GS42
Hot Water Tank	Cold Water Inlet Pipe	1 Thermistor (GS32 not required as one Gs32 / 2 Thermistor)
Hot Water Tank	Hot Water Outlet Pipe	1 Thermistor + 1 GS32

6.4.8   Overarching Monitoring Installation

In addition to the monitoring equipment installed in each home, additional monitoring equipment was also installed. A Pyranometer was installed (see figure below) to record solar radiation. An external temperature sensor was also installed to measure the external temperature. The Pyranometer and external temperature sensor data was taken as being representative for all three dwellings.

Figure 6.21 – Pyranometer Installation

Source: © G.B.MURPHY www.flickr.com/murphygb

Table 6.5 – Overarching monitoring equipment installed

Location	To Measure	Monitoring Equipment Reference
PassiveHouse	**Log all transmitters**	**Data Logger Receiver RX250AL (Squirrel)**
Outdoors	**Solar Intensity**	**Pyranometer Sensor SKS1110 (http://downloads.skyeinstruments.com/Datasheets/Pyranometer.pdf)**
Outdoors	**Outside Temperature**	**GC 05 (http://www.eltekdataloggers.co.uk/transmitter.shtml)**

6.4.9   Initial Observations

PassiveHouse

Figure 6.22 – PassiveHouse MVHR Ducting Unit; insulation issue

Source: © G.B.MURPHY www.flickr.com/murphygb

Figure 6.22 highlights that the insulation around the Paul Thermos 200DC has been incorrectly installed. This oversight could have the effect of reducing the temperatures in the PassiveHouse and therefore requiring additional electricity to heat the home further.

Energy Efficient Home
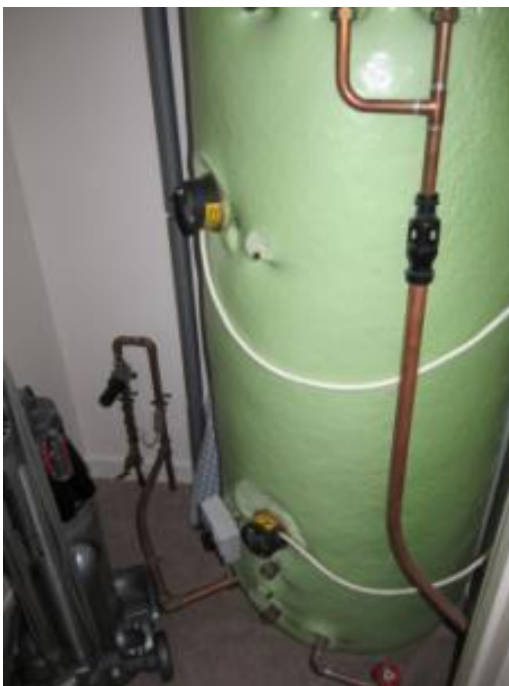
Figure 6.23 – Low Energy Home – Initial Observations

Source: © G.B.MURPHY www.flickr.com/murphygb

1980s House

Figure 6.24 – 1980's House Initial Observations

Source: © G.B.MURPHY www.flickr.com/murphygb

Figures 6.23 and 6.24 above highlight that the insulation of piping related to the hot water tank will reduce heat loss and reduce cost. Initial observations highlight the importance of insulation of services systems inside of each of the dwellings.

6.4.10 MONITORING RESULTS

Figure 6.25 below presents a summary of one week's data output from the monitoring process. The outdoor temperature can be seen to never rise above 10°. The temperatures of the main living area of each dwelling is shown; this highlights that dwelling 2 (highly insulated home) is consistently higher than either dwelling 1 (PassiveHouse) or dwelling 3 (1980's Home).
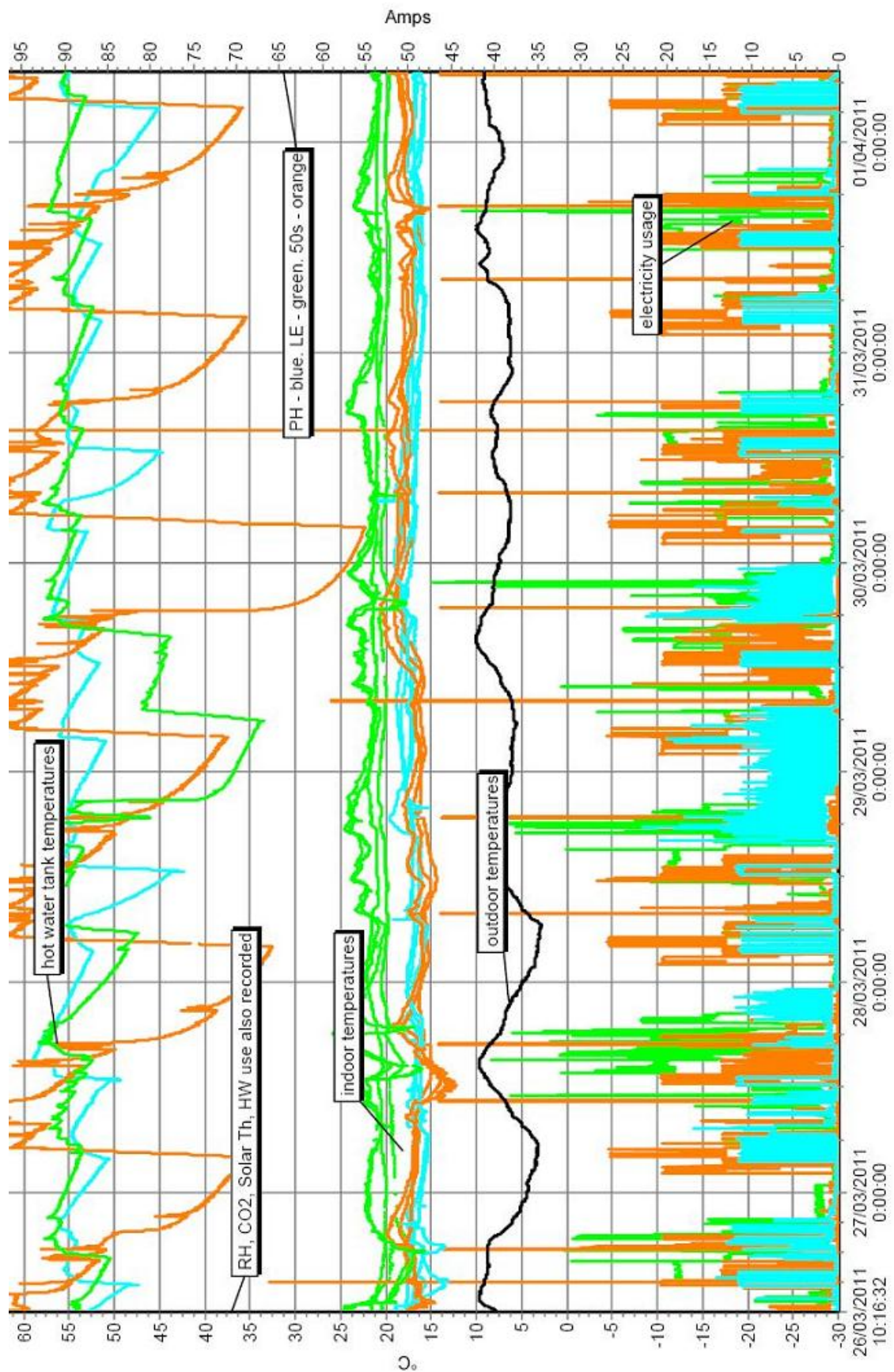
Figure 6.25 - Results Summary, image created by the Eltek Darca software; image courtesy P. Tuohy

Figure 6.25 above highlights results over one week in March for each of the three monitored dwellings. In this image, the blue colour results relate to the

Passive House, the green colour results to the Energy Efficient Home and the orange colour results refer to the 1980's home. Also displayed on the image by the black line is the external temperature which was also recorded over that week, it can be seen to vary from between approximately 5°C and 10°C .

6.4.10.1 Monitoring Results – Graphs

A sample week in March is highlighted for each dwelling. The graphs are displayed in Appendix M: Monitoring Results.

6.4.10.2 Monitoring Results – Initial Summary and Energy Saving Advice

Based upon the initial monitoring results, the following conclusions and recommendations were provided to each dwelling as follows:

6.4.10.2.1 PassiveHouse

- The overall temperatures are low, considering the fact that the dwelling is a PassiveHouse

- Doors require undercutting between kitchen and living room

- There are issues with the SDHW

- The ducting surrounding the MVHR unit was found to be missing insulation in certain areas

- Remedial work has been carried out upon this but further action is required for the PassiveHouse standards to be met: Figure 6.26

Figure 6.26 – Remedial work to MVHR ducting. Further improvements required so that PassiveHouse standards are met

216

6.4.10.2.2 Highly Insulated House

- Good air quality in the home

- The house is performing well and has been built to a high specification

- Temperature of Lounge and Kitchen area could be reduced

- This is a personnel preference

- Indicative figures highlight that turning down the thermostat by one degree could save £50 a year

6.4.10.2.3 1980's House

- Temperatures are in a sensible range

- There is little overheating so energy is not being wasted on heating

- Additional Draft Proofing could be installed in the home

- Indicative figures highlight that increasing draft proofing could save 10% on your heating bill due to the reduction of heat loss

- The main issue to tackle is the insulation of the hot water tank and pipes

6.4.11 Monitoring Discussion

This monitoring work focused on the implementation and the initial findings from monitoring three dwellings including the first PassiveHouse in Scotland. Appropriate improvements were highlighted during initial observations for each of the dwellings. The dwelling requiring most attention appears to be the PassiveHouse; the PassiveHouse has been heralded as an exemplar dwelling. It appears that the construction and design of the PassiveHouse has met the high PassiveHouse criteria standards. Unfortunately the same cannot be said about the servicing systems installed into the dwelling: issues were found the SHDW, MVHR and Heat Pump. Up-skilling of the industry and post occupancy evaluation could help alleviate issues such as

these. Efforts were made to remedy the issues found with close collaboration between all parties once the issues had been highlighted during the course of this project.

6.4.12 Monitoring Conclusion

This section of the research presented the process of monitoring 3 dwellings in Dunoon, Scotland. One of the monitored dwellings is the first certified PassiveHouse in Scotland and the first affordable PassiveHouse in the UK. Of the other two dwellings, one is a highly insulated home (meeting Code for Sustainable Homes level 4 (Gaze, 2009)) and one is an example of a dwelling constructed in the 1980s. Both of the modern buildings were found to have been built to a very good standard. It was found that there were recommendations that could be made for each of the dwellings. The PassiveHouse was found to have significant issues with its servicing systems and these appeared to have a knock on effect with the PassiveHouse experiencing low internal temperatures and high energy bills. **The results from the highly insulated home highlighted the overall hot temperatures in the dwellings and suggested that modelling occupant behaviour is very difficult.** The 1980s dwelling highlighted the improvements that can be made to simply improve the energy efficiency of a home, such as insulating the piping around a domestic hot water tank.

6.4.13 Monitoring Further Work

Further work could be centred on monitored data once a year of monitoring has been completed for the three sites. Comparisons based upon seasonal variations can then be carried out. Further work could also involve detailed modelling for all dwellings using appropriate methodologies. SAP 2009 could be used to model each of the case study dwellings. Modelling each of the test case dwellings in SAP 2009 could be used to highlight the effect the design has upon Energy Use and EPC Rating. In a similar fashion, PHPP (Feist and

PassivHaus Institut, 2007) will be used to model the PassiveHouse. PHPP is suitable for only PassiveHouses and cannot be used to model the other test case dwellings. A discussion about the applicability of PHPP can then be entered into at that point. SAP has also been compared to the Passive House Planning Package (PHPP) and it has been found that SAP may underestimate the heating required for a low energy house compared to PHPP (AECB, 2008). A comparison could be made between real measured data for the PassiveHouse, PHPP and SAP.

A simple dynamic calculation method, calibrated with SAP, IDEAS (Murphy et al., 2011, Murphy and Counsell, 2011) could also be used to model each of the monitored dwellings including aspects which are difficult for SAP to cope with. This could be used to provide further detail and to suggest where SAP could be improved based upon real measured data and dynamically simulated modelling. For example the effect of different weather profiles can be taken into account in IDEAS: how would these dwellings perform in a SAP Sheffield Climate as opposed to a simulated localised Dunoon climate, as opposed to what was actually monitored? IDEAS could also take into account solar aspects where SAP is limited such as the modelling of the effect of Incident Angle to the solar thermal collectors (Murphy et al., 2010, Murphy et al., 2009). Future versions of IDEAS can be developed which could produce Passive House compliant results, this would allow for greater flexibility in the modelling of Passive Houses anywhere in the world using a simplified published dynamic framework which produces results comparable to those of Passive House.

The benefit of the monitoring of each of the three dwellings presented in this case study is that the real monitored results can be modelled in an IDEAS framework from which suggestions can be made as to where each dwelling

could be improved and what the implications would be of improvements such as updated heating systems or increased insulation. This work is only possible in a flexible framework such as IDEAS. The rigid nature of SAP does not allow for detailed modelling of impacts arising from areas such as the reachability of heating systems or the dynamic cost and comfort temperature implications of changing a heating system in a modelled dwelling.

6.5 Conclusions

This chapter has presented examples of the external use of the IDEAS tool to highlight the ease of use of the tool and its applicability to various areas. The external heat pump work was built upon and a new heat pump model created; this is also detailed as a case study in this chapter. The information produced from this case study could help suggest to SAP how future versions of the methodology should adapt.

Additionally, this chapter highlighted the demonstration of practical work in the form of a monitoring project of the first PassiveHouse in Scotland. This work has been a success and highlights the useful results gained from such work. **The monitoring work could assist both the IDEAS model and SAP especially in the modelling of PassiveHouses.** There is no data more accurate than measured data and this should be the benchmark for energy assessment methodologies as much as is possible.

CHAPTER SEVEN

7 OUTCOMES AND FUTURE WORK

7.1 Introduction

This final chapter concludes this body of work and makes recommendations as to where further work may be appropriate. The first chapter of this thesis defined the main aims, and hence boundaries, of this research as follows:

1. Evaluate the benefit which the SAP methodology allows for the use of solar renewables in dwellings. This evaluation will be compared to the treatment of solar renewables in dynamic simulation tools such as TRNSYS (Beckman et al., 1994) and PVSyst (Schoen et al., 2001). From this conclusions will be drawn to suggest why the differences arise and where the SAP methodology could improve. This work will also assess the impact which weather profiling has upon SAP, based upon weather profile available from SAP, Meteonorm (Meteotest, 2011).

2. Fully analyse the treatment of temperatures in SAP; the temperatures assumed in SAP are unclear and this is a major component of calibrating an advanced dynamic calculation method with SAP.

3. Present a new SAP compliant advanced dynamic calculation method (IDEAS) which can be used in the energy modelling of dwellings. IDEAS is novel due to its use of an inverse dynamics based controller and the perfect control law RIDE to guarantee that the SAP standard occupancy profile is met. This method will bridge the current gap which currently exists between SAP and Dynamic Building Simulation by producing SAP compliant results. IDEAS will meet the Credibility, Repeatability and Discrimination of reduced parametric simulation methods as highlighted in Table 1.4. The IDEAS method will aim to improve on the Transparency and Ease of Use factors of typical reduced

parametric simulation methods.

4. Validate IDEAS against SAP, to ensure that SAP comparable energy consumption and mean internal temperatures are produce in IDEAS.

5. Highlight the use of IDEAS via case studies, and demonstrate areas such as monitoring of dwellings which could extend the method

The second chapter of this thesis was used as a literature review to set the context and applicability of the research. The third chapter detailed the method employed to assess solar energy technologies in dwellings and completed the first aim of this research. The fourth chapter completed the second and third aim of this thesis; temperatures in SAP are research in depth and a new SAP compliant dynamic modelling tool was produced. The fourth aim of this body of research (that of validating the IDEAS model against SAP) was completed across chapters 4 and 5, with chapter 5 presenting numerous examples of the steps required for validation against SAP. Chapter 6 demonstrated the flexibility of IDEAS model by presenting examples of its use and subsequent addition of modular work to extend these examples. Chapter 6 also presented practical work carried out during this research; that of the importance of monitoring, especially homes which will become more commonplace in the future.

This final chapter will conclude the work of this thesis and offer suggestions where this work can act as a foundation for further research and projects.

7.2 Outcomes - Solar Energy Technologies

The importance of accuracy within the methodology employed to measure the energy performance of dwellings has been highlighted by legislation such as

the Energy Performance of Buildings Directive. The research presented in chapter 3 of this thesis utilised SAP as an exemplar for simplified dwelling assessment methodologies whilst highlighting other countries procedures and also countries which have adopted the SAP framework. This clarifies that the research presented here is applicable to not only the UK and to SAP but to countries throughout the world that employ simplified dwelling assessment methodologies, especially those with comparable levels of solar radiation. The comparisons between SAP 2005 v9.82 and PVSyst simulations show a very good agreement for the base case photovoltaic system (30° slope, facing south, standard system components, and Sheffield weather data). The difference in energy output at the inverter is 2%. SAP only uses the rated nominal power of the PV array in the calculation and assumes a central weather location. Detailed PVSyst simulations show that using different system components (e.g. thin film versus mono-crystalline cells) can lead to differences of +/-10% in output. This leads to a difference of +/-1 in the SAP rating if the PV output calculated by PVSyst is used in the SAP assessment. Further research of the PV Panels compared in this study highlighted the differences which can be found between the nominal power and Peak Maximum Power Point (P_{MPP}) of a selected Panel. For example, the nominal power of the Sulfurcell SCG 50-HV-F was recorded by PVSyst as 50Wp, with a P_{MPP} of 52.8W – 5% higher than the nominal power. Conversely, the Eurener PEPV 200 is recorded as a 200Wp nominal power panel but the P_{MPP} is 2.6% lower at 194.8W. These differences between nominal power and P_{MPP} are currently not taken into account in simplified assessments such as SAP.

Simulations were performed using weather data recorded at one station representative of Southern Scotland, and one station representative of Southern England. This leads to differences within [-11% / +19%] PV output and [-1 / +2] in equivalent SAP rating. By combining the impact of different weather

locations and different system components, PVSyst shows differences within [-18% / +33%] in PV output and [-1 / +3] in equivalent SAP rating. Results for different slopes and azimuth angles also show that SAP seems to systematically overestimate the performance of PV systems for unfavourable orientations (e.g. vertical North facing), and slightly underestimate the performance for more favourable orientations (e.g. 60° facing South). This is probably explained by the fact that SAP does not take into account the impact of incidence angle.

SAP assessment of solar thermal domestic hot water systems (SDHW) was compared to detailed TRNSYS simulations. TRNSYS results for a standard system using SAP default parameters for collector efficiency show a solar input which is 23% higher than SAP results, but the tank losses are also larger for the entire tank (but lower when compared against the SAP calculated tank losses for the non-solar store section of the tank) which results in the water heater output to be only 7% lower. The SAP default parameters for collector efficiency are significantly lower than typical values published by the IEA. Results show that using SAP default parameters instead of IEA default parameters leads to under-predicting the savings at the water heater output by 35%. This highlights the importance of using manufacturer supplied data in SAP. If certified parameters are available, they can be used in SAP, and comparisons using the same efficiency parameters in TRNSYS and SAP shows that the differences increase for higher performance collectors. Using IEA typical Evacuated Tube data, TRNSYS predicts a higher solar input (+47%), a lower water heater output (-23%) and an improved SAP rating (C75 vs. C74).

As for the PV, SAP assumes one location representative of the whole UK. Using weather data for Southern England (Efford), leads to differences of up to 60% in solar input and up to 31% in water heater output. The SAP rating obtained by utilising these values in the SAP procedure leads to an improved

rating: (C 75 vs. C 74). The results also show that SAP seems to underestimate the performance of SDHW systems when the slope is increased, as it ignores the impact of a better match between supply and demand when available radiation is increased in winter and reduced in summer. SAP seems to use a conservative estimate for the energy required for water pumping, which is set to 75 kWh for all systems. TRNSYS simulations using a typical pump rated power (25 W) show that the energy use is between 50% and 75% of the SAP value.

7.3   Further Work – Solar Energy Technologies

As stated in the discussion section, further research is required to clarify the differences that have been identified between the calculated PV and SDHW output from detailed simulation tools, such as PVSyst and TRNSYS, and the results from simplified methods such as SAP. Precise further work will further identify the reasons for these differences. Specifically this will clarify what additional variables, or modification of current SAP variables, would result in simplified outputs which are more consistent with the detailed counterparts.

Further work is required to state if simplified methodologies such as SAP should explicitly or implicitly record the performance of a PV Inverter, based upon the European Efficiency of Inverters. The European Efficiency of Inverters has been in use throughout Europe since 1991 and is the function of the efficiency of an inverter at defined percentage values of nominal AC power (Valentini et al, 2008). Further work should also focus on the difference between Nominal Rated Power and Peak Maximum Power Point (PMPP) of a PV Panel. This will clarify the variation this can cause with calculated PV output and if simplified assessments such as SAP should be updated to allow the recording of PMPP of panels. Supplementary research related to the effect of an Incidence Angle Modifier (IAM) (Nilsson et al., 2006) and Maximum Power Point Tracker (MPPT) (Enrique et al.), and how simplified

methodologies such as SAP take this into account is also required.

The impact of Solar Incident Angle Modifier to a SDHW calculated output should also be further researched. Specific work is required to confirm the impact of this upon the output of evacuated tube collectors. Further work should investigate the performance of SDHW systems in more detail: impact of design parameters (e.g. set-point temperature, tank volume and losses), and draw-off profile. The systematic differences noted in this study (ignoring the incidence angle impact for PV and the supply-demand match and solar radiation utilisation for SDHW) will also be investigated in detail with the view to suggest improvements to the SAP methodology. Further study will confirm if SAP should take into account the second-order loss coefficient in addition to the a_1 coefficient. Additional focus on tank losses and the SAP SDHW Utilisation Factor and Collector Performance Factor would also be beneficial. The impact of shading for SDHW and PV systems and how SAP can best take this factor into account should also be assessed. It is well known that shading can have a devastating effect on PV performance, and it is unclear how the basic categories in SAP can address this.

Comparisons between SAP and other comparable simplified methodologies (such as others used to meet other European nations EPBD obligations) would highlight if the issues raised from this research are common for other simplified assessment methodologies. A comparative assessment between different simplified methodologies and SAP is important further work to benchmark SAP against similar comparable methodologies.

7.3.1.1 *SAP vs SBEM Empirical Factor for PV*

Differences exist between the SAP and SBEM methods. Further work is recommended to clarify what these differences are and why they exist. For example, there is a difference in the assumptions made between SAP and SBEM

for the assumed losses from a PV array. It would have been expected that for largely building independent components such as PV the SAP and SBEM methods would be largely similar.

The SAP Empirical Factor for PV is 0.8 whereas the SBEM equivalent is 25%, further research is required to compare SAP and SBEM. Comparing the method employed by both SAP and SBEM in dealing with largely building independent factors such as PV is a recommended starting point.

Inverter losses	7.5 %
Module shading	2.5 %
Module temperature	3.5%
Shading	2%
Mismatching and DC losses	3.5%
MPP mismatch error	1.5%
AC losses	3%
Other	1.5%
Total Losses	25.0%

Table 27: Photovoltaic system losses

Figure 7. 1 - SBEM PV System Losses

7.4   Outcomes - IDEAS

Several developmental iterations were required to produce the IDEAS model. The final version of the IDEAS model is the 4th order model produced in Matlab/Simulink which tracks comfort temperature with an even ratio of air, internal wall and furniture & internal mass. The importance of comfort ratio is highlighted in the results section. The 4th order final model has been shown to be robust due to the close comparison in results produced when these are compared with BREDEM / SAP. Additionally, the malleability of the model is highlighted by its use as demonstrated in the case studies chapter.

The IDEAS tool has been produced from scratch and verified against

SAP / BREDEM. The case studies have shown that this is a tool which can be used with little training by those who were not involved in its development.

7.5   Further Work – IDEAS

The IDEAS method and model as presented in this thesis could be extended with the following further work:

- Add cooling to future versions of IDEAS
  - This would allow for IDEAS to be compared with SAP 2009 which makes use of a cooling algorithm; for the vast majority of dwellings based upon the SAP Sheffield weather location cooling will not be required.
- Extend the model to 2 zones and calibrate with 2 zone BREDEM
  - Modern homes such as PassiveHouses stipulate that 1 zone is sufficient for the entire dwelling. This PhD research has led to the production of single zone BREDEM and IDEAS models. However, SAP 2009 and prior versions are based upon 2 zones and so an extension of the IDEAS model to 2 zones is a recommendation for further work.
  - Additional zoning could also be added to the IDEAS model where this may be applicable for specific dwelling or for specific projects.
- Model additional Renewables such as PV and SDHW in the IDEAS model
  - This work could build upon the research carried out in this thesis to compare the PV and SDHW in dynamic simulation tools to SAP.
  - The malleability of adding different heating systems to IDEAS has been highlighted by the addition of optimum start to the 4th order model.

- Additionally, the case studies chapter highlighted the many uses of the IDEAS model and the foundation of it to be used as a basis for advanced control projects and also the process required to add different systems to IDEAS such as heat pumps

- Compare IDEAS with PHPP
  - A comparison of IDEAS and PHPP could tie in with the monitoring work detailed in Chapter 6. The importance of real monitored data cannot be overestimated and it is recommended that monitoring work of this sort is continued, for the benefit of the buildings research community.

7.6 Conclusion

The research carried out over the years required to produce this thesis has concluded with the following original contributions to knowledge:

- **The novel comparison of the modelling of SDHW and PV in SAP and dynamic simulation tools**
  - This research made a number of suggestions which were adopted by SAP and BREDEM such as the addition of a PV Inverter variable into BRDEM and an update of the Usability Factor in the SDHW calculation to SAP

- **The complete analysis of the treatment of temperatures in SAP.**
  - **It is now clear that for a dynamic simulation tool such as IDEAS to be calibrated with SAP then a comfort temperature (with a ratio of 0.33 for air, internal structure**

and furniture & internal mass) must be tracked and not air temperature alone.

- **The creation of a brand new inverse dynamics based energy assessment tool (IDEAS)**
  - The IDEAS method extends the BREDEM / SAP methodology by introducing advanced dynamics, advanced control and malleability (as demonstrated in the case studies chapter)
  - **Research has highlighted that for a simple dynamic tool to be produced then it must be 4th Order, a 3rd Order model does not model the structure with sufficient detail required for energy analysis and SAP calibration to be made**
  - IDEAS PERFECTLY tracks a SAP Standard Occupancy Temperature Profile
  - **The IDEAS method has been calibrated with BREDEM / SAP, so SAP compliant results are produced**
  - IDEAS is fully transparent and the method is available to all
  - The IDEAS method has applications outwith SAP: such as its use as a symbolic low order test bed for advanced controls and to allow the creation of a dynamic extension to other energy assessment methods such as PHPP and SBEM

- **The use of the IDEAS tool to compare the Average Energy Cost of a heat pumps vs. a gas boilers**
  - **It was found that the most efficient method of heating a**

home is always with a SEDBUK Band A Gas Boiler.

- o The performance of the heat pump was improved when a SAP Standard Occupancy Profile was PERFECTLY tracked in IDEAS as opposed to a Fixed 21° Comfort Temperature. The performance of the heat pump was especially poor in dwellings which were poorly insulated.

- **The monitoring of the first PassiveHouse in Scotland to gain results which can be shared with the buildings research community**

  - o The importance of real monitoring test data cannot be underestimated

  - o **The monitoring work carried out found some serious issues with the servicing systems in the PassiveHouse and highlighted the importance of up-skilling the contractors and installers**

  - o Based upon the novel research and modelling carried out on the PassiveHouse, the owner was left with a home which performed better for less money. This work also the question of design vs. in use energy assessments.

REFERENCES

233

References

ACHTERBOSCH, G., DE JONG, P., KRIST-SPIT, C., VAN DER MEULEN, S. & VERBERNE, J. 1985. The development of a convenient thermal dynamic building model. *Energy and Buildings,* 8**,** 183-196.

AECB. 2008. *AECB Carbon Lite; Projecting Energy Use and CO2 emissions from low energy buildings – A comparison of the PassiveHaus Planning Package (PHPP) and SAP.* [Online]. [Accessed 10/05 2011].

ALLEN, S., HAMMOND, G., HARAJLI, H., MCMANUS, M. & WINNETT, A. 2010. Integrated appraisal of a Solar Hot Water system. *Energy,* 35**,** 1351-1362.

ANDALORO, A. P. F., SALOMONE, R., IOPPOLO, G. & ANDALORO, L. 2010. Energy certification of buildings: A comparative analysis of progress towards implementation in European countries. *Energy Policy,* 38**,** 5840-5866.

ANDERSON, B. 2006. *Conventions for U-Value calculations*, BRE.

ANDERSON, B. 2011. SAP developments for zero carbon. *Regulation update: towards "zero carbon" buildings (SESG/CIBSE seminar).* University of Strathclyde.: SESG.

ANDERSON, B., CLARK, A., BALDWIN, R. & MILBANK, N. 1985. BREDEM-BRE Domestic Energy Model: Background. *Philosophy and Description, Garston, Herts., Building Research Establishment*.

ANDERSON, B. R., CHAPMAN, P. F., CUTLAND, N. G., DICKSON, C. M., DORAN, S. M., HENDERSON, G., HENDERSON, J. H., ILES, P. J., KOSMINA, L. & SHORROCK, L. D. 2001a. *BREDEM 8 - Model Description*, BRE.

ANDERSON, B. R., CHAPMAN, P. F., CUTLAND, N. G., DICKSON, C. M., HENDERSON, G., HENDERSON, J. H., ILES, P. J., KOSMINA, L. & SHORROCK, L. D. 2001b. *BREDEM 12 - Model Description*, BRE.

ATTIA, S., BELTRÁN, L., DE HERDE, A. & HENSEN, J. Year. "ARCHITECT FRIENDLY": A COMPARISON OF TEN DIFFERENT BUILDING PERFORMANCE SIMULATION TOOLS. *In*, 2009.

BAHAJ, A. & JAMES, P. 2007. Urban energy generation: The added value of photovoltaics in social housing. *Renewable and Sustainable Energy Reviews,* 11**,** 2121-2136.

BASTER, E. 2011. *Modelling the performance of Air Source Heat Pump Systems*

University of Strathclyde.

BECKMAN, W. A., BROMAN, L., FIKSEL, A., KLEIN, S. A., LINDBERG, E., SCHULER, M. & THORNTON, J. 1994. TRNSYS The most complete solar energy system modeling and simulation software. *Renewable Energy,* 5**,** 486-488.

BLAESSER, G. & ROSSI, E. 1988. Extrapolation of outdoor measurements of PV array IV characteristics to standard test conditions. *Solar cells,* 25**,** 91-96.

BOARDMAN, B., KILLIP, G., DARBY, S. & SINDEN, G. 2005. Lower Carbon Futures: the 40% House Project. Tyndall Centre Technical Report 27.

BOWER, W., WHITAKER, C., SAN RAMON, C., ERDMAN, W., BEHNKE, M. & FITZGERALD, M. 2004. Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems. *Prepared for the California Energy Commission*.

BRADSHAW, A. & COUNSELL, J. 1992. Design of autopilots for high performance missiles. *ARCHIVE: Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering 1991-1996 (vols 205-210),* 206**,** 75-84.

BRE 2010. *The Government's Standard Assessment Procedure 2005 for Energy Rating of Dwellings – SAP 2005*, BRE.

BRE 2011. *The Government's Standard Assessment Procedure 2009 for Energy Rating of Dwellings – SAP 2009*, BRE.

BRÜNDLINGER, R., HENZE, N., HAEBERLIN, H., BURGER, B., BERGMANN, A. & BAUMGARTNER, F. Year. prEN 50530–The new European Standard for Performance Characterisation of PV Inverters. *In*, 2009.

CIBSE 1999. Environmental design: CIBSE Guide A. *London: Chartered Institution of Building Services Engineers*.

CLARKE, J. A. 2001. *Energy simulation in building design*, Butterworth-Heinemann.

CLARKE, J. A., JOHNSTONE, C. M., KELLY, N. J., STRACHAN, P. A. & TUOHY, P. 2008. The role of built environment energy efficiency in a sustainable UK energy economy. *Energy Policy,* 36**,** 4605-4609.

COOPER, G. 2008. *SAP 2005 and Low Energy Dwellings.* Oxford Brookes University.

COUNSELL, J. M. 1992. *Optimum and safe control algorithm (OSCA) for modern missile*

autopilot design. . PhD, Lancaster University.

COUNSELL, J. M., KHALID, Y. A. & BRINDLEY, J. 2010. CONTROLLABILITY OF BUILDINGS, A multi-input multi-output stability assessment method for buildings with slow acting heating systems. *Simulation Modelling Practice and Theory*.

COUNSELL, S. 2011. Energy Performance of Heat Pumps in Domestic Buildings. *Nuffield Bursary.* EA Technology.

CRAWLEY, D. B., HAND, J. W., KUMMERT, M. & GRIFFITH, B. T. 2008. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment,* 43**,** 661-673.

CRAWLEY, D. B., LAWRIE, L. K., PEDERSEN, C. O. & WINKELMANN, F. C. 2000. Energy plus: energy simulation program. *ASHRAE journal,* 42**,** 49-56.

CRAWLEY, D. B., LAWRIE, L. K., WINKELMANN, F. C., BUHL, W. F., HUANG, Y. J., PEDERSEN, C. O., STRAND, R. K., LIESEN, R. J., FISHER, D. E. & WITTE, M. J. 2001. EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings,* 33**,** 319-331.

CUTTING THE CARBON. 2010. *First UK Passivhaus Conference* [Online]. Available: http://www.cuttingthecarbon.co.uk/passivhaus [Accessed 2011/05/16].

DALGARNO, S. 2009. *RE: Personal Communication.*

DEXTER, A. 1981. Self-tuning optimum start control of heating plant. *Automatica,* 17**,** 483-492.

DIVICI, G. 2011. Bethania Architectural Plans,.

DTI 2003. *UK Energy White Paper. Our Energy Future – Creating a Low Carbon Economy*, The Stationary Office.

DUFFY, M. J., HILLER, M., BRADLEY, D. E., KEILHOLZ, W. & THORNTON, J. W. Year. TRNSYS–Features and functionalitity for building simulation 2009 Conference. *In*, 2009. 1950-1954.

DYRBØL, S. & AGGERHOLM, S. 2008. Implementation of the EPBD in Denmark. *Document available at: http://www.epbd-ca.org/Medias/Pdf/2_CO_EPBD_DK.pdf (note EPBD is the Energy Performance of Buildings Directive).*

ELMQVIST, H., MATTSSON, S. E. & OTTER, M. 1998. Modelica: The new object-oriented

modeling language. *12th European Simulation Multiconference, Manchester, UK*.

ENERGY SAVING TRUST. 2011a. *Generate your own Electricity; Solar Electricity.* [Online]. Available: www.energysavingtrust.org.uk/Generate-your-own-energy [Accessed 10/05 2011].

ENERGY SAVING TRUST. 2011b. *Generate your own Energy; Solar water heating* [Online]. Available: http://www.energysavingtrust.org.uk/Generate-your-own-energy/Solar-water-heating [Accessed 10/05 2011].

ENRIQUE, J. M., ANDÚJAR, J. M. & BOHÓRQUEZ, M. A. A reliable, fast and low cost maximum power point tracker for photovoltaic applications. *Solar Energy,* 84**,** 79-89.

ESRU. 2011a. *ESP-r Applications Tutorial* [Online]. Available: http://www.esru.strath.ac.uk/Programs/ESP-r_tut/esp_aps.htm [Accessed 2011/05/20].

ESRU. 2011b. *ESP-r. Environmental Systems Performance - Research – V.11.7.* [Online]. Available: www.esru.strath.ac.uk/Programs/ESP-r.htm [Accessed 10/10 2011].

EUROPEAN COMMISSION 2006. Energy Rating Systems in Europe

EUROPEAN COMMISSION. 2011. *Energy Labelling of Domestic Appliances* [Online]. Available: http://ec.europa.eu/energy/efficiency/labelling/labelling_en.htm [Accessed 2011/05/16].

EUROPEAN COMMITTEE FOR STANDARDIZATION 2008. 13790: 2008. *Energy performance of buildings-Calculation of energy use for space heating and cooling*.

EUROPEAN CONSTRUCTION TECHNOLOGY PLATFORM. 2005. Challenging and Changing Europe's Built Environment: A Vision for a Sustainable and Competitive Construction Sector by 2030.

EUROPEAN PARLIAMENT 2003. DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings. *Official Journal of the European Communities*.

FEIST, W. & PASSIVHAUS INSTITUT 2007. *Passive House Planning Package 2007: PHPP 2007: Requirements for Quality Approved Passive Houses*, Passivhaus Institut.

FRANKLIN, G. F., POWELL, J. D. & EMAMI-NAEINI, A. 2010. *Feedback control of dynamic systems, 6th edition*, Addison-Wesley Reading (Ma) etc.

FRENCH, M. J. 1999. *Conceptual design for engineers*, Springer Verlag.

FYNE HOMES. 2010. *05.10.10; Tigh-Na-Cladach officially opened by Alex Neil, Housing and Communities Minister* [Online]. Available: http://www.fynehomes.org.uk/news.html [Accessed 2011/05/16].

GAZE, C. 2009. *Complying with the Code for Sustainable Homes - Lessons learnt on the BRE Innovation Park*.

GIUSSANI, V. 1994. *THE UK CLEAN AIR ACT 1956 - An Empirical Investigation*, University of East Anglia.

GRIFFITHS, W. 2010. Information Paper 10/10. SAP for Beginners; An introductory guide for building professionals.

HAND, J. 2008. The ESP-r Cookbook. *ESRU.*

HAND, J. 2009. ESP-r Developers Guide. *ESRU.*

HENS, H. S. L. C. 2007. *Building physics-heat, air and moisture: fundamentals and engineering methods with examples and exercises*, Wiley-vch.

HITCHIN, R. 2010. A guide to the Simplified Building Energy Model (SBEM) - what it does and how it works.

HITCHIN, R. & DAVIDSON, P. 2009. EPBD Energy Calculation Procedures – an overview. . *The CENSE Project - Leading the CEN Standards on Energy performance of buildings to practice.*

HUDSON, G. & UNDERWOOD, C. Year. A simple building modelling procedure for MATLAB/SIMULINK. *In*, 1999. 777-83.

IEA. 2006. *European Electrical Standard Profiles - Annex 42 September 2006* [Online]. Available: http://www.ecbcs.org/annexes/annex42.htm [Accessed 2011/05/20].

IEA. 2009. *INTERNATIONAL ENERGY AGENCY - TRENDS IN PHOTOVOLTAIC APPLICATIONS Survey report of selected IEA countries between 1992 and 2008* [Online]. [Accessed 10/05 2011].

ISLAM, S., WOYTE, A., BELMANS, R., HESKES, P. & ROOIJ, P. 2006. Investigating performance, reliability and safety parameters of photovoltaic module inverter:

Test results and compliances with the standards. *Renewable energy,* 31**,** 1157-
1181.

JARNAGIN, R. E. 2009. ASHRAE Building EQ. *ASHRAE Journal, 51 (12): 18-19,* 51.

KHALID, Y. 2011. *Controllability of Building Systems.* PhD, Strathclyde.

KUMMERT, M., ANDRÉ, P. & NICOLAS, J. 2001. Optimal heating control in a passive
solar commercial building. *Solar energy,* 69**,** 103-116.

KUMMERT, M., BRADLEY, D. & MCDOWELL, T. 2004. TRNSYS Validation–Using
validation tool sin the development of TRNSYS 16. *TRNSYS Users Day–
Transsolar Stutgart March,* 26**,** 2004.

LYLE, A. 2009. *RE: Personal Communication.*

MACKENZIE, F., POUT, C., SHORROCK, L., MATTHEWS, A. & HENDERSON, J. 2010.
Energy Efficiency in New and Existing Buildings.

MASDAR INITIATIVE. 2011. *The Masdar Initiative* [Online]. Available:
http://www.masdarcity.ae [Accessed 10/10 2011].

MCWHINNEY, M., FANARA, A., CLARK, R., HERSHBERG, C., SCHMELTZ, R. & ROBERSON,
J. 2005. ENERGY STAR product specification development framework: using
data and analysis to make program decisions. *Energy Policy,* 33**,** 1613-1625.

MENDES, N., OLIVEIRA, G., ARAÚJO, H. & COELHO, L. Year. A Matlab-based simulation
tool for building thermal performance analysis. *In*, 2003. Citeseer.

METEOTEST. 2011. *Meteonorm - Global Meteorological Database version 6.1* [Online].
Available: www.meteotest.ch/en [Accessed 10/10 2011].

MÍGUEZ, J. L., PORTEIRO, J., LÓPEZ-GONZÁLEZ, L. M., VICUÑA, J. E., MURILLO, S.,
MORÁN, J. C. & GRANADA, E. 2006. Review of the energy rating of dwellings in
the European Union as a mechanism for sustainable energy. *Renewable and
Sustainable Energy Reviews,* 10**,** 24-45.

MUIR, E. & BRADSHAW, A. 1996. Control law design for a thrust vectoring fighter
aircraft using robust inverse dynamics estimation (RIDE). *ARCHIVE: Proceedings
of the Institution of Mechanical Engineers, Part G: Journal of Aerospace
Engineering 1989-1996 (vols 203-210),* 210**,** 333-343.

MURPHY, G. & COUNSELL, J. 2011. Symbolic Energy Estimation Model with Optimum
Start Algorithm Implementation *CIBSE Technical Symposium, DeMontfort*

University, Leicester UK – 6th and 7th September.

MURPHY, G., KHALID, Y. & COUNSELL, J. 2011. A Simplified Dynamic Systems Approach for the Energy Rating of Dwellings *Building Simulation 2011.* Sydney, Australia.

MURPHY, G., KUMMERT, M., ANDERSON, B. & COUNSELL, J. 2009. A comparison of the UK Standard Assessment Procedure and detailed simulation of building-integrated renewable energy systems. *Building Simulation 2009.* Glasgow, Scotland.

MURPHY, G. B., KUMMERT, M., ANDERSON, B. & COUNSELL, J. 2010. A comparison of the UK Standard Assessment Procedure and detailed simulation of solar energy systems for dwellings. *Journal of Building Performance Simulation,* 4**,** 75-90.

MURPHY, P. & CEDAR, M. 2005. IEA Solar Heating & Cooling Programme. *2004 Annual Report***,** 16-22.

MURRAY, M., FINLAYSON, N., KUMMERT, M. & MACBETH, J. Year. Live Energy TRNSYS–TRNSYS simulation within Google Sketchup. *In*, 2009. Citeseer.

NEYMARK, J., JUDKOFF, R., BEAUSOLEIL-MORRISON, I., BEN-NAKHI, A., CROWLEY, M., DERU, M., HENNINGER, R., RIBBERINK, H., THORNTON, J. & WIJSMAN, A. 2008. International Energy Agency Building Energy Simulation Test and Diagnostic Method (IEA BESTEST) In-Depth Diagnostic Cases for Ground Coupled Heat Transfer Related to Slab-on-Grade Construction. NREL/TP-550-43388. Golden, CO: National Renewable Energy Laboratory. www. nrel. gov/docs/fy08osti/43388. pdf.

NIELSEN, J. 1993. *Usability engineering*, Morgan Kaufmann.

NILSSON, J., BROGREN, M., HELGESSON, A., ROOS, A. & KARLSSON, B. 2006. Biaxial model for the incidence angle dependence of the optical efficiency of photovoltaic systems with asymmetric reflectors. *Solar Energy,* 80**,** 1199-1212.

OFFICE OF PUBLIC SECTOR INFORMATION 1956. *THE UK CLEAN AIR ACT* Her Majesty's Stationary Office

PERERS, B. 1993. Dynamic method for solar collector array testing and evaluation with standard database and simulation programs. *Solar energy,* 50**,** 517-526.

PERERS, B. & BALES, C. 2002. A solar collector model for TRNSYS simulation and system

testing. *IEA SHC Task,* 26.

PHELAN, R. 1977. *Automatic control systems*, Cornell University Press, Ithaca, New York.

PLIMMER, F., POTTINGER, G., HARRIS, S., WATERS, M. & POCOCK, Y. 2008. Knock it down or do it up? Sustainable house building: New build and refurbishment in the Sustainable Communities Plan.

REASON, L. & CLARKE, A. 2008. PROJECTING ENERGY USE AND CO2 EMISSIONS FROM LOW ENERGY BUILDINGS; A COMPARISON OF THE PASSIVHAUS PLANNING PACKAGE (PHPP) AND SAP. AECB.

REMUND, J. & KUNZ, S. 1997. *METEONORM: Global meteorological database for solar energy and applied climatology*, Meteotest.

RIJAL, H., TUOHY, P., NICOL, F., HUMPHREYS, M., SAMUEL, A. & CLARKE, J. 2008. Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. *Journal of Building Performance Simulation,* 1**,** 17-30.

SALAS, V. & OLÍAS, E. 2009. Overview of the state of technique for PV inverters used in low voltage grid-connected PV systems: Inverters below 10 kW. *Renewable and Sustainable Energy Reviews,* 13**,** 1541-1550.

SCHNIEDERS, J. 2003. CEPHEUS–measurement results from more than 100 dwelling units in passive houses. *Time to Turn Down Energy Demand, eceee***,** 340-351.

SCHNIEDERS, J. & HERMELINK, A. 2006. CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building. *Energy Policy,* 34**,** 151-171.

SCHOEN, T., PRASAD, D., RUOSS, D., EIFFERT, P. & SØRENSEN, H. Year. Task 7 Of The IEA PV Power Systems Program-Achievements And Outlook. *In*, 2001.

SCHOTT-ROHRGLAS GMBH. 2009. *SCHOTT Evacuated Tube Collector ETC 16 Technical Data* [Online]. [Accessed 10/05 2011].

SCOTTISH GOVERNMENT SOCIAL RESEARCH. 2009. *Modelling Greenhouse Gas Emissions from Scottish Housing: Final Report.* [Online]. [Accessed 10/05 2011].

SEAI 2011. Dwelling Energy Assessment Procedure (DEAP). *Sustainable Energy Authority of Ireland.*

SHORROCK, L. D. & ANDERSON, B. R. 1995. *A guide to the development of BREDEM*, BRE.

STEWART MILNE GROUP. 2009. *The Sigma Home – The future of low energy, carbon neutral homes.* [Online]. [Accessed 10/05 2011].

STRACHAN, P., KOKOGIANNAKIS, G. & MACDONALD, I. 2008. History and development of validation with the ESP-r simulation program. *Building and Environment,* 43**,** 601-609.

SYED, A. M., FUNG, A. S. & UGURSAL, V. I. Year. Analysis of the Potential of Using Photovoltaic and Wind Turbine Energy Systems in the Canadian Residential Sector. *In*, 2007. 665-672.

TESS. 2009. *RE: TRNSYS Type 604, multi-node pipe model.*

THE SCOTTISH GOVERNMENT 2007. *A Low Carbon Building Standards Strategy for Scotland (The Sullivan Report)*, Scottish Building Standards Agency.

THOMSEN, K. E. 2008. ENERGY PERFORMANCE OF BUILDINGS IN THE EU MEMBER STATES-main challenges for the EPBD now and in the future. *Editor: Jürgen Görres Landeshauptstadt Stuttgart Amt für Umweltschutz Gaisburgstrasse 4***,** 8.

TODD, S. 2001. A review of the proposals for amending the energy efficiency provisions in the Building Regulations for dwellings. *Structural Survey,* 19**,** 89-99.

TSB. 2009. *Technology Strategy Board (TSB) ; Retrofit for the Future competition* [Online]. Available: http://www.innovateuk.org/ourstrategy/innovationplatforms/lowimpactbuildi ng/retrofit-.ashx [Accessed 10/05 2011].

TUOHY, P. 2009. ESRU: Benchmarking Scottish Energy Standards: Passive House and CarobonLite Standards: A comparison of energy demand using SAP, SBEM and PHPP Methodologies.

TUOHY, P. & MURPHY, G. 2011. Monitoring the first Passive House in Scotland: Initial Findings. *UK Passivehaus Conference 2011.* London.

U.S. DEPARTMENT OF ENERGY. 2011. *Building Energy Software Tools Directory,* [Online]. Available: http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=39/p

agename=alpha_list [Accessed 10/05 2011].

UGLOW, C. E. 1981. The calculation of energy use in dwellings. *Building Services Engineering Research and Technology,* 2**,** 1.

UGLOW, C. E. 1982. Energy use in dwellings: An exercise to investigate the validity of a simple calculation method. *Building Services Engineering Research and Technology,* 3**,** 35.

UTLEY, J. & SHORROCK, L. 2008. Domestic energy fact file 2007. *Building Research Establishment*.

VALENTINI, M., RADUCU, A., SERA, D. & TEODORESCU, R. Year. PV inverter test setup for European efficiency, static and dynamic MPPT efficiency evaluation. *In*, 2008. IEEE, 433-438.

VANDERPERREN, Y. & DEHAENE, W. Year. From UML/SysML to Matlab/Simulink: current state and future perspectives. *In*, 2006. European Design and Automation Association, 93-93.

VEKEN, J. V. D., SAELENS, D., VERBEECK, G. & HENS, H. 2004. Comparison of Steady-State and Dynamic Energy Simulation Programs. *Buildings IX, ASHRAE*.

WARD, T. & SANDERS, C. 2007. BR 497 - CONVENTIONS FOR CALCULATING LINEAR THERMAL TRANSMITTANCE AND TEMPERATURE FACTORS.

WEATHER 2 LTD. 2011. *Historical Weather Data,* [Online]. [Accessed 10/05 2011].

WEISS, W., BERGMANN, I. & FANINGER, G. 2008. *Solar Heat Worldwide, Markets and Contribution to the Energy Supply 2006, Edition 2008* [Online]. [Accessed 10/05 2011].

WITTCHEN, K. B. 2003. BUILDING INTEGRATED PHOTOVOLTAICS IN A THERMAL BUILDING SIMULATION TOOL.

WRIGHT, A. J. 1997. Electric storage heaters in building simulation. *IBPSA, Building Simulation***,** 38-40.

YANG, I. H., YEO, M. S. & KIM, K. W. 2003. Application of artificial neural network to predict the optimal start time for heating system in building. *Energy conversion and management,* 44**,** 2791-2809.

YAO, R. & STEEMERS, K. 2005. A method of formulating energy load profile for domestic buildings in the UK. *Energy and Buildings,* 37**,** 663-671.

ZAHER, O., COUNSELL, J. & BRINDLEY, J. 2011. Robust Control of Room Temperature and Relative Humidity using Advanced Nonlinear Inverse Dynamics and Evolutionary Optimisation. *Ninth International Eurogen Conference.* Capua, Italy. .

Appendix B: Simulink Block Diagrams for Final 4th Order Model

Simulink representation of 4th Order IDEAS Model
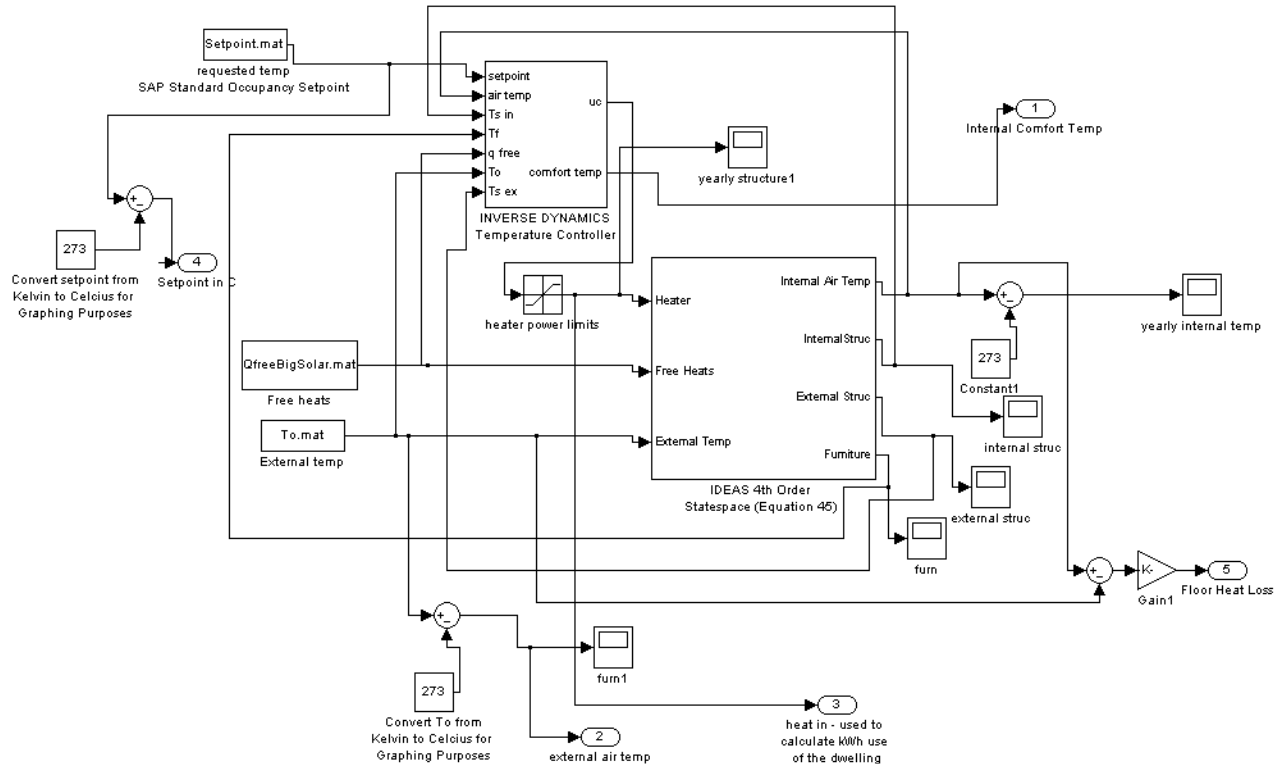
Figure B.1 – Simulink representation of 4th Order IDEAS Model

Figure B.1 is the Simulink representation of the 4th Order IDEAS Model. In B1 various Simulink blocks are used with examples as follows:

- "Requested Temp, SAP Standard Occupancy Setpoint"

  o Constant block. Here a constant SAP Standard Occupancy Setpoint in Kelvin is stored in the file 'setpoint.mat' and used as a constant which is then pass to the Inverse Dynamics Temperature Controller

- "Inverse Dynamics Temperature Controller"

  o Subsystem. This is the Inverse Dynamics Temperature Controller which is used to perfectly track the SAP setpoint. This subsystem is detailed in figure B.5

  o The outputs of the ID Temp Controller are internal comfort

temperature (which is stored in an outport sink, denoted by 1 in figure B.1) and heater demand.   The heater demand, U(t), is determined by the controller to maintain the required temperature as defined by the requested temperature.   The perfect inverse control law RIDE is invoked, $U(t) = g(CB)^{-1}\left(v(t) - y(t)\right) + U_{eq}(t)$, to give U(t)

- "Heater Power Limits"

  - Saturation Block. The heater demand is then passed to the "IDEAS 4th Order Statespace Subsystem" (see figure B.4) by way of a Saturation Block. The saturation block sets the heater power limits. The variable qdothmax is defined in the Matlab m file (see Appendix C) and is the upper limit of the heating system in Watts. With this addition, sizing of heating systems is possible in IDEAS
- "Sinks"
  - In Simulink, Sinks are used to output results or information. In IDEAS, 5 Outport sinks are used to store information from the model as follows: 1 (Internal Comfort Temperature produced by the ID Controller), 2 (External Air Temp, external temperature in K – 273 to output this in Celsius), 3(Heat input, from the ID Controller and limited by the Heater Power Limits), 4(Setpoint in C), 5(Floor Heat Loss, based upon equation 2 Thesis Chapter 4, section 2.2). When the Simulink file is called from Matlab, the sinks are required to be noted:

    ```
    [t,x,y1,y2,y3,y4,y5]=sim('SAP_Model_Fourth_Order');
    ```

  - Another example of Sinks used in IDEAS is a Floating Scope sink. These also store information from the IDEAS model; they are primarily used during development to chart the simulation progress
- "Sum"
  - A sum block is used to sum two values.
  - In Figure B.1, it can be seen that sum blocks are generally used in IDEAS to convert a temperature in K (all internal IDEAS temperature are in Kelvin) to Celsius (for display purposes).

Simulink representation of 4ᵗʰ Order Model with Optimum Start
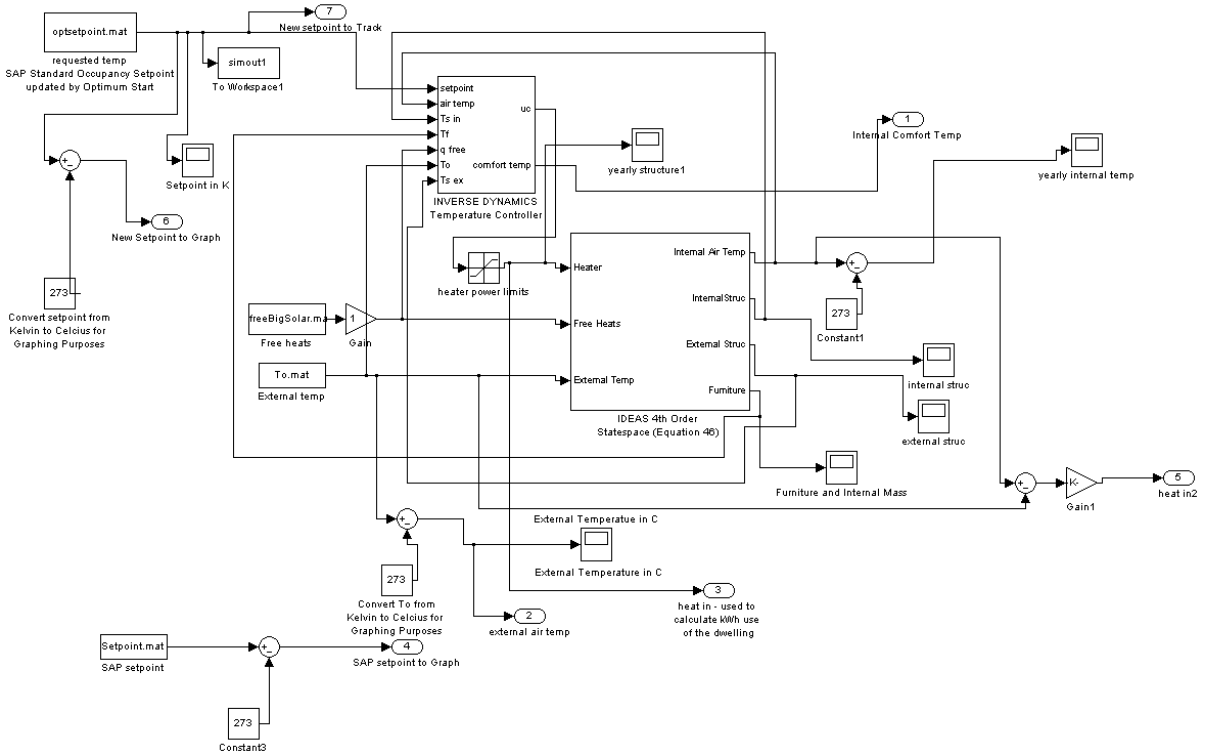
Figure B.2 – Simulink representation of 4th Order Model with Optimum Start

- Figure B.2 is the 4ᵗʰ Order IDEAS Model plus the addition of Optimum Start.
  - Optimum Start is self-contained and detailed in figure B.3

Optimum Start Model
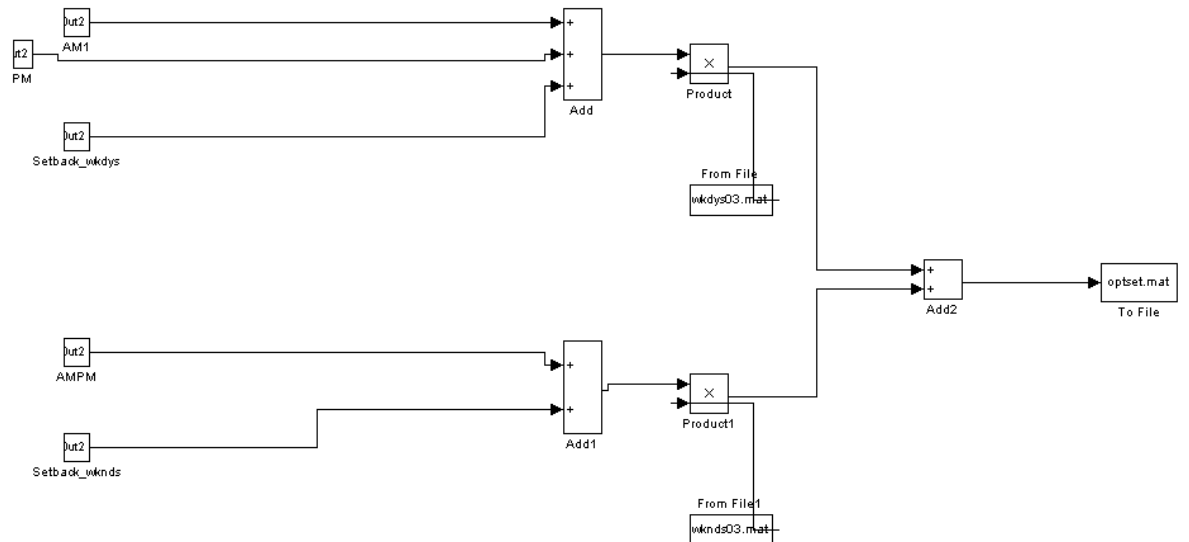
Figure B.3 – Optimum Start Model

- Figure B.3 details the Optimum Start sub model which is called in the m file as follows:
  - Dd `[t,x]=sim('optimum_start_setmodel');`

247

- The Optimum Start sub model is fed by parameters determined in the Matlab m file as follows:

```
%set start point as defined by SAP
tSAP1 = 7*3600;
tSAP2 = 16*3600;

%define end of comfort period
tSAP_end1 = 9*3600;
tSAP_end2 = 23*3600;

%set start point minus a factor based upon the value of g
%compensate for the phase lag (tor)
tsc1 = tSAP1 - (3/g)
tsc2 = tSAP2 - (3/g)
Tcomfort = 21+273;
Tsetback = 0+273;

%now slope required from setback, the possible maximum
ramp
%power limit - gradient
dTmax = b11 * qdothmax

%what we have to step back for the ramp
t_opt = (Tcomfort - Tsetback) / dTmax
t_opt1 = tsc1 - t_opt
t_opt2 = tsc2 - t_opt
```

- The output of the this sub model is a new setpoint (optsetpoint.mat)
  - This is then tracked by the Inverse Dynamics Temperature Controller

4th Order Statespace subsystem (Equation 46)
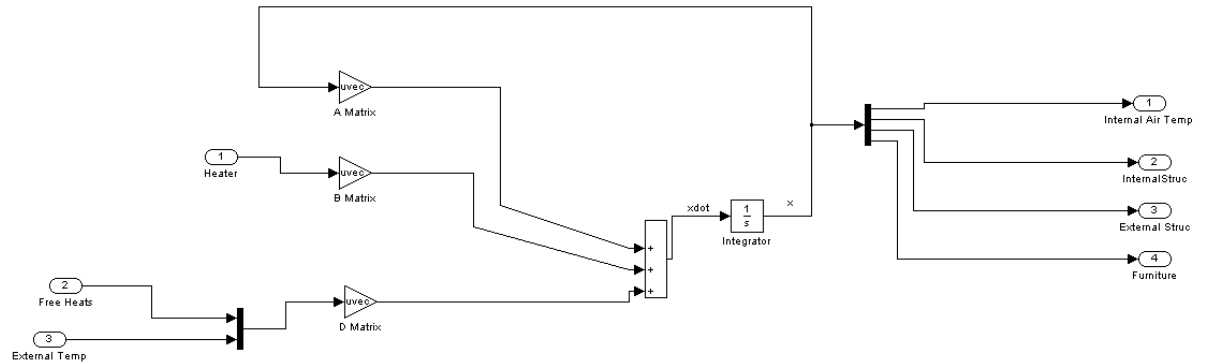
Figure B.4 – 4th Order Statespace subsystem (Equation 46)

- Figure B.4 is the simulink representation of the 4th Order IDEAS model:

-
$$\begin{bmatrix} \dot{T}(t) \\ \dot{T}_{SI}(t) \\ \dot{T}_{SE}(t) \\ \dot{T}_{FT}(t) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 & a_{14} \\ a_{21} & a_{22} & a_{23} & 0 \\ 0 & a_{32} & a_{33} & 0 \\ a_{41} & 0 & 0 & a_{44} \end{bmatrix} \begin{bmatrix} \dot{T}(t) \\ \dot{T}_{SI}(t) \\ \dot{T}_{SE}(t) \\ \dot{T}_{FT}(t) \end{bmatrix} + \begin{bmatrix} b_{11} \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \dot{Q}_H(t) \end{bmatrix} + \begin{bmatrix} d_{11} & d_{12} \\ 0 & 0 \\ 0 & d_{32} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{Q}_{FREE}(t) \\ T_o \end{bmatrix}$$

- Where the A, B, C and D Matrices can be seen in Figure B.4

- The Matrices are defined in the Matlab M File as follows:

```
A = [a11, a12, a13, a14; a21, a22, a23, a24; a31, a32, a33, a34; a41,
a42, a43, a44];
```

248

```
B = [b11; b21; b31; b41];
C = [c11, c12, c13, c14; c21, c22, c23, c24; c31, c32, c33, c34; c41,
c42, c43, c44];
D = [d11, d12; d21, d22; d31, d32; d41, d42];
```
- With each term such as a12 also being defined in the Matlab M file as
  follows: `a12 = (hi*As)/(Ma*Ca);`
  - Where values such as As (area of the structure) are also stored in the
    M file. For a comparison with BREDEM / SAP, values such as As are
    taken directly from BREDEM / SAP. However, any values could be
    used based upon the values of the building to be modelled
- The heat input is passed into the B Matrix
- The Free Heats and External Temperature are passed into the D matrix, as
  these are both disturbances in the model
- The outputs of this subsystem are the internal zone, internal structure,
  external structure and furniture & internal mass temperatures

Inverse Dynamics Temperature Controller Subsystem
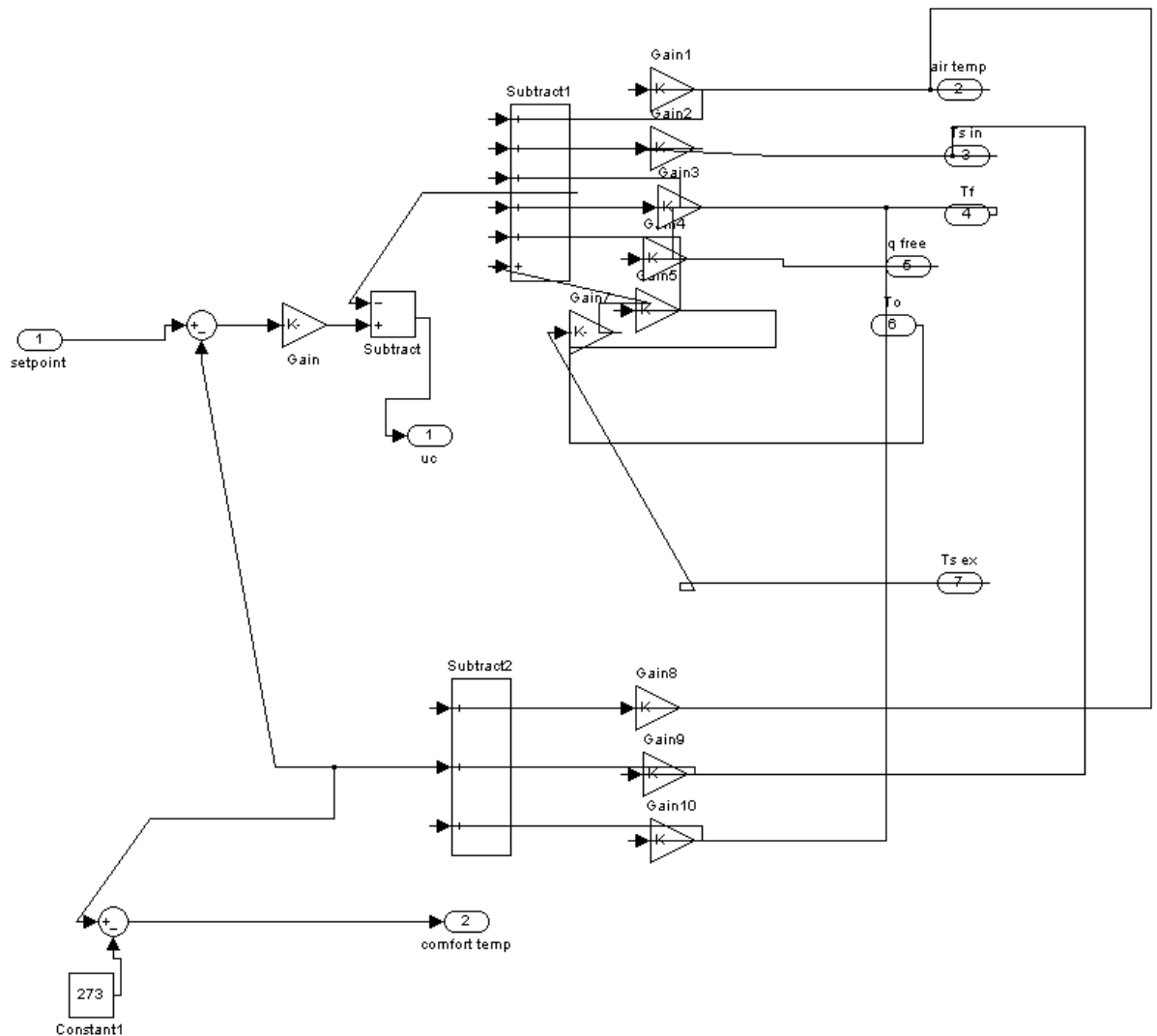
Figure B.5 – Inverse Dynamics Temperature Controller Subsystem

- Figure B.5 details the Inverse Dynamics Controller Subsystem
- The following information is pass to the ID Controller Subsystem:
  - Setpoint (with or without Optimum Start)
  - Temperatures: (Internal Zone / Internal Structure / External Structure / Furniture & Internal Mass / Outside)
  - Free Heats (W)
- The full state feedback Inverse Dynamics Controller parameters are defined in the M file as follows:

```
CB=C*B;
CBinv=1/CB;
CA=C*A;
CD=C*D;
CBinvCA=CBinv*CA;
CBinvCD=CBinv*CD;
```

  - Where A, B, C and D refer to the corresponding Matrix
  - The heat required U(t) is calculated based upon the values, which have the following gains placed upon them:
    - Internal Zone T (Gain 1: CBinvCA(1))
    - Internal Structure T (Gain 2: CBinvCA(2))
    - External Structure T (Gain 7: CBinvCA(3))
    - Furniture & Internal Mass T (Gain 4: CBinvCA(4))
    - Outside T (Gain 1: CBinvCD(2))
    - Free Heat Gains Gain 5: CBinvCD(1))
      - Where the use of the D matrix for Outside Temperature and Free Heat Gains highlights that these values are treated as disturbances
  - From Figure B.5, it can be seen that the setpoint is passed through a gain to help to provide the uc
    - The gain block here (block named Gain) is g*(CBinv(1)) where g is the responsivity of the heating system and CBinv = 1/CB
    - This gain block is known as the Controller Gain Matrix as defined in Chapter 4, section 3 of this thesis
  - The comfort temperature is created by using a Gain block for T, Tsi, & Tft, where:
  - ```c11 = ratio_Ta; / c22 = ratio_Tsi; / c44 = ratio_Tft;```
- The output of the ID Controller Subsystem are therefore:
  - The heat required to meet the setpoint requirements
  - The Comfort Temperature based upon the ratio of T, Tsi, & Tft

Appendix C: Matlab Source Code for Final 4th Order Model with Optimum Start

```
%G.B.MURPHY - IDEAS - WITH OPTIMUM START
%FOURTH ORDER MODEL - ABSOLUTE VALUES MODEL
%This version is a test case example for a Poorly Insulated Dwelling
%DATE: 2011/11/11
%FAST HEATING SYSTEM: SAP Responsivity of 1.0
%************************************************************************
*****
clc                     %Clear Command Window
close all               %Close Graphs from Previous iterations

Mv  = 0.039662493237701; %FROM BREDEM      %(Kg/s)      Mass of the
dwelling air
%REF: =(('Semi-Detached'!AA41*'Semi-Detached'!AC6)/3600)*E11
%Where AA41 = Annual Effective Air Change Rate / AC6 = House Volume
(m2)  /
%E11 = Pa   = 1.205;      %STANDARD VALUE  %kg/m3      Density of Air

Ma  = 267.51;      %Va (Volume of Air from FROM BREDEM CELL AC6)* Pa
(Density of Air STANDARD VALUE)
%kg Mass of the air

Ca = 1005;         %STANDARD VALUE     %J/(kgK)    Specific heat
capacity of air
%REF:           http://www.engineeringtoolbox.com/air-properties-
d_156.html

Usap = 2.1;        %FROM BREDEM CELL AB47    %(W/m²K)    SAP Heat
transfer coeff. of the structure

As = 81.8;         %FROM BREDEM CELL AA47    %m^2        Surface area
of structure

Ar  = 44.4;        %FROM BREDEM CELL AA49    %(m²)       Area of Roof

Ur  = 2.3;         %FROM BREDEM CELL AB53    %(W/m²K)  Heat Transfer
Co-Efficient of the Roof

Uw  = 4.167;       %FROM BREDEM CELL AB53    %(W/m²K)    Heat Transfer
Co-Efficient of the Windows

Aw  = 16.9;        %FROM BREDEM CELL AA53    %(m²)       Area of the
Windows

Pa  = 1.205;       %STANDARD VALUE  %kg/m3      Density of Air
%REF:           %http://www.engineeringtoolbox.com/air-properties-
d_156.html

Va  = 222;         %FROM BREDEM CELL AC6     %m3         Volume of Air

Uf  = 0.7;         %FROM BREDEM CELL AB48    %(W/m²K)   Heat Transfer
Co-Efficient of the Floor

Af  = 44.4;        %FROM BREDEM CELL AA48    %(m²)       Area of the
Floor
```

```matlab
Aft = 120.7         %FROM BREDEM CELL AA75 + AA76 (Internal Mass)    %m2
Area of Internal Mass in a Dwelling, 120.7 is figure from BREDEM


Kwall = 1.31;       %STANDARD VALUE      %W/(m.K)    Thermal
conductivity of internal wall structure: k value
%REF:              %http://www.engineeringtoolbox.com/thermal-
conductivity-d_429.html


Twall = 0.2286;     %STANDARD VALUE      %m          Wall thickness
(9inch brick in this example)
%REF:              "Refurbishing dwellings – a summary of best
%%practice CE189)"


Mft = 5193.412;     %FROM BREDEM CELL AJ74        %kg          Mass of
the Furniture


Msi = 16062.12/2;   %FROM BREDEM CELL AM74        %kg          Mass of
Structure Internal


Mse = 16062.12/2;   %FROM BREDEM CELL AM74        %kg          Mass of
Structure External


Cs  = 1700;         %J/(kg.K)    Specific Heat Capacity of Structure &
Internal Mass
%REF:              %http://www.engineeringtoolbox.com/specific-heat-
capacity-d_391.html


Cft = 1700;         %J/(kg.K)    Specific Heat Capacity of Furniture &
Internal Mass
%REF:              %%http://www.engineeringtoolbox.com/specific-heat-
capacity-d_391.html


Uft = 1.2;          %(W/m²K)   Heat Transfer Co-Efficient of the
Furniture & Internal Mass

qdothmax = 20000; %heater max
qdothmin = 0;     %heater min

g = 1/(3*300);          %controller time constant



%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculation of Internal/External Heat Transfer Coefficient
disp('************Calculation of Internal/External Heat Transfer
Coefficient************')
disp('************hratio = 1.09;************')
hratio = 1.09; %dimensionless - increase value to reduce energy
hi = Usap*Kwall*(hratio + 1)/(hratio*(Kwall - Usap*Twall));
he = hratio*hi
disp('************END************')

%Comfort Temp Ratio
ratio_Ta  = 0.33    %Ratio of internal air temp used for comfort temp
ratio_Tsi = 0.33      %Ratio of internal structure temp used for
comfort temp
ratio_Tft = 0.33    %Ratio of thermal mass temp used for comfort temp
```

```matlab
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculation of ss matrices
%Temperature Terms
a11 = (-(Mv*Ca)-(hi*As)-(Uf*Af) -(Ur*Ar)-(Uw*Aw)-(Uft*Aft))/(Ma*Ca);
a12 = (hi*As)/(Ma*Ca);
a13 = 0;
a14 = (Uft*Aft)/(Ma*Ca);
%Tsi Terms
a21 = ((hi*As)/(Msi*Cs));
a22 = (-(hi*As)-(As*(Kwall/Twall)))/(Msi*Cs);
a23 = (As*(Kwall/Twall))/(Msi*Cs);
a24 = 0;
%Tse Terms
a31 = 0;
a32 = (As*(Kwall/Twall))/(Msi*Cs);
a33 = (-(he*As)-(As*(Kwall/Twall)))/(Mse*Cs);
a34 = 0;
%Tft Terms
a41 = (Uft*Aft)/(Mft*Cft);
a42 = 0;
a43 = 0;
a44 = -(Uft*Aft)/(Mft*Cft);


b11 = 1/(Ma*Ca);
b21 = 0;
b31 = 0;
b41 = 0;

c11 = ratio_Ta;
c12 = 0;
c13 = 0;
c14 = 0;
c21 = 0;
c22 = ratio_Tsi;
c23 = 0;
c24 = 0;
c31 = 0;
c32 = 0;
c33 = 0;
c34 = 0;
c41 = 0;
c42 = 0;
c43 = 0;
c44 = ratio_Tft;

d11 = 1/(Ma*Ca);
d12 = ((Mv*Ca)+(Uf*Af)+(Ur*Ar)+(Uw*Aw))/(Ma*Ca);
d21 = 0;
d22 = 0;
d31 = 0;
d32 = (he*As)/(Mse*Cs);
d41 = 0;
d42 = 0;

A = [a11, a12, a13, a14; a21, a22, a23, a24; a31, a32, a33, a34; a41,
a42, a43, a44];
B = [b11; b21; b31; b41];
```

```matlab
C = [c11, c12, c13, c14; c21, c22, c23, c24; c31, c32, c33, c34; c41,
c42, c43, c44];
D = [d11, d12; d21, d22; d31, d32; d41, d42];


%Full state feedback ID controller parameters
CB=C*B;
CBinv=1/CB;
CA=C*A;
CD=C*D;
CBinvCA=CBinv*CA;
CBinvCD=CBinv*CD;




%Start Optimum Start Work
%set start point as defined by SAP
tSAP1 = 7*3600;
tSAP2 = 16*3600;

%define end of comfort period
tSAP_end1 = 9*3600;
tSAP_end2 = 23*3600;

%set start point minus a factor based upon the value of g
%compensate for the phase lag (tor)
tsc1 = tSAP1 - (3/g)
tsc2 = tSAP2 - (3/g)


Tcomfort = 21+273;
Tsetback = 0+273;

%now slope required from setback, the posssible maximum ramp
%power limit - gradient
dTmax = b11 * qdothmax

%what we have to step back for the ramp
t_opt = (Tcomfort - Tsetback) / dTmax

t_opt1 = tsc1 - t_opt
t_opt2 = tsc2 - t_opt

% call setpoint model
[t,x]=sim('optimum_start_setmodel');
load('optset.mat')

% fix spikes
for i = 1:length(Y);
    if Y(1,i) >= 86400*i && Y(1,i) <= 88200*i;
        Y(2,i) = Tsetback;
    end
end

save('optsetpoint.mat','Y');

%End Optimum Start Work

%Call zone model
```

```
[t,x,y1,y2,y3,y4,y5,y6,
y7]=sim('SAP_Model_Fourth_Order_Optimum_start_v11');

thours = t/(60*60);
tweeks = t/(60*60*24*7);


jan = y3(1:44640);
feb = y3(44641:84961);
mar = y3(84962:129602);
apr = y3(129602:172803);
may = y3(172804:217444);
jun = y3(217445:260644);
jul = y3(260645:305285);
aug = y3(305286:349926);
sep = y3(349927:393127);
oct = y3(393128:437768);
nov = y3(437769:480969);
dec = y3(480970:525600);


%New method, N.B. kWh Required, so sum of each month / 60 minutes *
1000 kW
jan_energy = sum(jan)/(60*1000)
feb_energy = sum(feb)/(60*1000)
mar_energy = sum(mar)/(60*1000)
apr_energy = sum(apr)/(60*1000)
may_energy = sum(may)/(60*1000)
jun_energy = sum(jun)/(60*1000)
jul_energy = sum(jul)/(60*1000)
aug_energy = sum(aug)/(60*1000)
sep_energy = sum(sep)/(60*1000)
oct_energy = sum(oct)/(60*1000)
nov_energy = sum(nov)/(60*1000)
dec_energy = sum(dec)/(60*1000)


jant = y1(1:44640);
febt = y1(44641:84961);
mart = y1(84962:129602);
aprt = y1(129602:172803);
mayt = y1(172804:217444);
junt = y1(217445:260644);
jult = y1(260645:305285);
augt = y1(305286:349926);
sept = y1(349927:393127);
octt = y1(393128:437768);
novt = y1(437769:480969);
dect = y1(480970:525600);


jan_t = (sum(jant)/44640)
feb_t = (sum(febt)/40320)
mar_t = (sum(mart)/44640)
apr_t = (sum(aprt)/43200)
may_t = (sum(mayt)/44640)
jun_t = (sum(junt)/43200)
jul_t = (sum(jult)/44640)
aug_t = (sum(augt)/44640)
sep_t = (sum(sept)/43200)
oct_t = (sum(octt)/44640)
nov_t = (sum(novt)/43200)
dec_t = (sum(dect)/44640)
```

```matlab
year_energy =
jan_energy+feb_energy+mar_energy+apr_energy+may_energy+jun_energy+jul_
energy+aug_energy+sep_energy+oct_energy+nov_energy+dec_energy;

figure(1)
plot(thours(1:8640),y6(1:8640))

figure
subplot(4,1,1:2);
plot(thours,y1,thours,y4);
set(gca,'YTick',[10 12 14 16 18 20 22 24 26 28 30])
set(gca,'YMinorTick','on')
set(gca,'YMinorGrid','on')
title('hourly comfort temp')
axis([7440 7484 0 25]);

subplot(4,1,3);
plot(thours,y3);
title('hourly heat in')
axis([7440 7484 0 21000]);

subplot(4,1,4);
plot(thours,y2);
set(gca,'YTick',[-10 -5 0 5 10 15 20 25 30 35])
title('hourly external air temp')
axis([7440 7484 -6 30]);




%END MATLAB FILE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix D: Definition of Typical IDEAS Data Parameters

IDEAS Variable	Nomenclature	Typical Value	Units	Value Calculation
Mv	Mass of the Dwelling Air Ventilation	0.039662	kg/s	=(('Semi-Detached'!AA41*'Semi-Detached'!AC6)/3600)*B12 ((Effective Air Change Rate * Dwelling Volume)/3600) *Density of Air
Ca	Specific Heat Capacity of Air	1012	J/(kg.K)	http://www.engineeringtoolbox.com/spesific-heat-capacity-gases-d_159.html
Us	Heat Transfer Co-Efficient of the Structure (U-Value)	2.1	(W/m²K)	U-Value of the walls of the dwelling: from BREDEM 2009 ='Semi-Detached'!AB47
As	Surface Area of Structure	81.8	(m²)	Area of the walls of the dwelling: from BREDEM 2009 ='Semi-Detached'!AA47
Ur	Heat Transfer Co-Efficient of the Roof (U-Value)	0.13	(W/m²K)	U-Value of the roof of the dwelling: from BREDEM 2009 ='Semi-Detached'!AB49
Ar	Area of Roof	44.4	(m²)	Area of the roof of the dwelling: from BREDEM 2009 ='Semi-Detached'!AA49
Uw	Heat Transfer Co-Efficient of the Windows (U-Value)	1.415094	(W/m²K)	U-Value of the Windows of the dwelling: from BREDEM 2009 ='Semi-Detached'!AB53
Aw	Area of the Windows	16.9	(m²)	Area of the Windows of the dwelling: from BREDEM 2009 ='Semi-Detached'!AA53
Ma	Mass of the air	230.0586	kg	Mass of Air = Density of Air * Volume of Air
Pa	Density of Air	1.205	kg/m³	http://www.engineeringtoolbox.com/air-properties-d_156.html

Va	Volume of Air	190.92	m³	Volume of Air = Volume of Air taken from BREDEM 2009 – Volume of Internal Mass =CELL AA6 – (Cell AA75 + Cell AA76)
Ms	Mass of Structure	13104.36	kg	Based upon values from BREDEM: Cell AM74
Cs	Specific Heat Capacity of Structure	800	J/(kg.K)	http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html
Uf	Heat Transfer Co-Efficient of the Floor	0.2	(W/m²K)	U-Value of the Floor of the dwelling: from BREDEM 2009 ='Semi-Detached'!AB48
Af	Area of the Floor	44.4	(m²)	Area of the ground floor of the dwelling: from BREDEM 2009 ='Semi-Detached'!AA48
Cf	Specific Heat Capacity of Floor	800	J/(g.K)	http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html Value for Concrete, stone used.
Pb	Brick density	801	kg/m³	http://www.engineeringtoolbox.com/density-solids-d_1265.html
Mft	Mass of the Internal Mass	3108	kg	Based upon values from BREDEM: Cell AJ74
Cft	Specific Heat Capacity of Internal Mass	1600	J/(kg.K)	1600 J/(kg K) based upon information here: http://physics.info/heat-sensible/
Uft	Heat Transfer Co-Efficient of the Internal Mass	2	(W/m²K)	U-Value of the Internal Mass in the dwelling.
Aft	Area of Internal Mass in a Dwelling	120	m²	Based upon values from BREDEM: Cell AA75 + Cell AA76
Kwall	Thermal Conductivity of the Structure	1.31	W/(m.K)	Chosen to correlate with the SAP U Value: this example figure for solid brick (http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html)
Twall	Thickness of the Structure	0.2286	m	Chosen to correlate with the SAP U Value: Wall thickness in metres (this example for 9 inch brick)

Appendix E: Third Order IDEAS Excel Model Definition

Microsoft Excel – 3rd Order Model - Continuous RIDE

4 tabs were created in Excel 2007 as follows:

Tab 1: Home

- Set initial conditions for
    - Temperature outside
    - Temperature inside the dwelling
    - Temperature of the internal mass
    - Temperature of the structure
- Set limits of the model such as
    - Upper and lower limits of the heating system
- Display Yearly Graphs for Temperatures
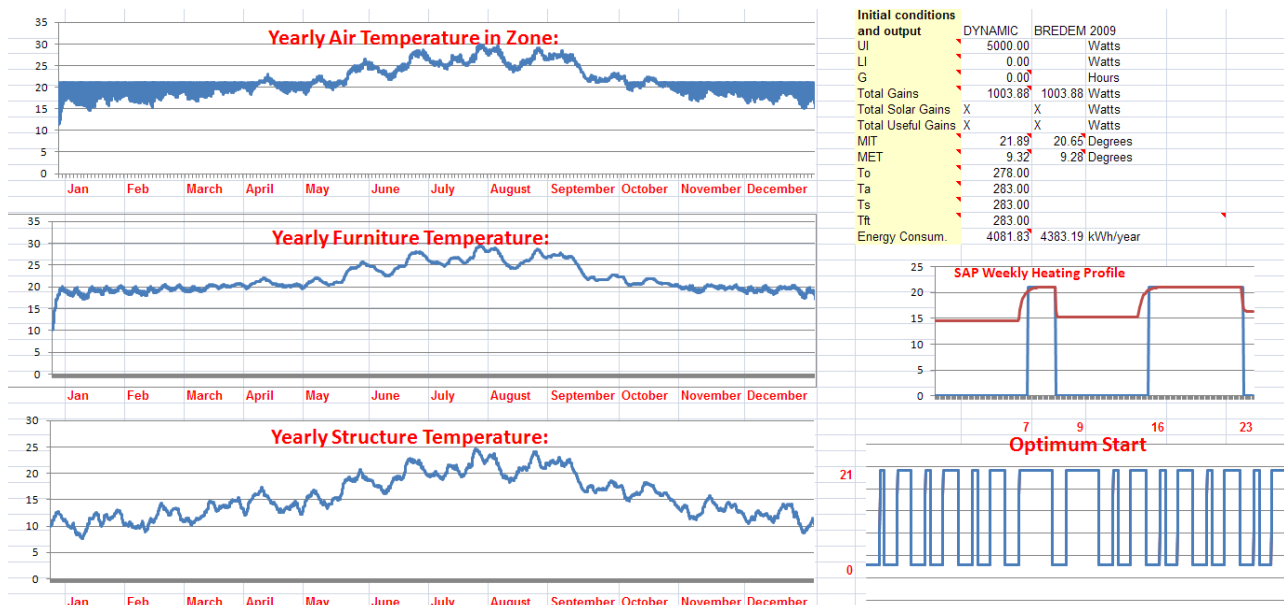
Figure E.1 – IDEAS implementation in Excel 2007, Home Tab

Tab 2: Results

- The hub of the model, columns are added for the following, with all values calculated at a 5 minute time resolution, resulting in over 105,000 rows per column, for a yearly model
    - Target Room Temperature
        - This value is taken from the Optimum Start calculations
    - K
        - Count

- **Time**
  - In hours
- **T(k) (Zone Air)**
  - Temperature inside the zone in Kelvin
- **Ts (k) (Structure)**
  - Temperature of the structure in Kelvin
- **Tft(k) (Furniture and Internal Mass)**
  - Temperature of the Furniture and Internal Mass in Kelvin
- **Qfree**
  - Free Heats gains from appliances, people and solar
    - Varying monthly based upon values from BREDEM
- **To – Kelvin**
  - Outside Temperature in Kelvin
- **u(k) (heat in Watts)**
  - Heater Input Calculated as: $=(G/b\_11)*(A3-D2)-(1/b\_11)*(a\_11*D2+a\_12*E2+a\_13*F2+d\_11*G2+d\_12*H2)$
  - Where:
    - $G = (1/(3*T))$ where T = 300seconds
    - $b\_11 =$ constant B11 as defined in equation 16
    - $a\_11 =$ constant A11 as defined in equation 16
    - $D2 =$ The previous value for T(k) (Zone Air)
    - $a\_12 =$ constant A11 as defined in equation 16
    - $E2 =$ The previous value for Ts(k) (Structure)
    - $a\_13 =$ constant A13 as defined in equation 16
    - $F2 =$ The previous value for Tft(k) (Furniture & Internal Mass)
    - $d\_11 =$ constant D11 as defined in equation 16
    - $G2 =$ The previous value for Qfree (free heats)

260

- - o d_12 = constant D1 as defined in equation 16
    - o H2 = The previous value for To(k) (Outside Temperature)
  - • This is the perfect control law RIDE as described in equation 27
- u(k) (discontinuity)
  - • This is the heat in Watts determined by the perfect control law, but limited by the upper and lower limits of the heating system as set in the Home tab
- BREDEM setpoint in C
  - • This is the BREDEM setpoint for a single zone which is set to demand 21° from 7->9 am and 4->11pm midweek and 7am->11pm on a weekend.
- Ta(k) in C
  - • The Temperature of the zone air, used for graphing
- Structure Temp in C
  - • Structure temperature, used for graphing
- Furniture Temp in C
  - • Furniture and Internal Mass Temperature, used for graphing
- Time (seconds)
  - • Used for analysis
- Weather - Yearly in C
  - • External Temperature at a 5 minute resolution, taken for a Sheffield weather location from the Meteonorm climate software
- Day
  - • Each day is assigned a number, where 1 = Monday
  - • The day starts on a Wednesday (3) so that the Free Heats are matched to the year 2003
- Total Internal Gains
  - • Varies monthly, taken from BREDEM calculated figures
- Month
  - • Month in simulation run where 1 = January
- Print: Zone Air (C)
  - • Temperature in the zone. An offset is used (such as

=OFFSET(L14,ROW()*4,0)) so that each 4th row is reported back to this column, this is used for graphing purposes as Excel 2007 has a limit: "The maximum number of data points you can use in a data series for a 2-D chart is 32,000". This column is used to display the yearly graphs as seen in the home tab

- ▪ Print: T Structure (C)
  - • Temperature of the structure, required for the same purpose as Print: Zone Air (C)
- ▪ Print: T Furniture Air (C)
  - • Temperature of the Furniture and Internal Mass, required for the same purpose as Print: Zone Air (C)
- ▪ Print: External Air (C)
  - • Temperature of the External Air, required for the same purpose as Print: Zone Air (C)

Target Room Temp	k	time t (h)	T(k) (Zone Air)	Ts (k) (Structure)	Tft(k) (Furniture)	Qfree	To - Kelvin	u(k) (heat in Watts)	u(k) (discontinuity)	BREDEM Setpoint in C	Ta(k) in C	StructureTemp in C	Furniture Temp in C	Time (Seconds)	Weather - Yearly in C	Day	Total Internal Gains	Month	Print: Zone Air (C)	Print: T Structure (C)	Print: T Furniture Air (C)	Print: External Air (C)
273	0	0	283	283	283	797	281.4	0	0	0	10	10	10	0	8.4	3	797.4	1	11.5	10	10	8.93
273	11	0.91667	284.516	283	283.06	797	282.1	-2423.6	0	0	11.52	10	10.06	3300	9.1								
273	12	1	284.531	283	283.06	797	282.2	-2426.9	0	0	11.53	10	10.06	3600	9.2	3	797.4	1	11.7	10	10	8.47
273	13	1.083																	11.7	10	10	8.39
273	14	1.166																	11.7	10	10	8.35
273	15	1.																	11.7	10	10	8.31
273	16	1.333																	18.1	10	11	8.3
273	17	1.416																	20.2	10	11	8.3
273	18	.																	20.8	10	11	8.28
273	19	1.583																	21	10	11	8.24
273	20	1.666																	21	10	11	8.2
273	21	1.																	12.4	10	11	8.2
273	22	1.833																	12.4	10	11	8.2
273	23	1.916																	12.4	10	11	8.18
273	24																		12.5	10	12	8.13
273	25	2.083																	12.5	10	12	8.1
273	26	2.166																	12.5	10	12	8.1
273	27	2.25	284.563	283.01	283.16	797	281.9	-2428.2	0	0	11.56	10.01	10.16	8100	8.9	3	797.4	1	12.5	10	12	8.1
273	28	2.33333	284.566	283.01	283.16	797	281.9	-2428.9	0	0	11.57	10.01	10.16	8400	8.9	3	797.4	1	12.5	10	12	8.1

Embedded charts (within the data region): "SAP Weekly Heating Profile - Winter - 1st December", "SAP Weekly Heating Profile - Spring - 1st March", "SAP Weekly Heating Profile - Summer - 1st June", "SAP Weekly Heating Profile - Autumn - 1st September", and "Yearly Weather from Meteonorm".
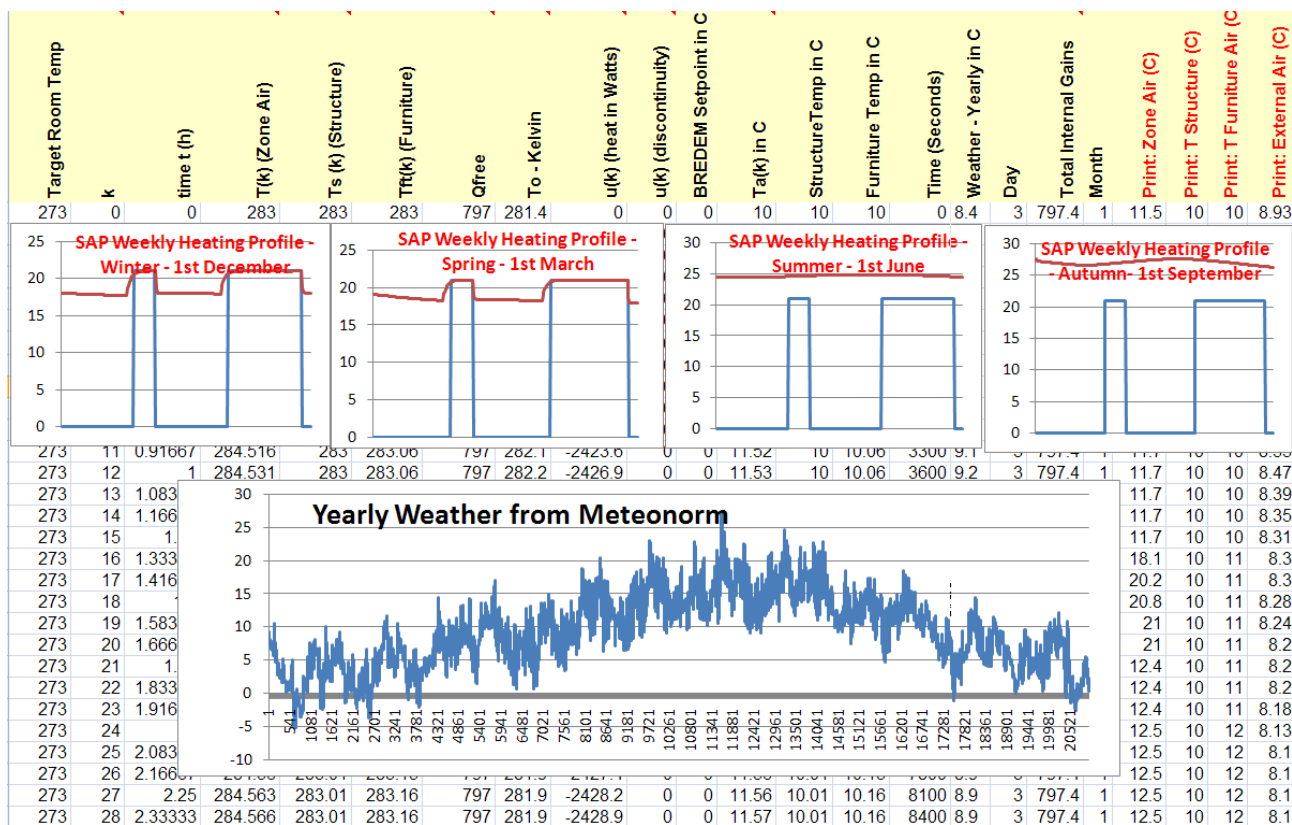
Figure E.2 - IDEAS implementation in Excel 2007, Results Tab

Tab 3: Optimum Start

- • The implementation of the Optimum Start algorithm in Excel 2007 is defined in this tab

- This tab would be hidden from a user to reduce the risk of inappropriate modification
- Each day has an optimum start calculated based upon the yearly BREDEM setpoint
- A new setpoint is then created which is tracked by the perfect control algorithm RIDE, the SAP setpoint is not tracked and is used for graphing purposes.
- For a very responsive system the Optimum Start setpoint will closely mimic the SAP/BREDEM setpoint, whilst a very unresponsive system could demand 21°, 24 hours a day for the setpoint to be met

DAY #	DAY	topt1 hours	tstart1 (hours)	tstart2 (hours)	tend1	tend2
1	01/01/2003	0.22038324	6.77961676	15.77961676	9	23
2	02/01/2003	0.970450921	6.02954908	15.02954908	9	23
3	03/01/2003	0.97038324	6.02961676	15.02961676	9	23
4	04/01/2003	0.97038324	6.02961676		23	
5	05/01/2003	0.97038324	6.02961676		23	
6	06/01/2003	0.97038324	6.02961676	15.02961676	9	23
7	07/01/2003	0.97038324	6.02961676	15.02961676	9	23
8	08/01/2003	0.97038324	6.02961676	15.02961676	9	23
9	09/01/2003	0.97038324	6.02961676	15.02961676	9	23
10	10/01/2003	0.97038324	6.02961676	15.02961676	9	23
11	11/01/2003	0.97038324	6.02961676		23	
12	12/01/2003	0.97038324	6.02961676		23	
13	13/01/2003	0.97038324	6.02961676	15.02961676	9	23
14	14/01/2003	0.97038324	6.02961676	15.02961676	9	23
15	15/01/2003	0.97038324	6.02961676	15.02961676	9	23
16	16/01/2003	0.97038324	6.02961676	15.02961676	9	23
17	17/01/2003	0.97038324	6.02961676	15.02961676	9	23
18	18/01/2003	0.97038324	6.02961676		23	
19	19/01/2003	0.97038324	6.02961676		23	
20	20/01/2003	0.97038324	6.02961676	15.02961676	9	23
21	21/01/2003	0.97038324	6.02961676	15.02961676	9	23
22	22/01/2003	0.97038324	6.02961676	15.02961676	9	23
23	23/01/2003	0.97038324	6.02961676	15.02961676	9	23
24	24/01/2003	0.97038324	6.02961676	15.02961676	9	23
25	25/01/2003	0.97038324	6.02961676		23	
26	26/01/2003	0.97038324	6.02961676		23	
27	27/01/2003	0.97038324	6.02961676	15.02961676	9	23
28	28/01/2003	0.97038324	6.02961676	15.02961676	9	23
29	29/01/2003	0.97038324	6.02961676	15.02961676	9	23
30	30/01/2003	0.97038324	6.02961676	15.02961676	9	23
31	31/01/2003	0.97038324	6.02961676	15.02961676	9	23

Figure E.3 - IDEAS implementation in Excel 2007, Optimum Start Tab

Tab 4: Data Values

- The data values tab is the point where the BREDEM and IDEAS calculation methodologies meet
- As can seen from the figure below, the main area which links BREDEM and IDEAS is the 'Definition of Figures and Variables' section. This area defines variables such as Ur (U-Value of roof) which are directly fed from BREDEM to ensure that both methodologies use the same values
  - The definition of all dynamic model fields is detail in Appendix D

263

- The Monthly Energy Consumption section numerically compares the monthly energy consumption from the dynamic model and from BREDEM
  - Excel conditional formatting is used to highlight high and low values. The example shown below is of a highly insulated home (structure U-Value of 0.3) and as such it can be seen that there is a zero energy requirement in IDEAS in the months of June -> September. Curiously, over this period, there are months where BREDEM has a very low energy requirement but zero is never achieved
  - Over the course of the heating season (October -> May), the figures calculated between IDEAS and BREDEM are within 2% of each other
  - Monthly Energy Consumption comparison is also made graphically which highlights the close fit in energy between IDEAS and BREDEM
- The Zone Air Averages are also compared numerically and graphically
  - In the example shown below it can be seen that over the course of the heating season (October -> May), there is a good match for temperature of 2% between IDEAS and BREDEM
  - The Zone air averages highlight that IDEAS predicts that the internal temperature is approximately 1° lower over the coldest months (November to February)
    - This could be attributed to the temperature of the zone air decreasing too rapidly due to the relative coldness of the structure
  - The Zone air averages are significantly higher in IDEAS as opposed to BREDEM, with BREDEM values reaching a plateau of 21°. In the author's opinion, this is unrealistic and the values produced by IDEAS are more representative of what temperatures would occur on a highly insulated dwelling such as the one in question here.
    - One way to match the BREDEM and IDEAS values for temperature over the summer months would be the implementation of a window opening algorithm (Rijal et al., 2008), although this would have to be aligned with detailed monitoring and validation for dwellings to ensure

an accurate representation.

- The definition of constants section defines all constants as detailed in equation 16
  - The constants are calculated from variables taken from BREDEM, highlighted in the 'Definition of Figures and Variables' section and Appendix D
  - The constant values are then utilised by the calculations in the Results tab.

Definition of Figures and Variables

		Units	Description
Mv	0.040156217	kg/s	Mass of the Dwelling Air
Ca	1012	J/(kg.K)	Specific Heat Capacity of A
Us	0.3	(W/m²K)	Heat Transfer Co-Efficient
As	85.6	(m²)	Surface Area of Structure
Ur	0.13	(W/m²K)	Heat Transfer Co-Efficient
Ar	44.4	(m²)	Area of Roof
Uw	1.5	(W/m²K)	Heat Transfer Co-Efficient
Aw	16.9	(m²)	Area of the Windows
Ma	186.66	kg	Mass of the ai
Pa	1.22	kg/m3	Density of Air $\rho = \dfrac{m}{V}$
Va	153	m3	Volume of Air
Ms	13696	kg	Mass of Structure
Cs	800	J/(kg.K)	Specific Heat Capacity of S
Uf	0.2	(W/m²K)	Heat Transfer Co-Efficient
Af	44.4	(m²)	Area of the Floor
Pb	800	kg/m3	Brick density
Mft	27600	kg	Mass of the Furniture
Pft	400	kg/m3	Density of Furniture
Vft	69	m3	Volume of Furniture
Cft	900	J/(kg.K)	Specific Heat Capacity of F
Uft	2.57401	(W/m²K)	Heat Transfer Co-Efficient
Aft	138	m2	Area of Internal Mass in a I
Tfur	0.5	m	Thickness of Furniture

Monthly Energy Consumption

	DYNAMIC	BREDEM
January	973.6535	859.34
February	777.9172	668.32
March	486.289	485.28
April	198.3528	261.09
May	29.6897	66.08
June	0	11.71
July	0	1.04
August	0	2.06
September	0	42.00
October	183.7217	236.04
November	646.4162	591.12
December	785.7873	773.38
TOTAL:	● 4081.8	○ 3997.47

Zone Air Averages

	DYNAMIC	BREDEM	DIFF.	
January	291.75	18.75	20.13	-1.38
February	292.29	19.29	20.25	-0.96
March	292.92	19.92	20.51	-0.59
April	293.60	20.60	20.73	-0.13
May	295.46	22.46	20.94	1.53
June	298.21	25.21	20.99	4.22
July	299.90	26.90	21.00	5.90
August	299.45	26.45	21.00	5.45
September	296.31	23.31	20.96	2.35
October	293.72	20.72	20.76	-0.05
November	292.70	19.70	20.38	-0.68
December	292.15	19.15	20.21	-1.06

Definition of constants

		Weather - Average	
a11	-0.002579215	January	3.0
a12	0.00027189	February	3.5
b11	5.29381E-06	March	5.9
d11	5.29381E-06	April	7.8
d12	0.000426893	May	11.1
a21	4.6875E-06	June	13.7
a22	-0.000009375	July	16.1
d22	4.6875E-06	August	15.9
a31	1.43001E-05	September	13.4
a33	-1.43001E-05	October	10.5
a13	0.001880432	November	6.2
		December	4.4

	DYNAMIC	BREDEM
Total Gains	1003.88	1003.88
MIT	21.89	20.65
MET	9.32	9.28

	MIT over	DYNAM	BREDEM
MIT		20.073	20.48849
TOTALS		160.58	163.91	113.1

Percentage Comparison

Energy	102.1%
Temperature ove	102.07%

Monthly Energy Consumption — DYNAMIC / BREDEM

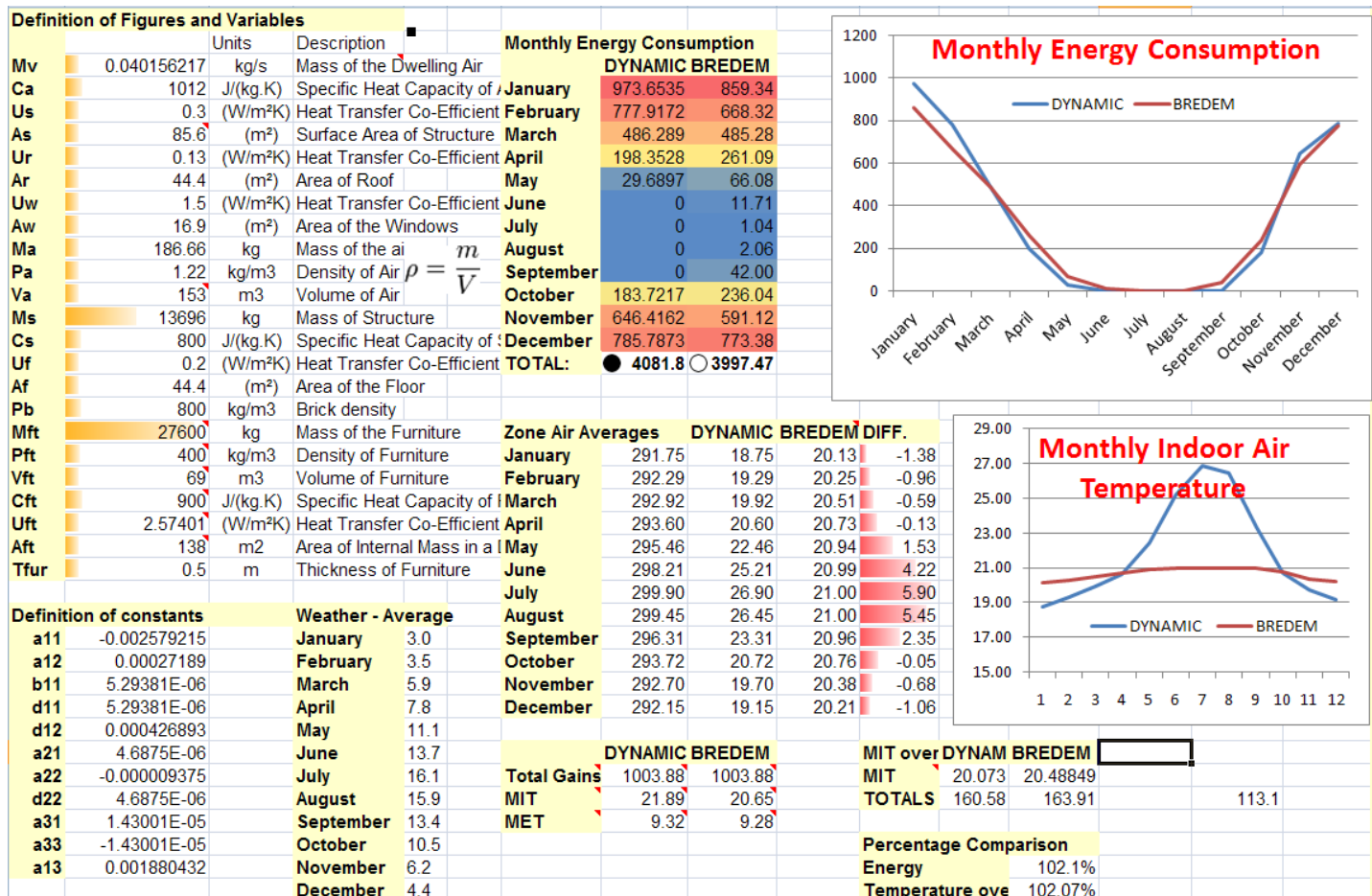Monthly Indoor Air Temperature — DYNAMIC / BREDEM

Figure E.4 - IDEAS implementation in Excel 2007, Data Values Tab

The BREDEM 2009 Excel spreadsheet was amalgamated with the 3rd Order IDEAS Model to allow for inputs to be shared and for a comparison to be made.

BREDEM 2009 Tab 1: Front

- This tab provides an energy consumption breakdown as calculated by BREDEM
- Figures for Mean Internal Temperature (21° in this example) and Mean

External Temperature (9° in this example) are provided here also

Dwelling	Delivered energy consumption (kWh/yr)								MIT	MET	TOTAL INTERNAL GAINS
	Space	Sec	Water	Lighting	Pumps and fans	Appliances	Cooking	Cooling			
Semi-detached	4383	0	2724	378	258	2707	732	51	21	9	1004

Heating season length assumption:
12 months

Figure E.5 - IDEAS implementation in Excel 2007, Front tab

BREDEM 2009 Tab 2: Semi-Detached

- This is the entire BREDEM 2009 methodology which SAP is based upon, on one Excel spreadsheet tab; the tab is split into three sections:
- Inputs
- As shown in the figure below, all inputs required for the BREDEM 2009 are input in this section
- The inputs have been modified so that they are appropriate for a single zone
- This section highlights how comparatively few inputs are required for the BREDEM 2009 Calculation, especially in comparison to dynamic tools such as IES and ESP-r
- IDEAS relies upon the inputs made in this section
    - This allows for a comparison between Steady State BREDEM and Dynamic IDEAS results such as energy consumption
    - This highlights that IDEAS can achieve a dynamic model with significantly less inputs than most dynamic tools
    - The most important inputs from a energy simulation perspective are found to be areas and U-values
- Calculation
- This section details the calculation processes behind the BREDEM / SAP Methodology
- The BREDEM 2009 calculation procedure which IDEAS is based upon and is compared against is a monthly calculation
    - The IDEAS 3rd Order Model has a 5 minute resolution
- The main results from BREDEM 2009 which are compared against IDEAS are
    - Mean Internal Temperature
    - Useful energy from primary heating source (kWh)

266

- Cooling Requirements are calculated in BREDEM 2009 for the months of June, July and August
  - Cooling a new to BREDEM 2009 and SAP 2009, as such it is not part of the IDEAS methodology at the moment
- Tables
- Monthly values are provided for the following
  - Mean daily solar irradiation on a horizontal plane (W/m²), by region for 1993-2007
  - Mean temperature at sea level by month and region for 1987 - 2009
  - There are 21 regions defined by BREDEM 2009
    - The only region used by SAP is the region of East Pennines which is very roughly the population centre for the UK as a whole
    - For comparison with IDEAS, the East Pennines weather region was selected and updated to match the monthly averages from the weather location inputted into IDEAS at a 5 minute resolution from the Meteonorm software.

Inputs

General inputs	Z1			
TFA (m²)	88.8		222	
Vol (m³)	222			
Number of occupants	0	(blank or zero for estimate based on floor area)		
Degree day region	11			
Height above sea level (m)	0			

Heat loss inputs	Z1 area (m²)		Total area	U-value				
Walls (excl. openings)	40.9		81.8	0.3	24.54			0.068407
Floor	44.4		44.4	0.2	8.88			
Roof	0		44.4	0.13	5.772			
Doors	3.8		3.8	0.22	0.836			
Other external element	0		0	0	0			
Party wall	18		36	0	0	Curtains?	LTF	LAF
Windows	8.45		16.9	1.5	25.35	Yes	0.8	0.83
Rooflights	0		0	0	0			
		71.15						
Thermal bridge factor	0.05	W/m²K						

Solar gain inputs	Z1 area		Total area	Orientation	Tans fac	Frame fac	Shading	Norm.
Window - type 1	8.45		16.9	E/W	0.72	0.7	0.77	0.9
Window - type 2								
Window - type 3								
Window - type 4								
Window - type 5								
Window - type 6								
Rooflights								

Thermal mass inputs	Area (m²)	κ-value
Basement floor		
Ground floor	44.4	110
Exposed floor		
Basement wall		
External wall	81.8	190
Roof	44.4	9
Party wall	36	180
Party floor		70
Party ceiling		
Internal wall	76.3	100
Internal ceiling	44.4	27

Figure E.6 - IDEAS implementation in Excel 2007, Semi Detached Tab

Appendix F: Engineering Principles Relating to Control Theory

This appendix provides a summary of the fundamental engineering principles relating to control theory which were researched in the development of IDEAS. Each area detailed in this appendix was important in the development of IDEAS. Of particular relevance to the development of IDEAS are:

- Figure 3 which details a Block Diagram of a Feedback System with an Error Actuated Controller

- The importance of stability in a system highlighted in the block diagram in Figure 5

- Figure 8 which details in block diagram form the effect of disturbances in IDEAS (such as dynamic free heat gains, changing external temperature and internal appliance heat gains)

ODES – Ordinary Differential Equations

- ODEs are linear in nature; ODEs important:

- The way things move all derive from Newton's principles. The fundamental core principles of the way mechanics and physical relations work with machines (or anything that moves) is all underpinned by one first or second order ODE

- When writing ODEs, signify what variables are a function of time by expressing these variables by (t)

Mechanics Domain

- $F = ma$ (1)

- Newton's Second Law of Motion

- Where the Mass is constant according to Newton but not constant according to Einstein

- $F = m\dfrac{dv(t)}{dt}$ (2)

- M is constant

- Force = Mass * Rate of Change of Velocity

- $F = ma$ (A first order ODE)   (3)

- $F = m\dfrac{d^2 x(t)}{dt^2}$ (A second order ODE)   (4)

Zeroth Order ODEs

- Richard Phelan – Introduced the idea of controlling a Zeroth Order system. The control of zeroth-order controlled systems (Phelan, 1977)

- $Fs(t) = KsX(t)$ (5)

- The force in a spring is equal to the stiffness of a spring multiplied by its displacement x.

- To design a control system to control the displacement of spring by applying a force to it, then the dynamics of the system would be zeroth-order.

- $F_0(t) = C\dfrac{dx(t)}{dt}$ (6)

- $F_0(t) = CV(t)$ (7)

- The Force is a damper = the coefficient C multiplied by the velocity

- N.B. A Capacitor behaves like a spring, not a Damper!

  - A Capacitor stores energy, the same as a spring.

Electrical Domain

- Zeroth Order ODEs : Ohms Law

- $V(t) = Ri(t)$ (8)

  - When written as a zeroth-order ODE

  - The Voltage across a resistor is the resistance multiplied by the current flowing through it

  - N.B. Analogy: Volts is Force, Current is Velocity

  - Therefore C is mechanical is actually R in Electrical

    - The physical electrical and mechanical ODEs can be generalised in a theory called Bond Graph Theory; focus on

differential equation not Bond Graph Theory!

$$o \quad C\frac{dV(t)}{dt} = i \qquad (9)$$

o   Where C = Capacitance

o   capacitance = current

o   This is a first order ODE which describes the way that voltage and current are related across the capacitor

o   A first order ODE

$$o \quad L\frac{di}{dt} = V(t) \qquad (10)$$

o   This is an inductor, coil of copper, what is the voltage across it

o   This is another first order ODE

- Everything is built on ODEs – these are the fundamental foundations

- Conclusion

  o   There are first and second ODEs and there are Zeroth Order ODEs

  o   The whole of the physical world that we live in and try to understand is built on these physical principles.

    - That is why a control theory based on ODEs was developed, and why an appreciation of IDEAS is necessary for IDEAS

Laplace Operator

- A common Mechanics ODE :

$$\bullet \quad m\frac{d^2x(t)}{dt^2} + C\frac{dx(t)}{dt} + Kx(t) = F \qquad (11)$$

- Represents a mechanical system known as a car suspension system

  o   There is a mass which is suspended on the shock absorber and a spring. We apply a force to the mass and equation (11) describes the relationship between the displacement of the mass and the force that we apply

- o We now have the give equation (11) an initial displacement and an initial velocity to solve it; then the Laplace equations could be used to obtain the total solution.

- Laplace Operator is the letter s to a control engineer

  - o Domain mapping

  - o Map the time domain into the Laplace domain

  - o If we assume that initial conditions in equation (11) are equal to zero

    - ▪ $x(t) = 0$ (12)

    - ▪ $\dfrac{dx(t)}{dt} = 0$ (13)

    - ▪ In Control Theory terms, we say, starting from a steady condition with zero value initial conditions

      - The initial velocity is zero so everything is steady

      - N.B. Initial Conditions are very important, if there is a bias in the system this is probably related to the initial conditions

  - o Control Engineers are happy to assume that $\dfrac{d}{dt}$ can be mapped into s and $\dfrac{d^2}{dt^2}$ can be mapped into s^2

  - o D Operator in control engineering: the D operator is a special case of the Laplace operator which assumes you have started from a steady state equation and have zero value initial conditions

    - ▪ In this particular case the d operator and the s operator are exactly the same

  - o We can write down equation (x) into Laplace:

    - ▪ $ms^2 x(t) + Csx(s) + Kx(s) = F(s)$ (14)

    - ▪ t is now s in Laplace

    - ▪ The Time Domain has been mapped into the Laplace Domain

Transfer Functions

- Invented by the Germans during World War 2
  - V1 (capable of speeds of 440mph)+ V2 Bomb
  - V1 is the First Guided Missile
  - Designed using Transfer Functions

- $ms^2 + Cs + Kx(s) = F(s)$ (15)
- such that $\dfrac{x(s)}{F(s)} = \dfrac{1}{ms^2 + Cs + K}$ (16)
  - Equation (16) is known as the Transfer Function
  - This is only a function of the constants in the system and the Laplace

Block Diagrams

$$\frac{x(s)}{F(s)} = G(s) = \frac{1}{ms^2 + Cs + K} \tag{17}$$

- We can express the above in a Block Diagram:
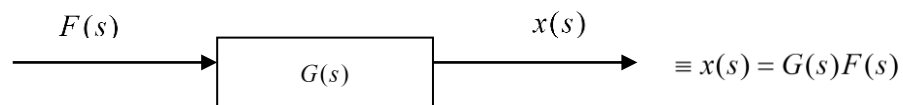
Figure 2 – Simple Block Diagram

- A feedback system with an error actuated controller
  - Some sort of input, the setpoint
  - N.B. Block Diagrams are always in the Laplace Domain

Block Diagram of a Feedback System with an Error Actuated Controller:
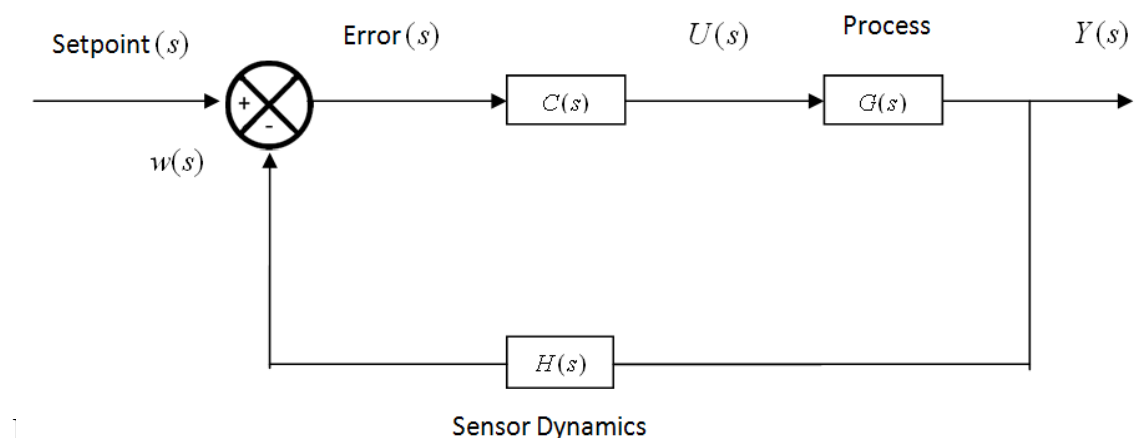
Figure 3 - Block Diagram of a Feedback System

Where:

Setpoint = Input Reference, the Setpoint

$\otimes$ = Comparator, one thing minus another

$w(s)$ = Feedback signal; Feedback Signal is what you measure and what you control (You can only control the feedback in a feedback system, everything else is uncontrollable)

Error = Error Signal, Difference between what was asks and what was delivered; the difference between the setpoint and what you feed back is called the Error Signal

$C(s)$ = The Controller, which has a transfer function

$U(s)$ = Actuator Signal, In this example, $U(s) = F(s)$, the force

$G(s)$ = The Process which takes the Actuator Signal as an input. The Process takes the signal, creates some change and then outputs what is measured. In this example, the process is the car suspension system

$Y(s)$ = The Output.

$H(s)$ = Feedback Transfer Function from the Output to the Feedback. In an engineering context, this tends to be known as sensor dynamics

- Block Diagrams provide a mental image of what inputs, processes, outputs there are in a particular system.
- Common Transfer Function we want to know:
    o Closed Loop Transfer Function

$$\frac{Y(s)}{\text{setpoint}(s)} = G_C(s) \tag{18}$$

$$\frac{w(s)}{\text{setpoint}(s)} = G_F(s) \tag{19}$$

$$G_C(s) = \frac{C(s)G(s)}{1 + C(s)G(s)H(s)} \tag{20}$$

$$G_F(s) = \frac{C(s)G(s)H(s)}{1 + C(s)G(s)H(s)} \tag{21}$$

- o Where the rule=
  - o $rule = \dfrac{ForwardPath}{1 + ForwardPath}$

Open and closed-loop poles and zeros

$$\frac{w(s)}{\text{set}(s)} G_F(s) = \frac{C(s)G(s)H(s)}{1 + C(s)G(s)H(s)} \tag{22}$$

- o Describe the basic transfer functions of each block as a numerator and a denominator:

$$C(s) = \frac{C_Z(s)}{C_P(s)} \tag{23}$$

$$H(s) = \frac{1}{S_P(s)} \tag{24}$$

$$G(s) = \frac{z(s)}{p(s)} \tag{25}$$

- o In a block transfer function, the roots of the numerator polynomial (the values of s that make it zero) are called zeros
- o For the process, we have a numerator / the denominator:

$$G(s) = \frac{z(s)}{p(s)} \tag{26}$$

- o The roots of the numerator such that z(s) =0 are known are zeros (strictly called transmission zeros)
  - o Control Theorists will refer to the zeros in the left or right hand plane
    - ▪ They are referring to the roots (which are complex numbers) of the polynomial are in an Eigen diagram in the right (positive real parts) or left hand (negative real parts) plane

Why are they called Zeros?

- o They are called zeros because they are the values of s which cause the output to be zero:

$$G(s) = \frac{0}{p(s)} = 0 \qquad (27)$$

- o They are strictly called Transmission Zeros = the value of s which results in a Zero Transmission for output

Poles

- o The roots of P(s), when P(s)=0, are known as the Poles

General Quadratic Formula:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad (28)$$

Therefore:

$$Poles = \frac{-c \pm \sqrt{c^2 - 4mK}}{2m} \qquad (29)$$

- o We have a quadratic in s
- o Control Theorists are interested by Poles
  - o Optimum Pole Placement very important
  - o Design system so roots give a certain transient response

$$C(s) = \frac{C_Z(s)}{C_P(s)} \qquad (30)$$

$$H(s) = \frac{1}{S_P(s)} \qquad (31)$$

$$G(s) = \frac{z(s)}{p(s)} \qquad (32)$$

- o The roots are the Poles of the sensors
- o The roots of z(s) and p(s) are generically termed as the
  - o The Open Loop Zeros
  - o The Open Loop Poles
    - ▪ These are the natural zeros and poles of the process, as if it was an Open Loop system with no feedback control

Relative degree

o You cannot drive a number to infinity in reality

o Finite Closed Loop Poles

    o In finite positions, determined by the roots of Z(s)

o Asymptotes

    o Mathematically Unobservable

$$G(s) = \frac{1}{ms^2 + Cs(s) + K(s)} \hspace{3cm} (43)$$

o If we take a Transfer Function:

$$G(s) = \frac{s + a}{s^2} \hspace{3cm} (44)$$

o If used with an infinite gain process, we would have one Closed Loop Pole at -1

    o Where is the other Pole?

        ▪ That is called an Asymptote (infinite poles)

o Relative Degree

    o Tell you how many finite Closed Loop Poles you have under high gain and how many Asymptotes (infinite poles) there are

    o RD=m-n

        ▪ Where:

            • n is the order Z(s)

            • m is the order p(s)

        ▪ In this case, RD-m-n=2-1=1

        ▪ Therefore, we have an Open Loop System with a Relative Degree of 1

            • We know that there must be at least one finite zero

            • The number of finite zeros is m-n

    o RD is the order difference between the bottom and the top

        ▪ This is very important in control engineering

        ▪ Anything with a relative degree higher than 1 has a known CD matrix

Stability

Characteristic equation and stability

• A core interest in the development of IDEAS is the Closed Loop Stability

    o Closed Loop Transfer Function:

$$G(s) = \frac{z(s)}{p(s)} \qquad (45)$$

- Take an example:

$$P_c(s) = ms^2 + Cs + K + Ks$$
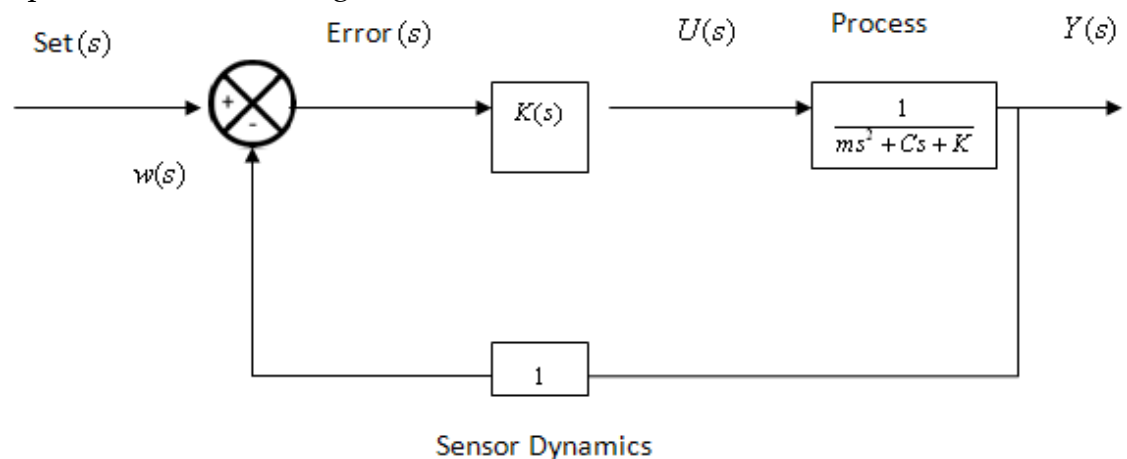
- Equivalent in Block Diagram Form:

Figure 5 - Block Diagram – Stability

$$Zc(s) = Kp \qquad (46)$$

- Stability
  - The Roots of Pc(s) determine Stability. These roots relate to the homogenous solution of the Closed Loop ODE. So if you were to write down the Close Loop ODE in the Time Domain and you trying to find out what the homogenous part of the solution then:
  - $W(t) = A_e xt + B_e xt + P_P$ $\qquad (47)$

    Where:
    - $A_e xt + B_e xt$ = Homogenous Part $\qquad (48)$
    - P_P = Particular Part $\qquad (49)$
    - We are interested in the Homogeneous Part
  - Solutions:
    - There are as many Lambdas as there are in the order of Pc(s), so in this case we have a second order closed loop transfer function, hence:
      - $\lambda_1 = s_1$ $\qquad (50)$

$$\bullet \quad \lambda_2 = s_2 \qquad\qquad (51)$$

Stability - Eigen Values:

- Lambda Values and roots of Pc(s) are known as Eigenvalues
  - Where Eigen in the German work for own
    - Which we plot in an Eigen Diagram
      - Which is a complex number
        - The roots of any equation, second order or higher, could have complex parts
      - The only system which does not have the potential for having a complex number as a route is a First Order System
- We know that the roots, S1 and S2 are given by:
  - $s_{12} = \sigma + jw$ \qquad\qquad (52)
  - Mathematicians use the letter i for imaginary, but i is current in Electrical Engineering so Electrical Engineers introduced the letter j to be used for imaginary, this is now also used by Mechanical Engineers
    - Here j is the imaginary number of $\sqrt{-1}$

- Eigen Diagram:
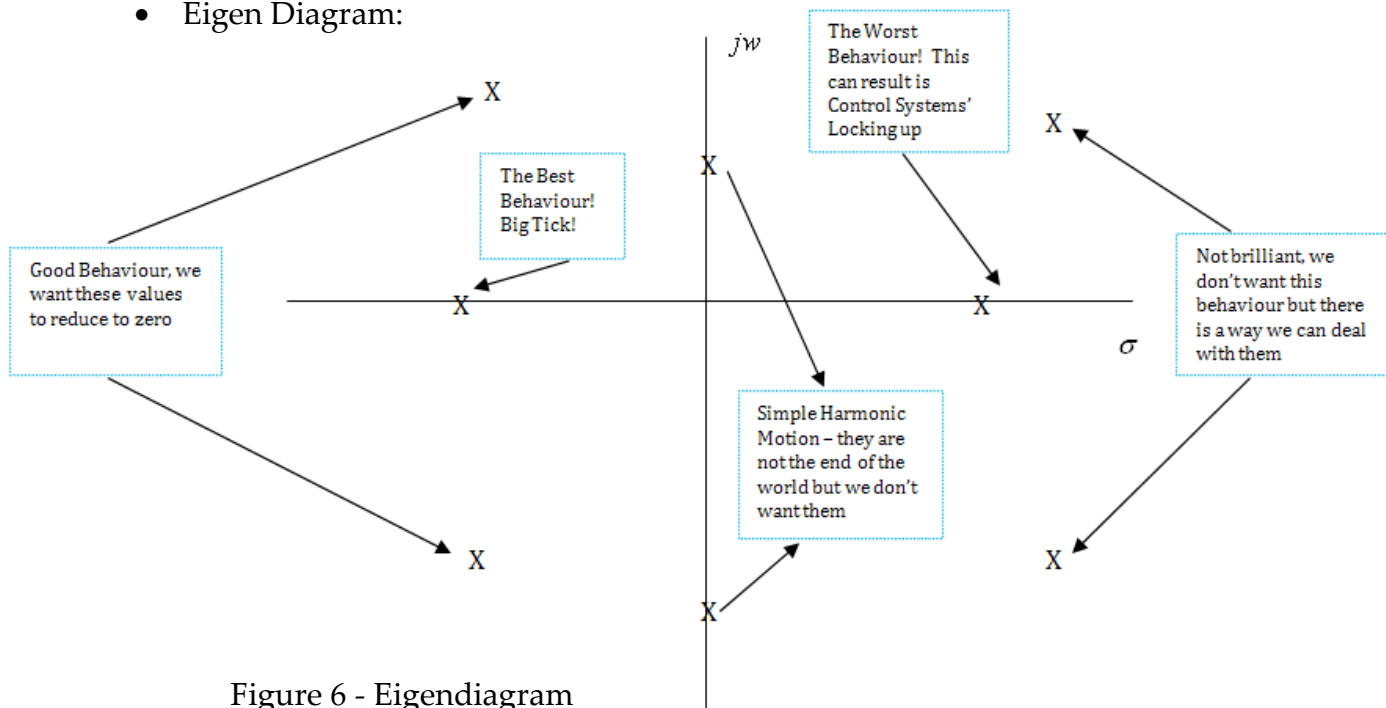
Figure 6 - Eigendiagram

- Associated with each Eigenvalue there is a transient response
  - N.B. Eigenvalue and Eigendiagrams are related to the time domain
  - Eigenvalue relates to the output

278

- Big tick if $\sigma < 0$
  - Therefore Stability = LHP (Left Half Plane)
- Instability of a Linear Ordinary Differential Equation is not the end of the world
  - All real control systems that exist in the world and been designed well have found their way into the RHP (Right Hand Plane) at some point in their behaviour and the control system has been fine
    - The real world is not are cruel as the mathematical world
- Summary
  - The closed loop poles in the LHP are good news
  - The closed loop poles in the RHP are bad news
  - Eigen values are in the time domain, but we used the Laplace domain to get the polynomial of the closed loop equation and then the values of s of the roots of that polynomial are the Eigen values that allow us to go back to the time domain
  - A badly designed control system starts stable, moves into simple harmonic motion and then becomes unstable

Tracking

- Very Important
- Tracking is everything in Control Engineering and to IDEAS
- E.g., the need to control the temperature to a specified degrees
- In IDEAS, the SAP defined Setpoint is tracked by default
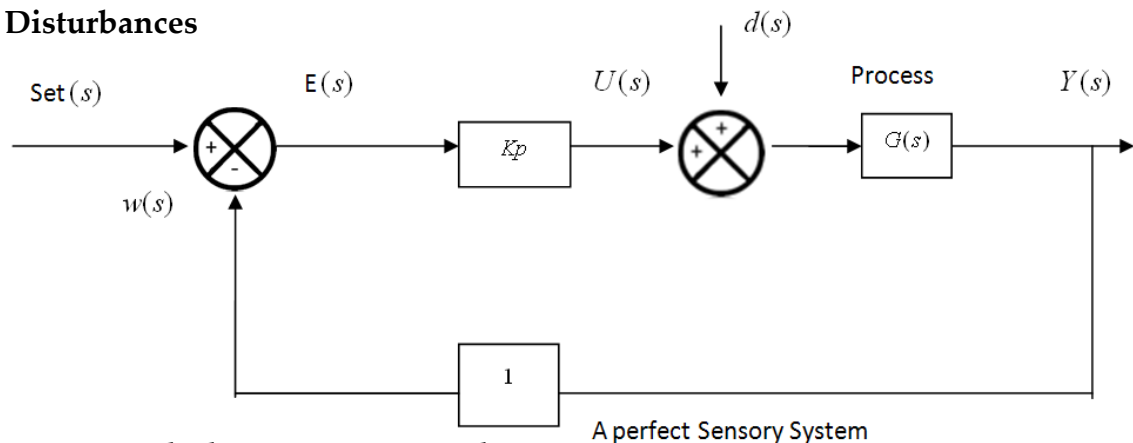
Disturbances

Figure 8 - Block Diagram – Disturbances

= a summing junction to add to two things

$d(s)$ = Disturbances, the Dark Side of Control Theory

- We are back in the Laplace Domain, as we have Block Diagrams
- More Disturbances
  - It is the objective of a Control Engineer to design a system which does not care what the disturbances are, they must be identified and removed in the Control System
    - Examples:
      - Free heats
      - Metabolic Gains
      - Appliance Gains
      - Solar Gains
  - A control engineers mentality is to design a control system which doesn't care what the Disturbances are
    - The disturbances will just be dealt with
  - N.B. Possible Conflict with Dynamic Simulation
- Energy Systems are easy to understand using this method
  - Example of Radiator with TRV and Thermal Response of Room
- The Transfer Function is a function of the room
  - We need to know what the transfer function is but not what the disturbances are

Input Transfer function

- Closed Loop Transfer Function:

$$G_F(s) = \frac{K_p G(s)}{1 + K_p G(s)} \qquad (58)$$

- Equation 58 above is the closed loop equation for the Block Diagram in Figure 8 above.
- There is another equation of importance:

$$G_D(s) = \frac{w(s)}{d(s)} = \frac{G(s)}{1 + KpG(s)} \qquad (59)$$

  - Equation (59) is a very important Transfer Function
    - E.g. what effect does having a party in your house (increase the disturbances) have upon the temperature measured by a TRV?
- If $K \rightarrow \infty$ the gain of $G_D(s)$ would be zero
  - Therefore, the transmission of any disturbance onto the room temperature is zero
    - Therefore if we can move the gain of the control system high then we don't care what the disturbances are
      - The only reason that there is for this to be modelled is to understand the energy consumption

- The point is that for Controllability they do not need to be modelled
- A model for Control Theory will not normally have anything to do with a model which is designed for Energy Consumption
- Therefore:
    - High Gain Control Reduces the Sensitivity of the Control System Performances to the Disturbances
        - But High Gain Control is not easy to achieve
    - Challenge is to get a system which is robust and safe but to also ignore Disturbances: therefore RIDE is used in IDEAS

Appendix G: Glazing and Structure Thermal Bridging using THERM

Introduction

To highlight the capability, detail and complexity of tools used to model buildings and their component parts, an overview of THERM is presented in this appendix. THERM is popular with users of PHPP to demonstrate the thermal bridging effects of different constructions. Although designed for glazing, THERM can be used to calculate the thermal bridging of composite structure elements also. The purpose of this appendix is to demonstrate a walk-through of the main functionality modules of the THERM tool to demonstrate its use in calculating the thermal bridging of glazing or structure components.

What is THERM

THERM is Two-Dimensional Building Heat-Transfer Modeling Software, created by Berkeley Lab, www.lbl.gov. THERM is available for free download from: http://windows.lbl.gov/software/therm/therm.html

Defining a workspace in THERM

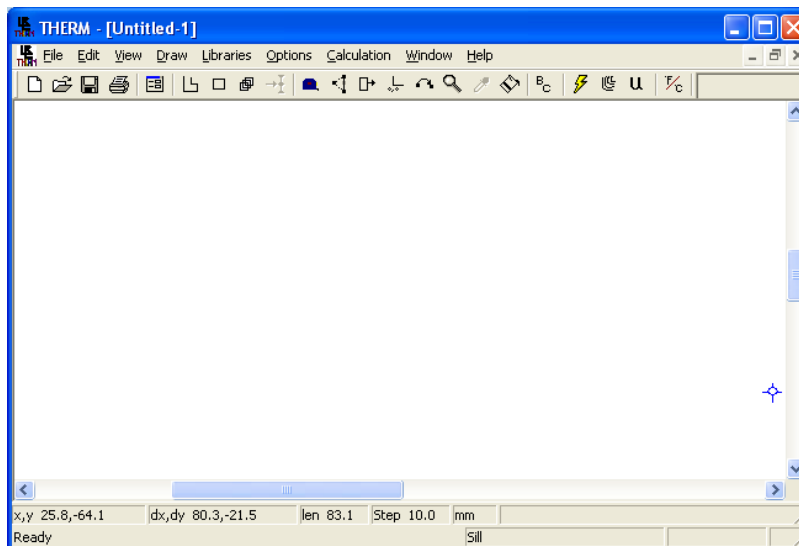On opening THERM, the following default workspace is presented.

Figure 1 – THERM Main Workspace

Snap Settings

Snap Settings can be modified from accessing the following menu:

Options->Preferences->Snap Settings

It is recommended that the snap settings shown in Figure 2 are set.

THERM File Options

THERM File Options can be modified from accessing the following menu:

Options->Preferences->THERM File Options

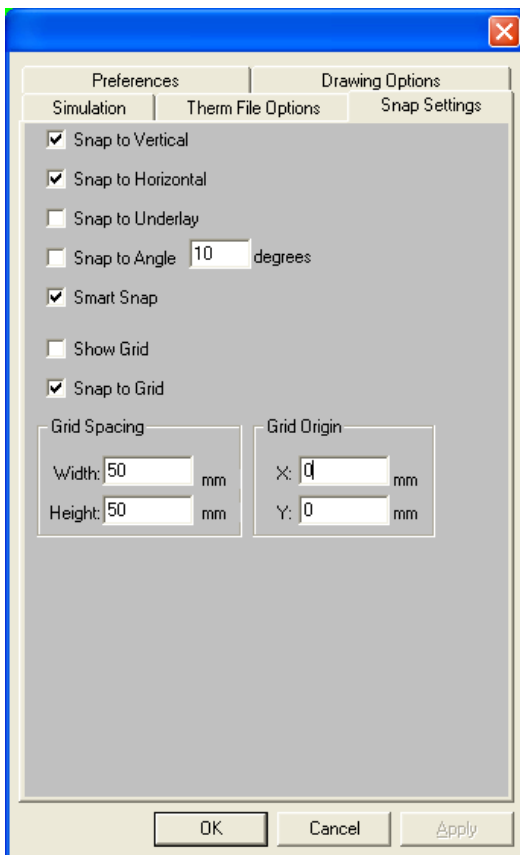Recommended THERM File Options are shown in Figure 3.
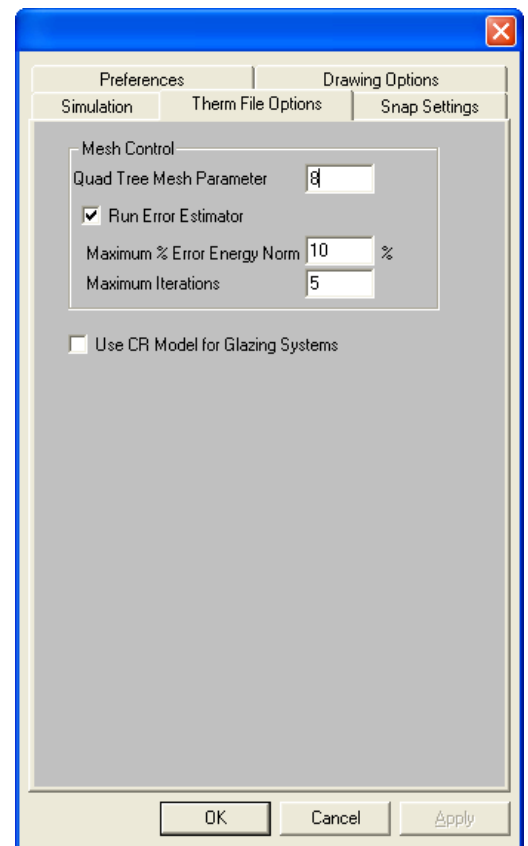
Figure 2 –THERM Snap Settings

Figure 3 – THERM file options

Select Imperial or Metric Units

Options -> change units (switch between Metric and Imperial)

Custom Zoom Level and Zoom operations

Custom Zoom Level can be entered by clicking the magnifying glass on the Main Workspace area – see figure 1 – and entering the required zoom level.

Alternatively:

- Right click on the workspace area to zoom in

- Hold Shift and Right click to zoom out

- Hold Control and Right Click to Fit your model to the screen so that all sections are visible

Steps to adding a new model in THERM

Step Size Addition:

->Click – Draw a Rectangle->Left Mouse Click on Workspace->Enter Length in mm->Press Right Arrow->Enter Height in mm->Press Up Arrow

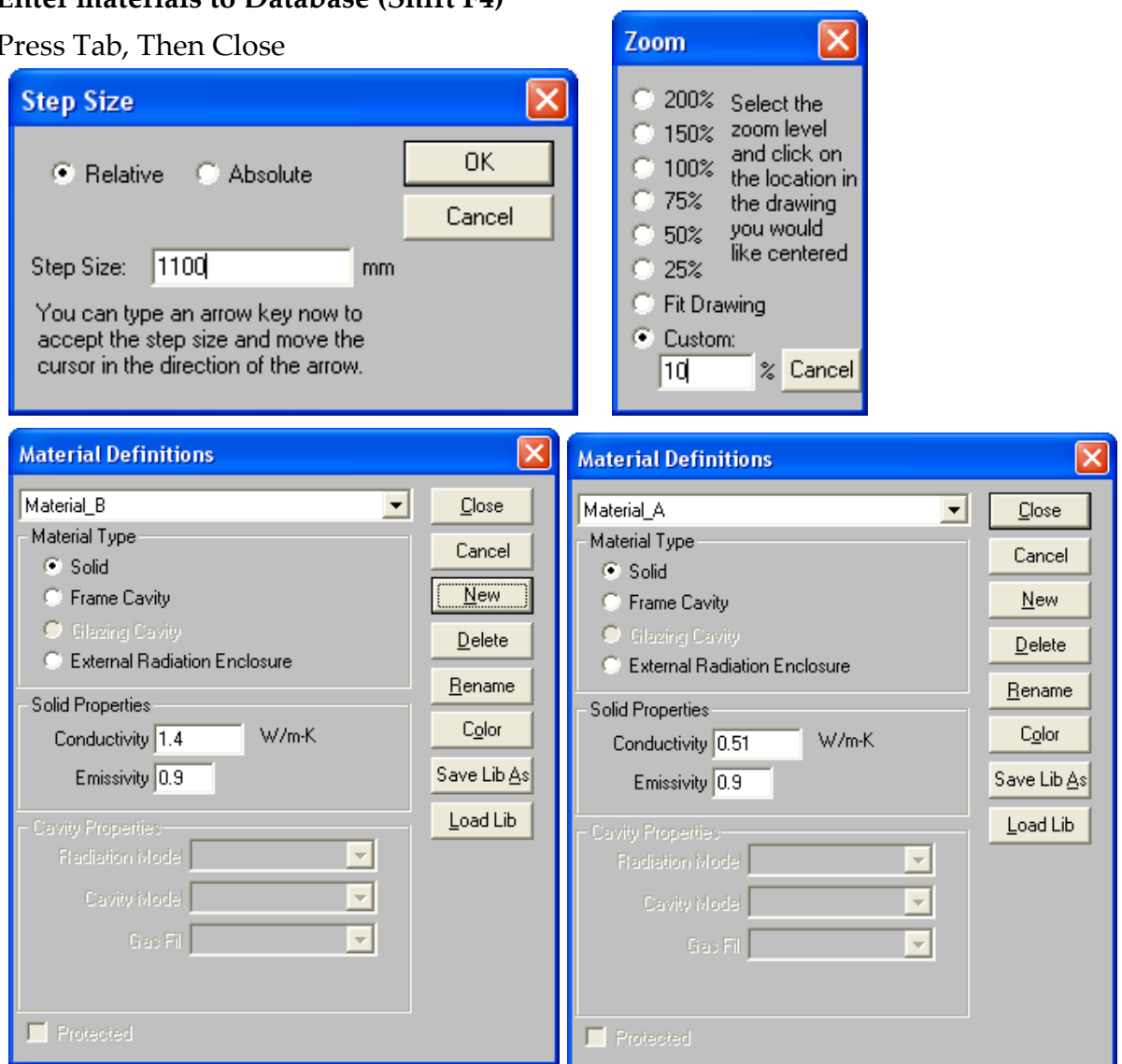**Enter materials to Database (Shift F4)**

Press Tab, Then Close

Figure 4 – steps to add a new model to THERM

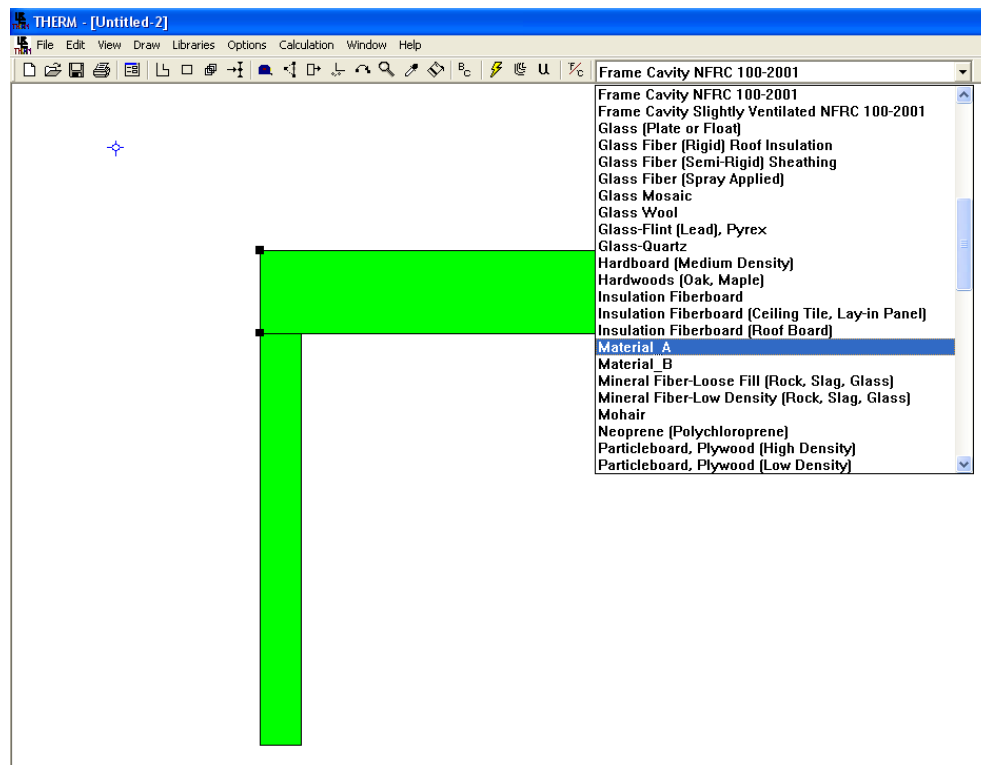**Assign Structure a Material:**

Figure 5 – select Material
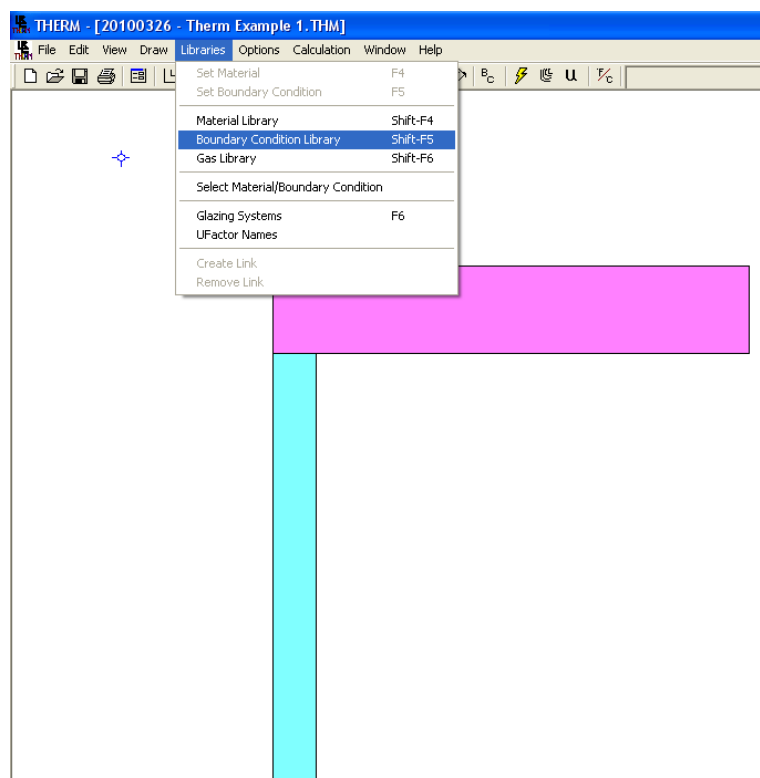
Set Boundary Conditions:

Figure 6 – Select Boundary Conditions Library
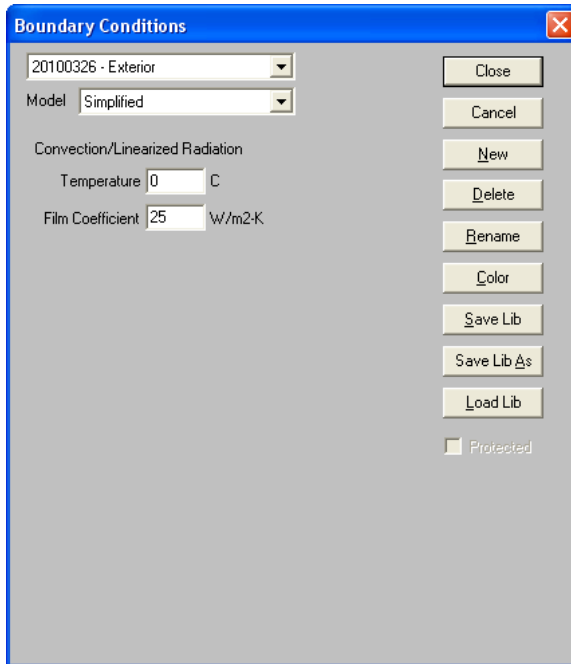
Add New Boundary Condition:

Figure 7 – Boundary Conditions

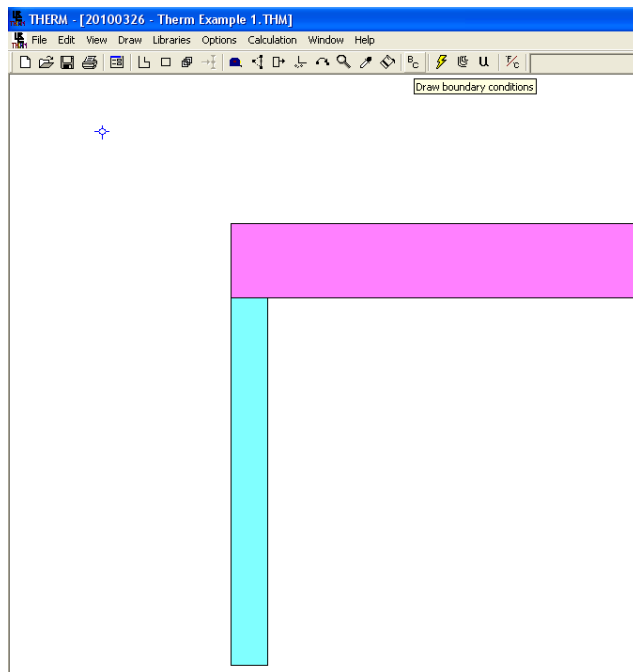Now Click B-C – (Draw Boundary Conditions):

Figure 8 – Draw Boundary Conditions

Hold Control and Click on all exterior Sections: Now Select Exterior Material for all:
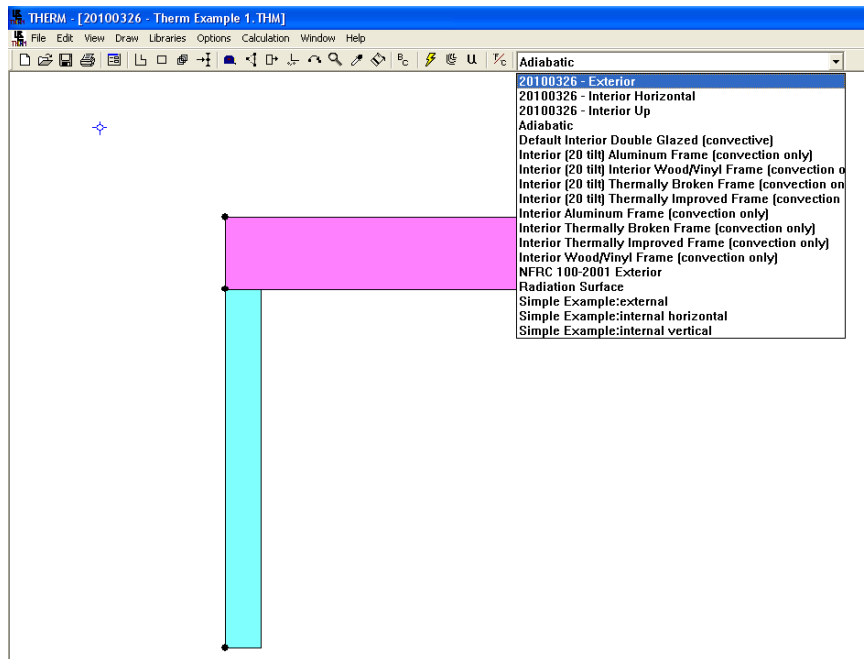
Figure 9 – Select Boundary Conditions

Select Boundary Condition Type:

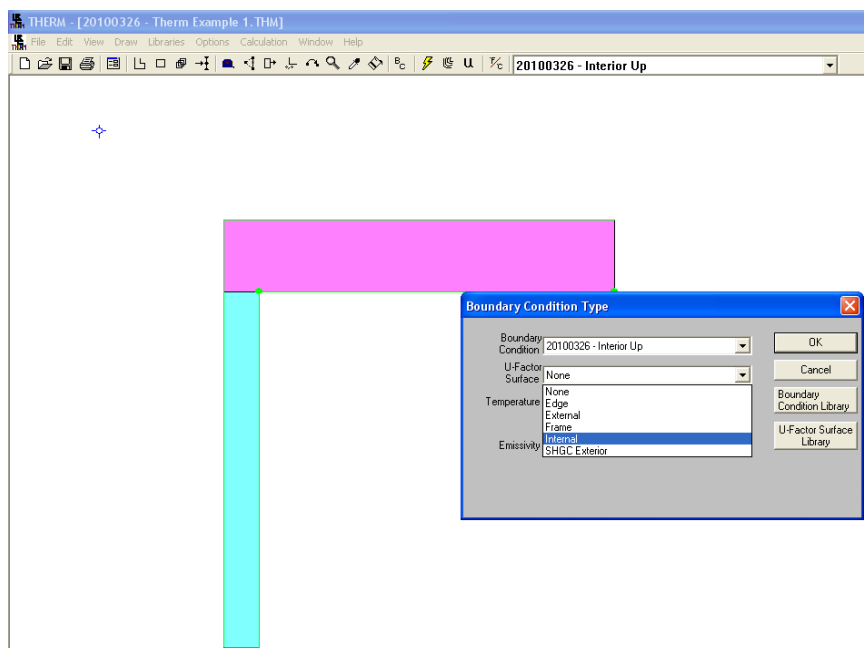

Figure 10 – Select Boundary Condition Type
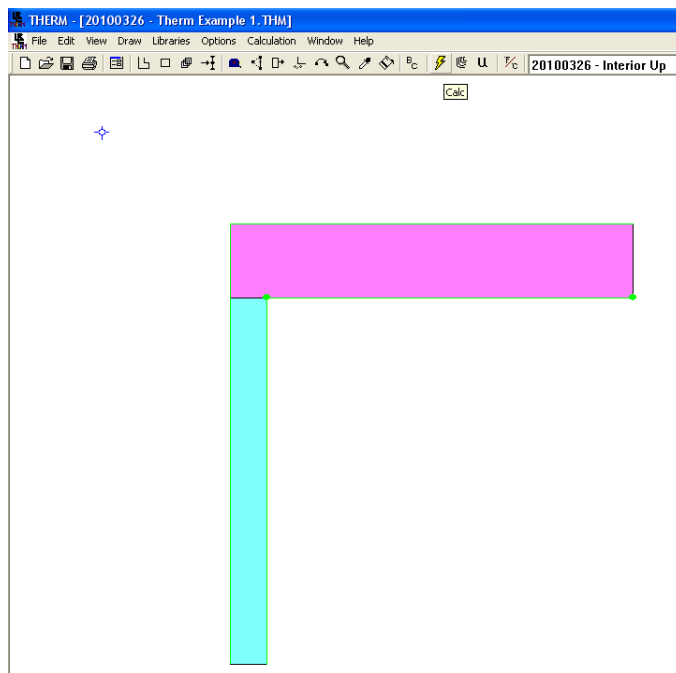
Calculate: Press Calc:

Figure 11 – Calculate

To Give:
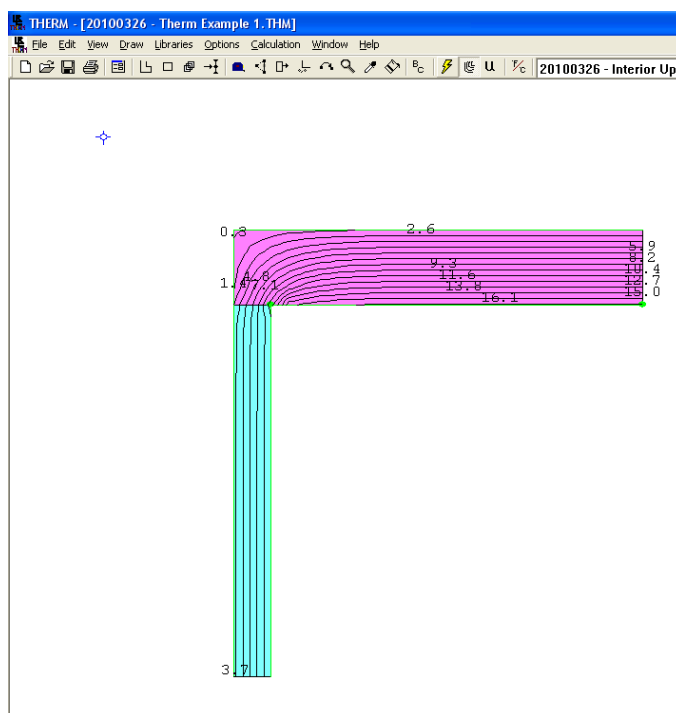
Figure 12 – Calculated Results

Now, Select InfraRed Colour:
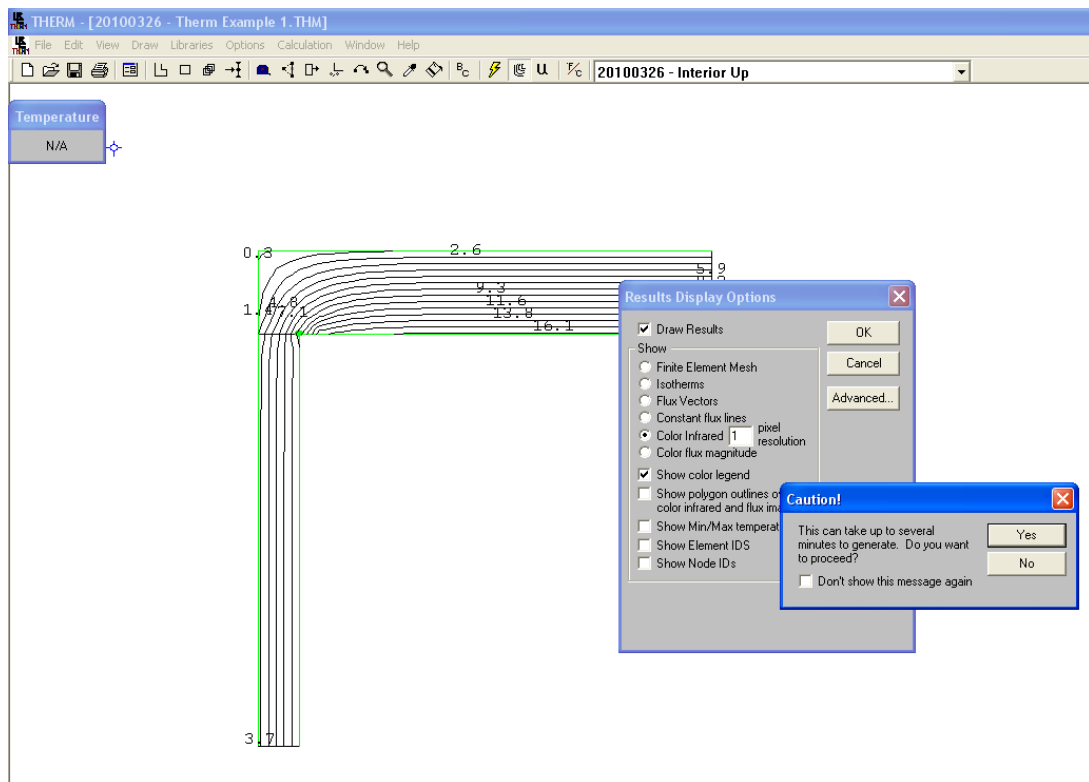
Figure 13 – Select InfraRed Colour

To give:
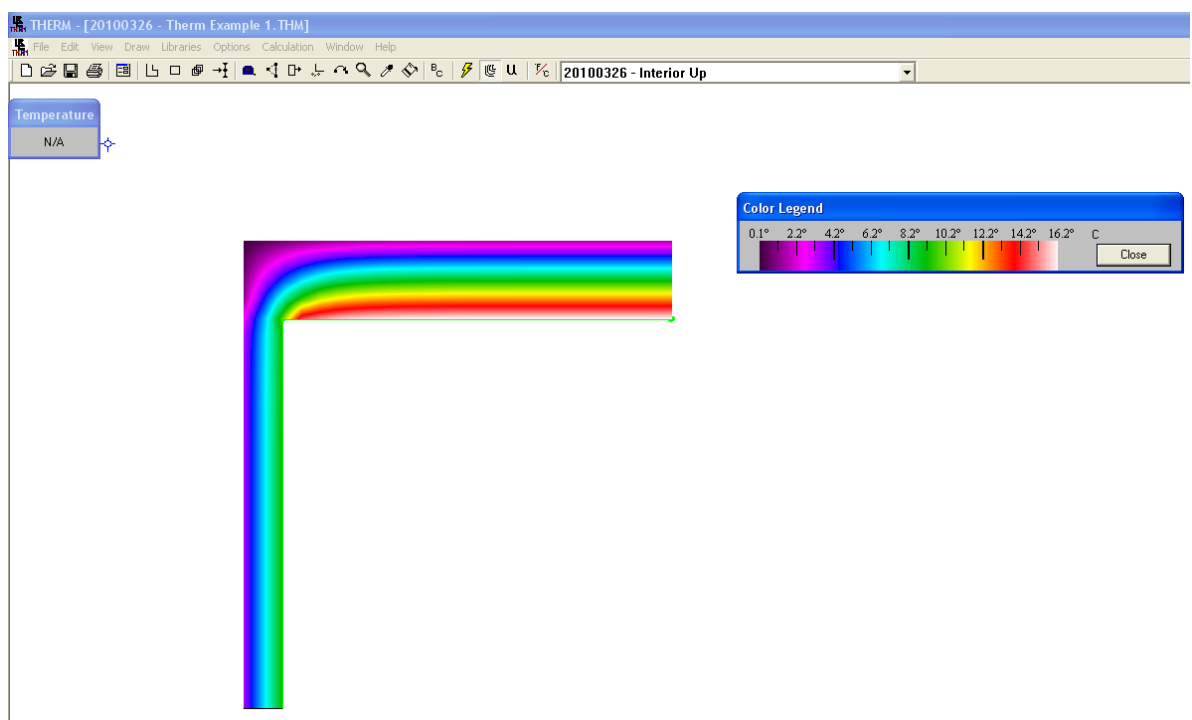
Figure 14 – InfraRed Colour Selected

Set Min and Max Colours:
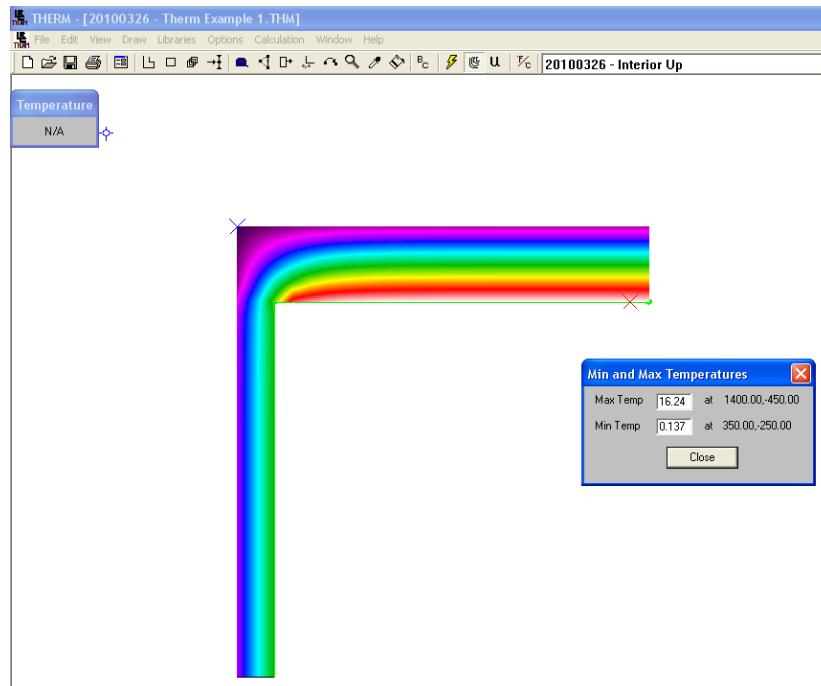
Figure 15 – Set min and max colours

Click on interior boundary, then click enter:
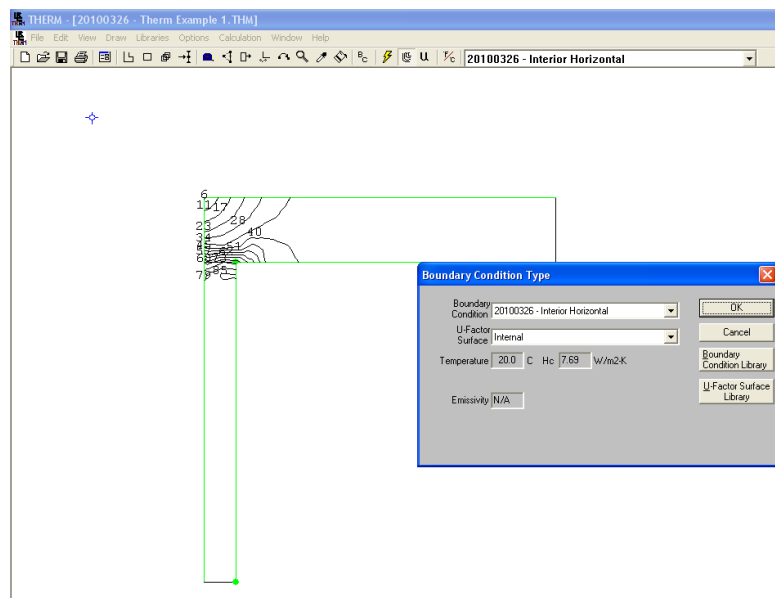
Figure 16 – Interior Boundary

Select U-Value Surface Library:
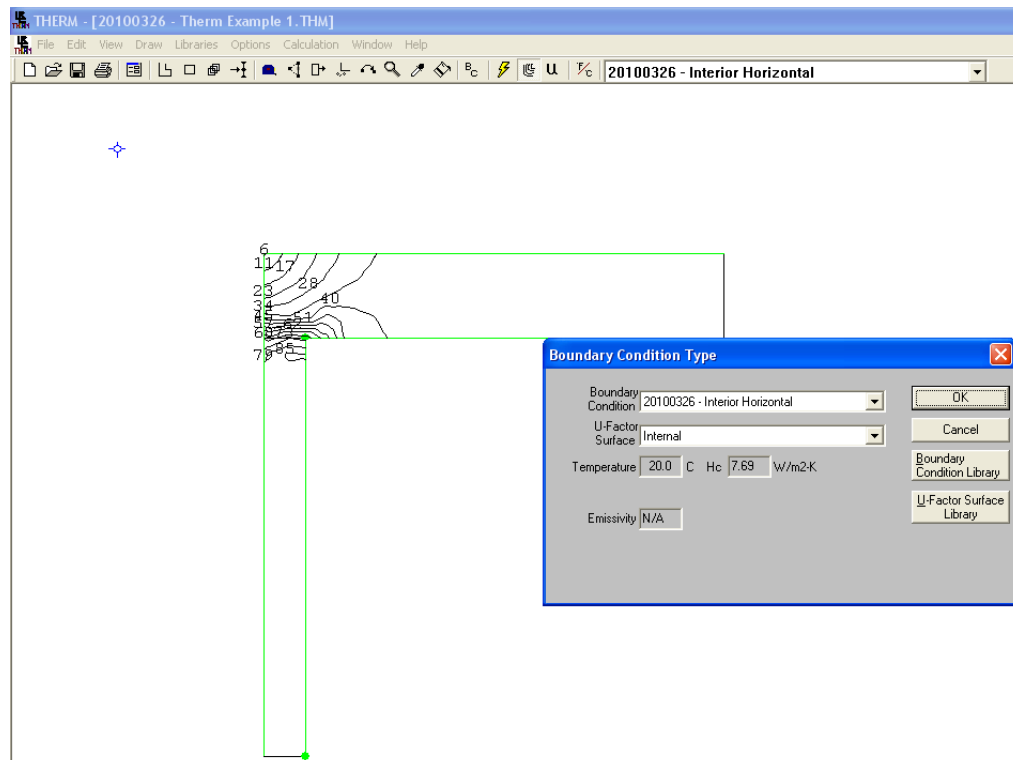
Figure 17 – Select U-Value Surface Library

U – Factors
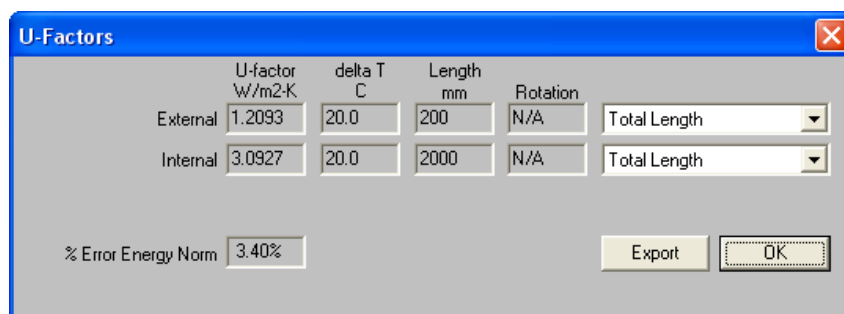
Figure 18 – U Factors

Conclusion

This Appendix has highlighted the complexity and capability of the THERM tool and how it can be used predict the thermal bridging of differing glazing and structure constructions.

Appendix H: Highly Insulated Dwelling Definition

| Variable	Value	Units	Description
Mv	0.037036	kg/s	Mass of the Dwelling Air
Ca	1012	J/(kg.K)	Specific Heat Capacity of Air
Us	0.3	(W/m²K)	Heat Transfer Co-Efficient of the Structure
As	85.6	(m²)	Surface Area of Structure
Ur	0.13	(W/m²K)	Heat Transfer Co-Efficient of the Roof
Ar	44.4	(m²)	Area of Roof
Uw	1.5	(W/m²K)	Heat Transfer Co-Efficient of the Windows
Aw	16.9	(m²)	Area of the Windows
Ma	249.795	kg	Mass of the air
Pa	1.22	kg/m3	Density of Air
Va	204.75	m3	Volume of Air
Ms	13696	kg	Mass of Structure
Cs	800	J/(kg.K)	Specific Heat Capacity of Structure
Uf	0.2	(W/m²K)	Heat Transfer Co-Efficient
Af	44.4	(m²)	Area of the Floor
Pb	800	kg/m3	Brick density
Mft	6900	kg	Mass of the Furniture
Pft	400	kg/m3	Density of Furniture
Vft	17.25	m3	Volume of Furniture
Cft	900	J/(kg.K)	Specific Heat Capacity of Furniture
Uft	2.574	(W/m²K)	Heat Transfer Co-Efficient of the Furniture
Aft	34.5	m²	Area of Internal Mass in a Dwelling

Appendix M – Monitoring Results

Monitoring Results – Graphs

A sample week in March is highlighted for each dwelling.

PassiveHouse
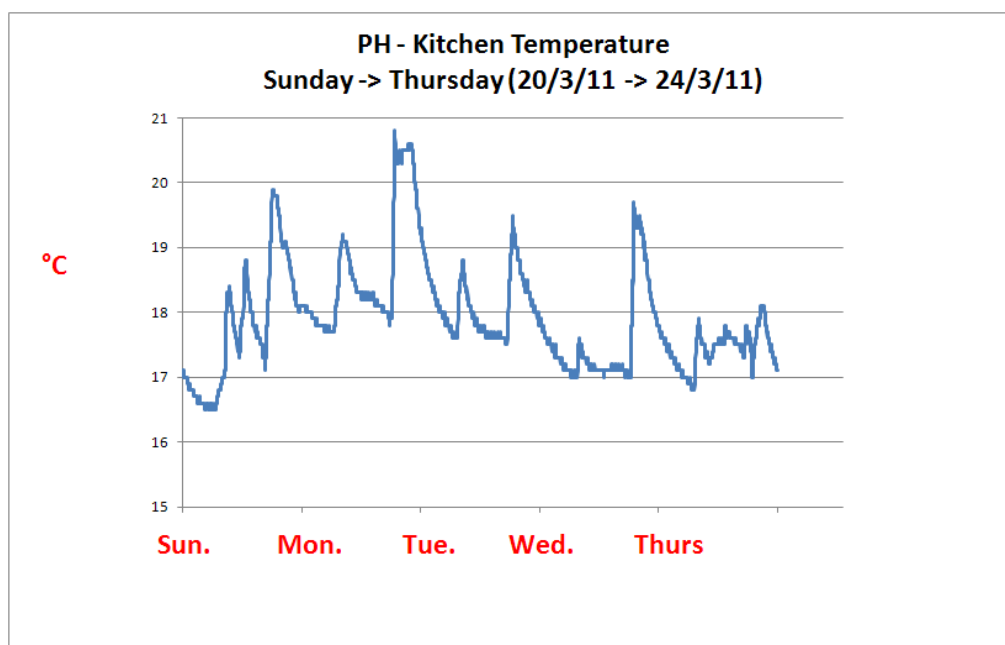
Figure M.1 – Passive House Sample Temperature Results: Kitchen
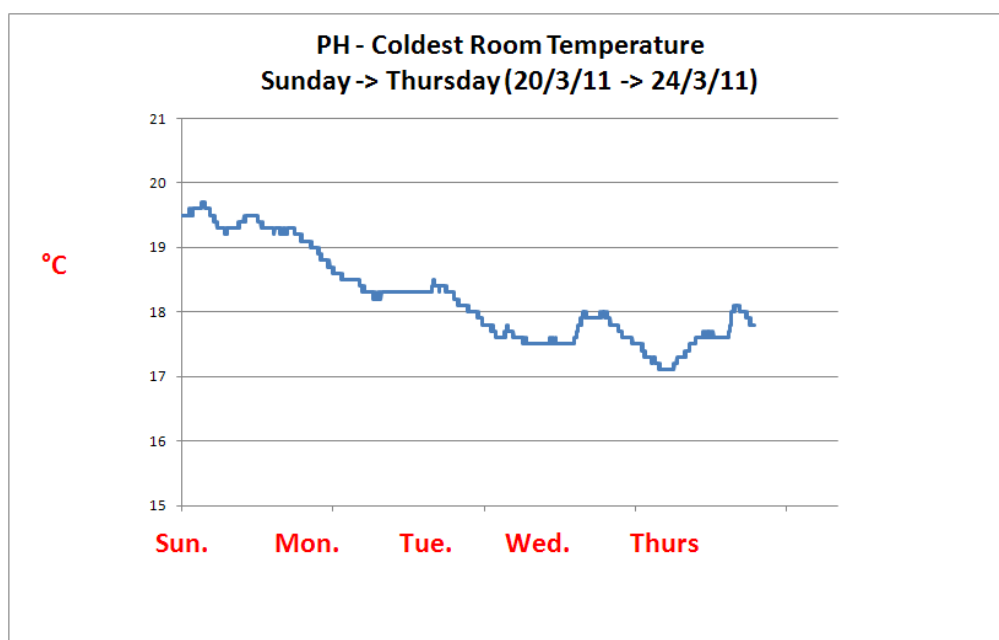
Figure M.2 – Passive House Sample Temperature Results: Coldest Room
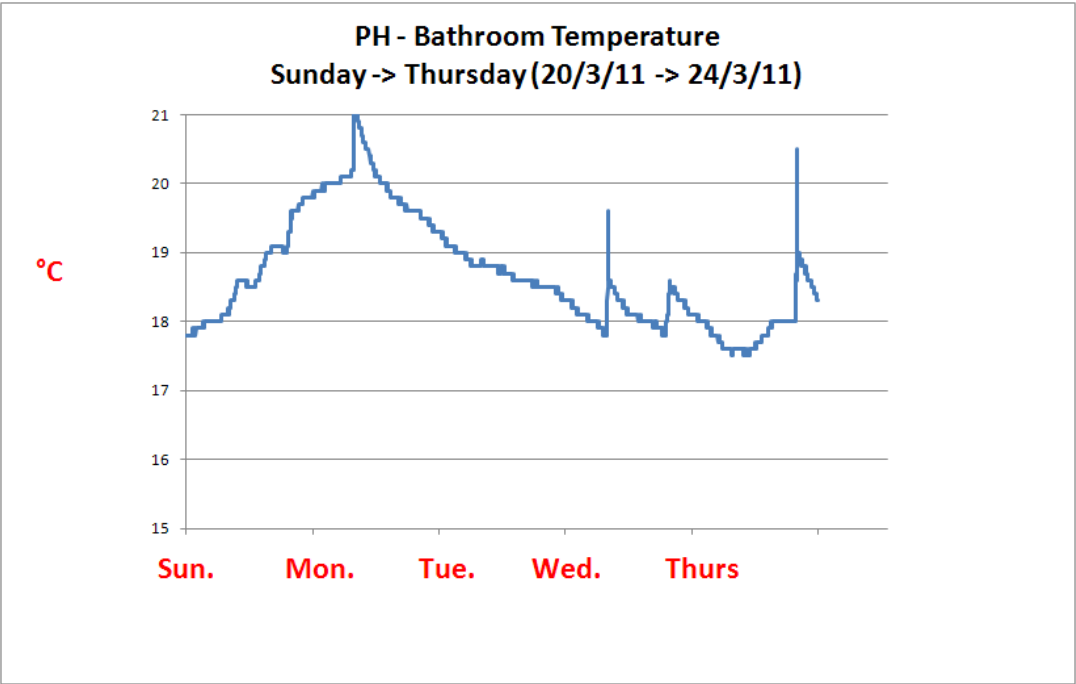
Figure M.3 – Passive House Sample Temperature Results: Bathroom Temperature
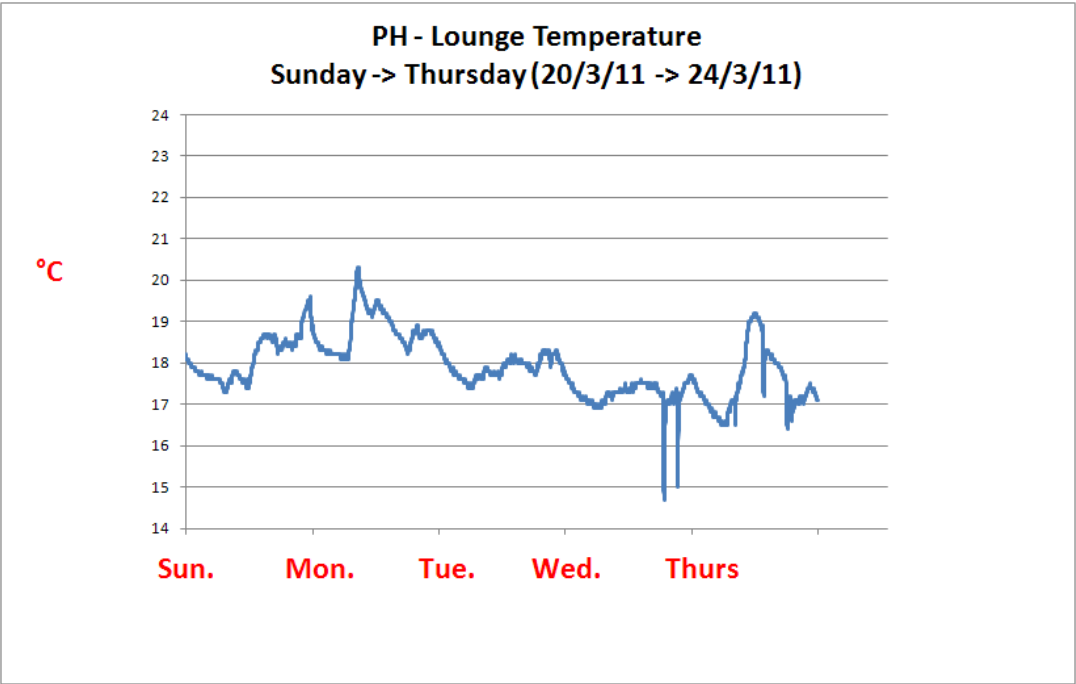
Figure M.4 – Passive House Sample Temperature Results: Lounge Temperature

Highly Insulated House
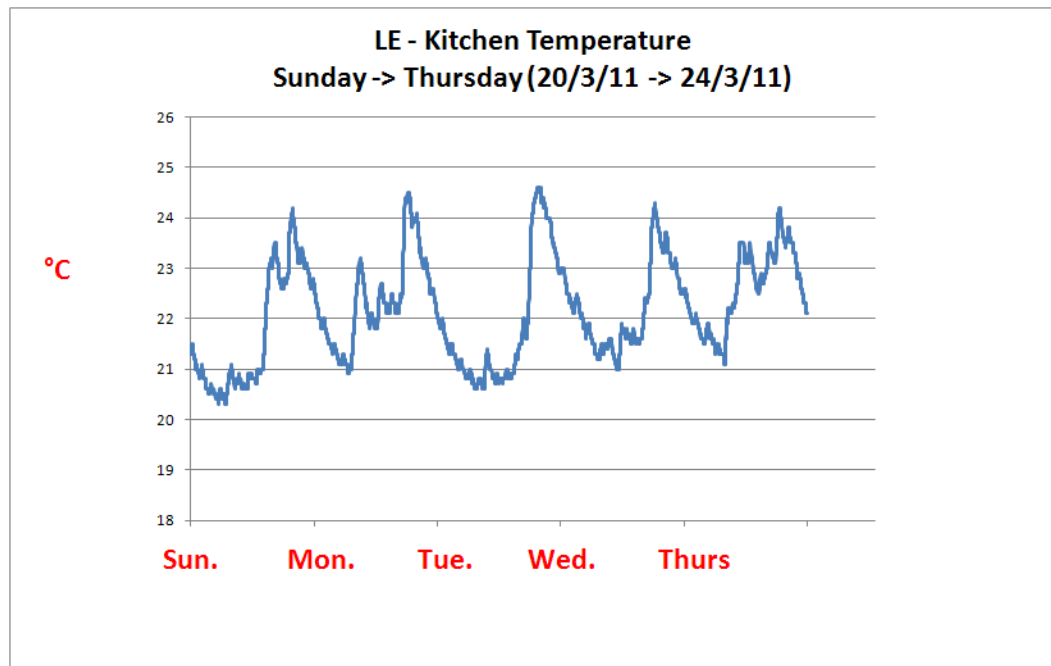
Figure M.5 – Energy Efficient Home Sample Temperature Results: Kitchen
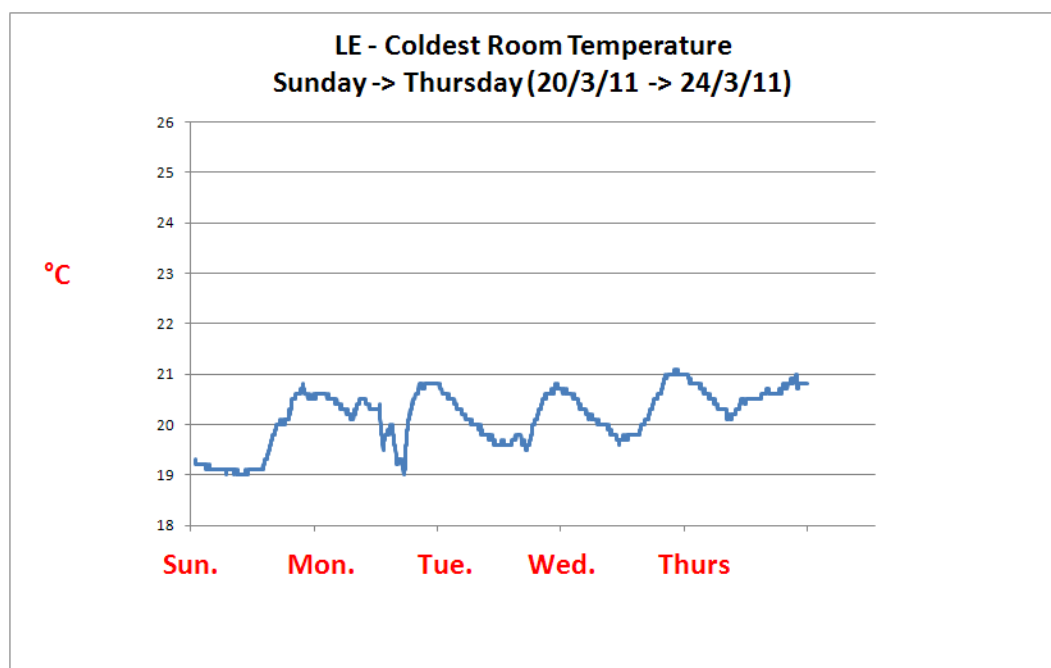
Figure M.6 – Energy Efficient Home Sample Temperature Results: Coldest Room
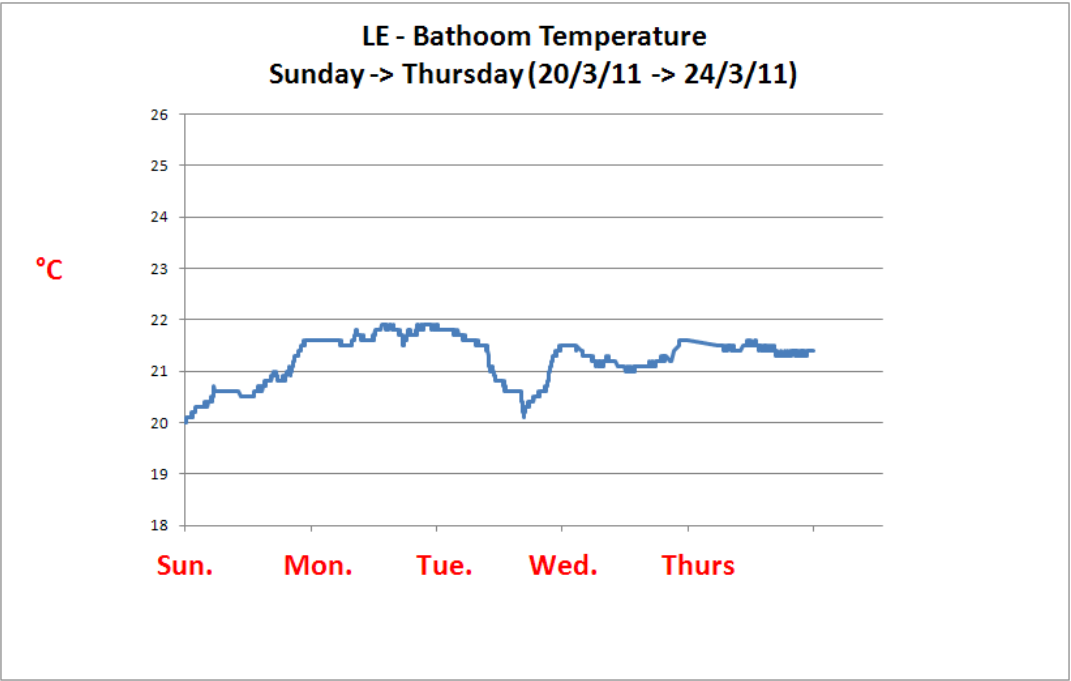
Figure M.7 – Energy Efficient Home Sample Temperature Results: Bathroom
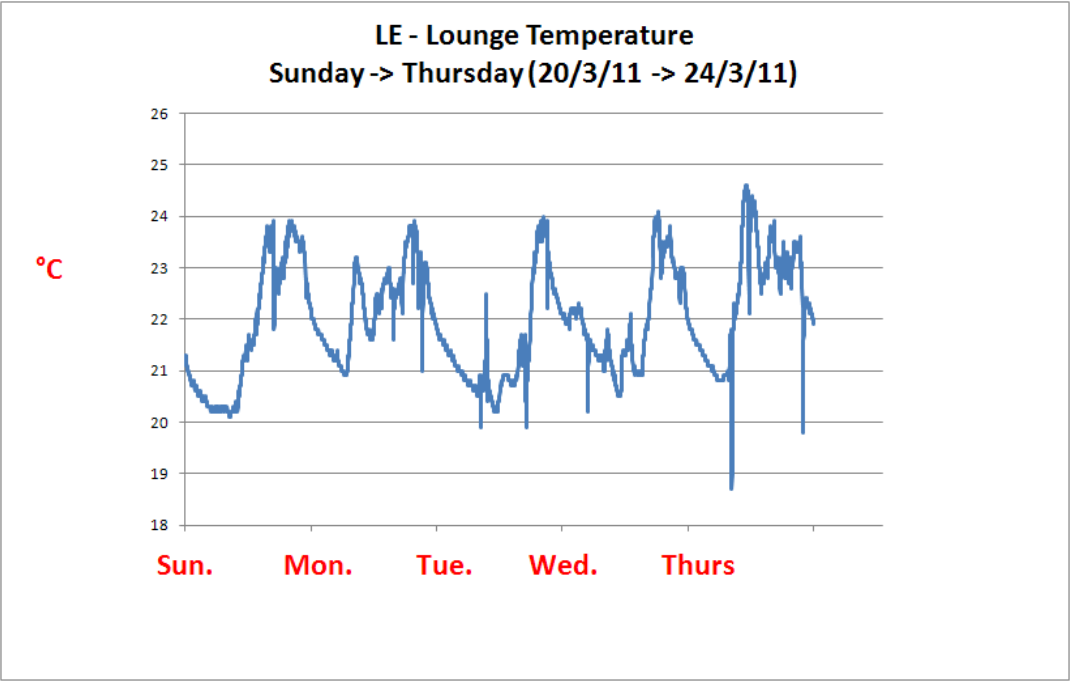
Figure M.8 – Energy Efficient Home Sample Temperature Results: Lounge

1980's House
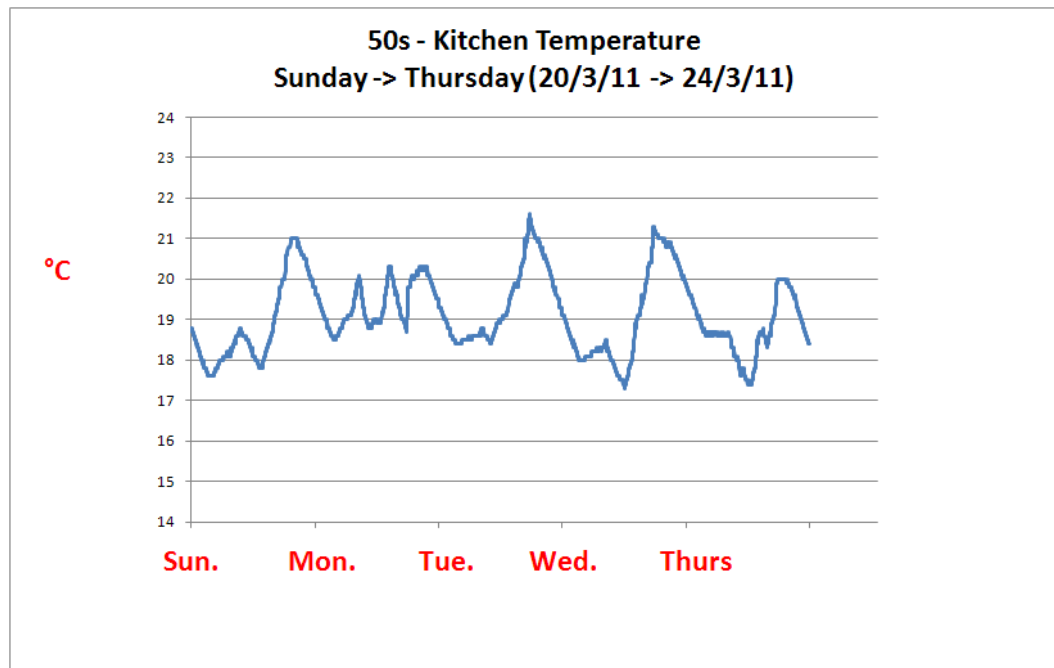
Figure M.9 – 1980's Home Sample Temperature Results: Kitchen
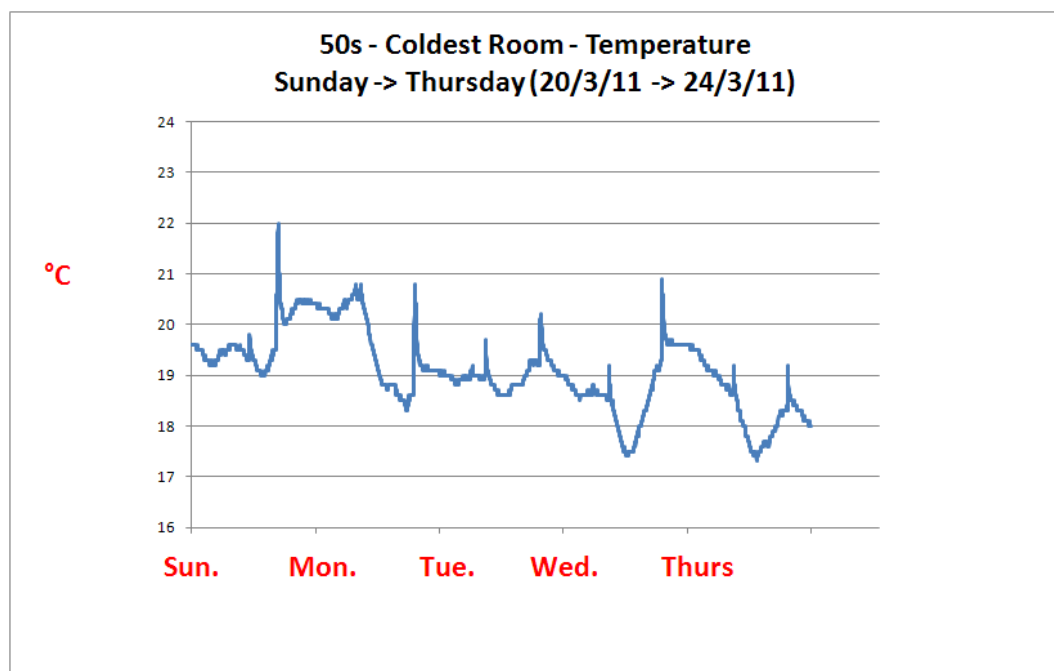
Figure M.10 – 1980's Home Sample Temperature Results: Coldest Room
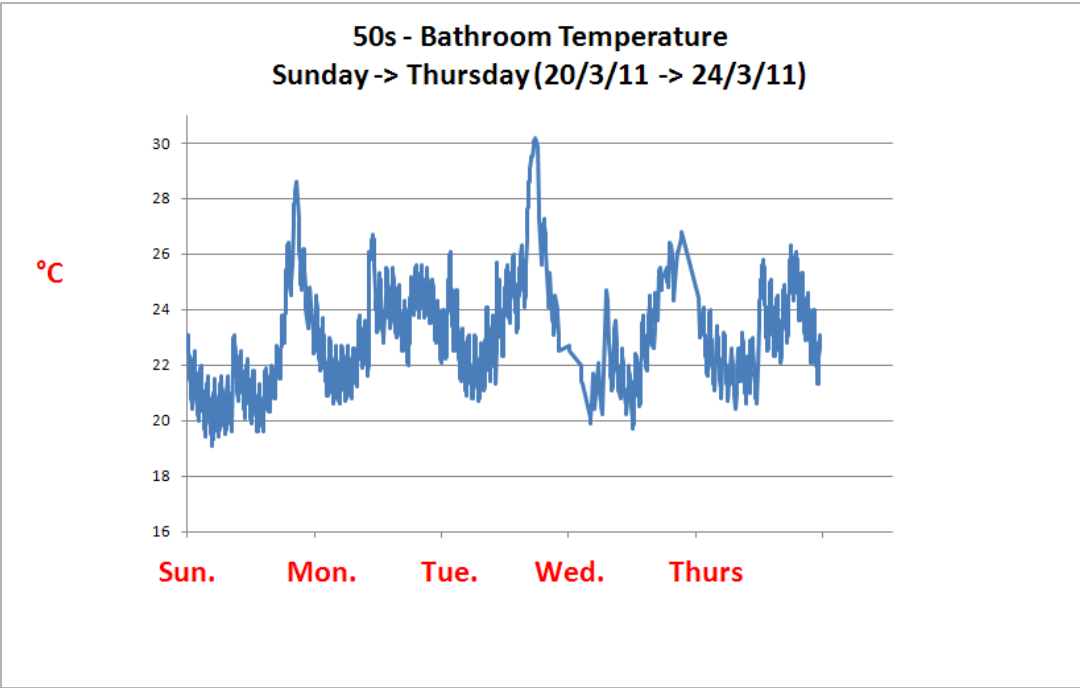
Figure M.11 – 1950's Home Sample Temperature Results: Bathroom
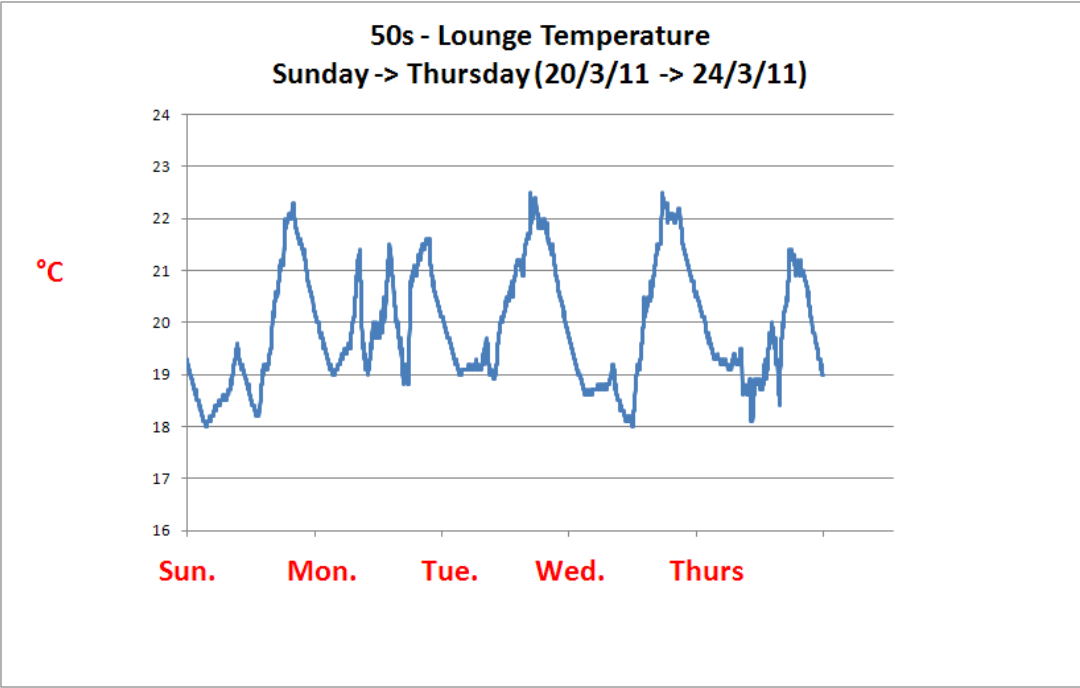
Figure M.12 – 1950's Home Sample Temperature Results: Lounge

Appendix P: Poorly Insulated Dwelling Definition

Variable	Value	Units	Description
Mv	0.037035971	kg/s	Mass of the Dwelling Air
Ca	1012	J/(kg.K)	Specific Heat Capacity of Air
Us	2.1	(W/m²K)	Heat Transfer Co-Efficient of the Structure
As	85.6	(m²)	Surface Area of Structure
Ur	2.3	(W/m²K)	Heat Transfer Co-Efficient of the Roof
Ar	44.4	(m²)	Area of Roof
Uw	5	(W/m²K)	Heat Transfer Co-Efficient of the Windows
Aw	16.9	(m²)	Area of the Windows
Ma	249.795	kg	Mass of the air
Pa	1.22	kg/m3	Density of Air
Va	204.75	m3	Volume of Air
Ms	13696	kg	Mass of Structure
Cs	800	J/(kg.K)	Specific Heat Capacity of Structure
Uf	0.7	(W/m²K)	Heat Transfer Co-Efficient
Af	44.4	(m²)	Area of the Floor
Pb	800	kg/m3	Brick density
Mft	6900	kg	Mass of the Furniture
Pft	400	kg/m3	Density of Furniture
Vft	17.25	m3	Volume of Furniture
Cft	900	J/(kg.K)	Specific Heat Capacity of Furniture
Uft	2.574	(W/m²K)	Heat Transfer Co-Efficient of the Furniture
Aft	34.5	m2	Area of Internal Mass in a Dwelling

Appendix S: SAP 2005 Sample Worksheet

Standard Test Case Dwelling SAP Worksheet
SAP 2005 WORKSHEET FOR NEW DWELLING

CALCULATION OF ENERGY RATINGS

SAP Standard Test Case GBM

1. Overall dwelling dimensions	Area (m²)	Av. storey height (m)	Volume (m³)	
Ground floor	52.00	2.40	124.80	(1)
First floor	52.00	2.65	137.80	(2)
Total floor area	104.00			(5)
Dwelling volume (m³)			262.60	(6)

2. Ventilation rate

		m³ per hour	
Number of chimneys	0 × 40	0	(7)
Number of open flues	0 × 20	0	(8)
Number of fans or passive vents	2 × 10	20	(9)
Number of flueless gas fires (9a)	0 × 40	0	

		ach	
Infiltration due to chimneys, flues and fans		0.08	(10)
Pressure test	Assumed		
Assumed q50	15.0		
Infiltration rate		0.83	(19)
Number of sides sheltered	2		(20)
Shelter factor	0.85		(21)
Adjusted infiltration rate		0.70	(22)
Natural ventilation			
Effective air change rate		0.75	(25)

3. <u>Heat losses and heat loss parameter</u>

Element	Area (m²)	U-value (W/m²K)	A × U (W/K)	
Doors	7.60	3.00	22.80	(26)
Windows	16.90	(2.10) 1.94	32.74	(27)
Roof windows	0.25	(2.30) 2.11	0.53	(27)
Ground floor	52.00	0.22	11.44	(28)
Walls	118.50	0.30	35.55	(29)
Roof	<u>51.75</u>	0.16	<u>8.28</u>	(30)
Total area of elements	<u>247.00</u>			(32)
Fabric heat loss			111.34	(33)
Thermal bridges (0.15 × total area)			<u>37.05</u>	(34)
Total fabric heat loss			148.39	(35)
Ventilation heat loss			<u>64.70</u>	(36)
Heat loss coefficient			213.08	(37)
Heat loss parameter (HLP)			2.05	(38)

4. <u>Water heating energy requirements</u>

		kWh/year	
Energy content of heated water		2152	(39)
Distribution loss		380	(40)
Cylinder volume	300		(43)
Cylinder loss factor (kWh/litre/day)	0.0115		(44)
Volume factor (44a)	0.737		
Temperature factor (44b)	0.60		
Energy lost from cylinder in kWh/year (120 litres)	224	(47)	
Primary circuit loss		<u>360</u>	(48)
Total		3115	

301

(49a)

Aperture area of solar panel (H1) 5.00

Collector zero-loss efficiency (H2) 0.75

Collector heat loss coefficient (H3) 6.00

Collector performance ratio (H4) 8.00

Annual solar radiation per m² (H5) 1042

Overshading factor (H6) 1.00

Solar energy available (H7) 3908

Solar/load ratio (H8) 1.544

Solar utilisation factor (H9) 0.477

Collector performance factor (H10) 0.636

Dedicated solar storage volume (H11) 180

Effective solar volume (H13) 216

Daily hot water demand (H14) 119

Volume ratio Veff/V (H15) 1.819

Veff/V factor (H16) 1.000

Solar input -1186 (50)

Output from water heater 1929 (51)

Heat gains from water heating 1309 (52)

302

5. <u>Internal gains</u>

<u>Watts</u>

Lights, appliances, cooking and metabolic	594	(53)
Reduction in lighting gains (53a)	-36	
Additional gains (Table 5a) (53b)	10	
Water heating	149	(54)
Total internal gains	718	(55)

6. <u>Solar gains</u>

Orientation		Area	Flux	g	FF	Shading	Gains (W)	
East/West	0.9 ×	16.90	48	0.72	0.70	0.77	283	(58)
Roof windows	0.9 ×	0.25	75	0.72	0.70	1.00	9	(64)
						total:	292	(65)

Total gains	1010	(66)
Gain/loss ratio	4.74	(67)
Utilisation factor	0.978	(68)
Useful gains	987	(69)

7. <u>Mean internal temperature</u>   <u>°C</u>

Mean temperature of the living area	18.85	(70)
Temperature adjustment from Table 4e	0.00	(71)
Adjustment for gains	0.13	(72)
Adjusted living area temperature	18.97	(73)
Temperature difference between zones	1.58	(74)
Living area fraction	0.529	(75)
Rest-of-house area fraction	0.471	(76)
Mean internal temperature	18.23	(77)

8. Degree-days

Temperature rise from gains		4.63	(78)
Base temperature		13.60	(79)
Degree-days		1691.4	(80)

9a. Energy requirements   kWh/year

Space heating requirement (useful)		8650	(81)
Fraction of heat from secondary system	0.10		(82)
Efficiency of main heating system		90.2	(83)
Efficiency of secondary heating system		100	(84)
Space heating fuel (main)		8631	(85)
Space heating fuel (secondary) (85a)		865	
Water heating requirement		1929	
Efficiency of water heater	90.2		(86)
Water heating fuel (86a)		2139	
Electricity for pumps and fans		250	(87)
(heating pump 130, flue fan 45, solar pump 75)			
Electricity for lighting (50% fixed LEL) (87g)		722	

_____

10a. Fuel costs using Table 12 prices	kWh/year	p/kWh	£/year	
Space heating - main system	8631	1.63	140.68	(88)
Space heating - secondary system	865	7.12	61.59	(89)
Water heating (91b)	2139	1.63	34.86	
Pump/fan energy cost	250	7.12	17.80	(92)
Electricity for lighting	722	7.12	51.40	(93)
Additional standing charges			34.00	(94)

Total energy cost	340.33	(97)

11a. <u>SAP rating</u>

Energy cost deflator	0.91	(98)
Energy cost factor (ECF)	1.88	(99)
SAP value (99a)	73.79	
SAP rating	**74**	(100)
SAP band	**C**	

_____

10a. <u>Fuel costs using BEDF prices (rev 251)</u>	kWh/year	p/kWh	£/year	
Space heating - main system	8631	3.10	267.55	(88)
Space heating - secondary system	865	11.46	99.13	(89)
Water heating (91b)	2139	3.10	66.30	
Pump/fan energy cost	250	11.46	28.65	(92)
Electricity for lighting	722	11.46	82.73	(93)
Additional standing charges			<u>106.00</u>	(94)
Total energy cost			650.36	(97)

_____

12a. <u>Carbon dioxide emissions</u>	Energy (kWh/year)	Emission factor	Emissions (kg/year)	
Space heating, main - box (85)	8631	0.194	1674	(101)
Space heating, secondary - box (85a)	865	0.422	365	(102)
Water heating - box (86a)	2139	0.194	<u>415</u>	(103)
Space and water heating			2454	(107)
Pumps and fans - box (87)	250	0.422	105	(108)
Electricity for lighting	722	0.422	<u>305</u>	(109)
Total kg/year			2864	(112)

			kg/m²/year	
CO2 emissions per m²			**27.54**	(113)
EI value			74.24	
	(113a)			
EI rating			**74**	(114)
EI band			**C**	

13a. <u>Primary energy</u>	Energy	Primary	P.Energy	
	(kWh/year)	factor	(kWh/year)	
Space heating, main - box (85)	8631	1.15	9925	(101)
Space heating, secondary - box (85a)	865	2.80	2422	(102)
Water heating - box (86a)	2139	1.15	<u>2460</u>	(103)
Space and water heating			14807	(107)
Pumps and fans - box (87)	250	2.80	700	(108)
Electricity for lighting	722	2.80	<u>2021</u>	(109)
Primary energy kWh/year			**17528**	(112)
Primary energy kWh/m²/year			**169**	(113)

Worksheet calculated by:

<u>Summary (SAP 2005 v 9.81):</u>   SAP Rating: C 74

Emissions: C 74   2.9

tonnes/year

Primary energy: 169

kWh/m²/year

Fuel use:

    Mains gas   10769 kWh

    Standard tariff   1837 kWh

Emissions:

    Space heating: 2145 kg   (including pumps & fans)

    Water heating: 415 kg

    Lighting: 305 kg

Appendix T – Continuous to Digital Transformation using a Zero-Order Hold (ZOH)

Instabilities caused with the Continuous RIDE algorithm due to the 5 min sampling rate

Due to the instabilities found at a 5 minute time resolution in excel, a continuous to digital transformation using a zero-order hold process was required. This produced digital equivalent matrices based upon the continuous versions. A main issue to resolve was in this process regarded the digital U-Trim equation; with CF-C being required (The negative values in this resultant Matrix are very important). CH D(k) is the formula. Once Digital U-Trim is calculated, a digital equivalent of the usual perfect inverse control law (RIDE) can be invoked.

Discrete Time Conditioning is required; we need a Digital RIDE algorithm in Excel:

Equation (1) is the continuous time State Equation:

$$\dot{x}(t) = Ax(t) + Bu(t) + Dd(t)$$

(1)

The digital equivalent of Equation 1 is:

$$x(k+1) = Fx(k) + Gu(k) + Hd(k)$$

(2)

Where:

$$F = I + ATM$$

(3)

$$G = MTB$$

(4)

$$H = MTD \tag{5}$$

Where I = the Identity Matrix:

$$I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{6}$$

The output Equation is:

$$Y(t) = Cx(t) \tag{7}$$

The digital equivalent of (7) is:

$$Y(k) = Cx(k) + Ju(k) \tag{8}$$

We assume Ju(k) = 0

$$C_{continuous} \equiv C_{digital} \tag{9}$$

The perfect inverse control law RIDE (continuous):

$$U(t) = g(CB)^{-1}\big(v(t) - y(t)\big) + U_{eq}(t) \tag{10}$$

The digital equivalent of Equation (10) is:

$$U(k) = g(CG)^{-1}(v(k) - Y(k)) + U_{Trim}(k) \tag{11}$$

Where:

$$U_{trim} = -(CG)^{-1}\big\{(CF - C)x(k) + c^2 d(k)\big\} \tag{12}$$

F Matrix:

Where F is the Digital Equivalent of Matrix A:

$$F = I + ATM \tag{13}$$

$$F = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix} T \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & 0 \\ M_{31} & 0 & M_{33} \end{bmatrix} \tag{14}$$

$$F = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + \begin{bmatrix} a_{11}T & a_{12}T & a_{13}T \\ a_{21}T & a_{22}T & 0 \\ a_{31}T & 0 & a_{33}T \end{bmatrix} \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & 0 \\ M_{31} & 0 & M_{33} \end{bmatrix} \tag{15}$$

$$F = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} +$$

$$\begin{bmatrix} a_{11}TM_{11} + a_{12}TM_{21} + a_{13}TM_{31} & a_{11}TM_{12} + a_{12}TM_{22} + 0 & a_{11}TM_{13} + 0 + a_{13}TM_{33} \\ a_{21}TM_{11} + a_{22}TM_{21} + 0 & a_{21}TM_{12} + a_{22}TM_{22} + 0 & a_{21}TM_{13} \\ a_{31}TM_{11} + 0 + a_{33}TM_{31} & a_{31}TM_{12} & a_{31}TM_{13} + 0 + a_{33}TM_{33} \end{bmatrix} \tag{16}$$

$$F = \begin{bmatrix} a_{11}TM_{11} + a_{12}TM_{21} + a_{13}TM_{31} + 1 & a_{11}TM_{12} + a_{12}TM_{22} & a_{11}TM_{13} + a_{13}TM_{33} \\ a_{21}TM_{11} + a_{22}TM_{21} & a_{21}TM_{12} + a_{22}TM_{22} + 1 & a_{21}TM_{13} \\ a_{31}TM_{11} + a_{33}TM_{31} & a_{31}TM_{12} & a_{31}TM_{13} + a_{33}TM_{33} + 1 \end{bmatrix} \tag{17}$$

G Matrix:

Where G is the Digital Equivalent of Matrix B:

$$G = MTB \tag{18}$$

$$G = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & 0 \\ M_{31} & 0 & M_{33} \end{bmatrix} T \begin{bmatrix} b_{11} \\ 0 \\ 0 \end{bmatrix} \tag{19}$$

$$G = \begin{bmatrix} M_{11}Tb_{11} \\ M_{21}Tb_{11} \\ M_{31}Tb_{11} \end{bmatrix} \tag{20}$$

H Matrix:

Where H is the Digital Equivalent of Matrix D:

$$H = MTD \tag{21}$$

$$H = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & 0 \\ M_{31} & 0 & M_{33} \end{bmatrix} T \begin{bmatrix} d_{11} & d_{12} & 0 \\ 0 & d_{22} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{22}$$

$$H = \begin{bmatrix} M_{11}T & M_{12}T & M_{13}T \\ M_{21}T & M_{22}T & 0 \\ M_{31}T & 0 & M_{33}T \end{bmatrix} \begin{bmatrix} d_{11} & d_{12} & 0 \\ 0 & d_{22} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{23}$$

$$H = \begin{bmatrix} M_{11}Td_{11} & M_{12}Td_{12} + M_{12}Td_{22} & 0 \\ M_{21}Td_{11} & M_{21}Td_{12} + M_{22}Td_{22} & 0 \\ M_{31}Td_{11} & M_{31}Td_{12} & 0 \end{bmatrix}$$

(24)

M Matrix:

Where the M Matrix is used to convert from Analogue to Digital:

$$M = I + \frac{AT}{2!} + \frac{A^2T^2}{3!} + \frac{A^3T^3}{4!} + \frac{A^4T^4}{5!} + \frac{A^5T^5}{6!}$$

(25)

$$M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + \frac{\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}T}{2*1} + \frac{\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}TT}{3*2*1}$$

$$+ \frac{\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}TTT}{4*3*2*1}$$

$$+ \frac{\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}TTTT}{5*4*3*2*1}$$

$$+ \frac{\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix}TTTTT}{6*5*4*3*2*1}$$

(26)

Implementation in Excel of Digital RIDE:

A / B / D Matrix and Digital Equivalents F / G / H:

A Matrix				B Matrix		D Matrix	
-0.0025067	0.0001994	0.0018804		0.0000053		0.0000053	0.0004269
0.0000034	-0.0000069	0.0000000		0.0000000		0.0000000	0.0000034
0.0000143	0.0000000	-0.0000143		0.0000000		0.0000000	0.0000000
Digital Equivalents				**Ccontinuous = Cdigit**			
F Matrix				**G Matrix**		**H Matrix**	
0.4739876	0.0418689	0.3943709		0.0011129		0.0011129	0.0897727
0.0007218	0.9979642	0.0002312		0.0000007		0.0000007	0.0010828
0.0029991	0.0001020	0.9966804		0.0000027		0.0000027	0.0002186
F Matrix - Symbolic				**G Matrix - Symbolic**		**H Matrix - Symbolic**	
0.4739876	0.0418494	0.3943662		0.0011129		0.0011129	0.0897727
0.0007218	0.9979642	0.0002314		0.0000007		0.0000007	0.0010828
0.0029991	0.0001021	0.9966804		0.0000027		0.0000027	0.0002185

Figure T. 1 – Continuous and Digital RIDE in Excel: Continuous A / B / D Matrix and Digital Equivalents F / G / H

- There is now confidence with the Continuous Time Matrix values
  - These are derived from figures entered in IDEAS / BREDEM
- The Digital Matrix results are shown to be identical when the Matrix Multiplication figures and the Symbolic Methods are compared.
- Additionally these figures have been checked in Mathematica and there is a direct correlation
- Calculated Digital Matrices are identical when the following methods are compared:
  - Matrix Multiplication in Excel
  - Symbolic Calculations in Excel
  - Use of Mathematica
    - We can have some confidence that that the Digital Equivalent Matrices (F / G / H) are correct
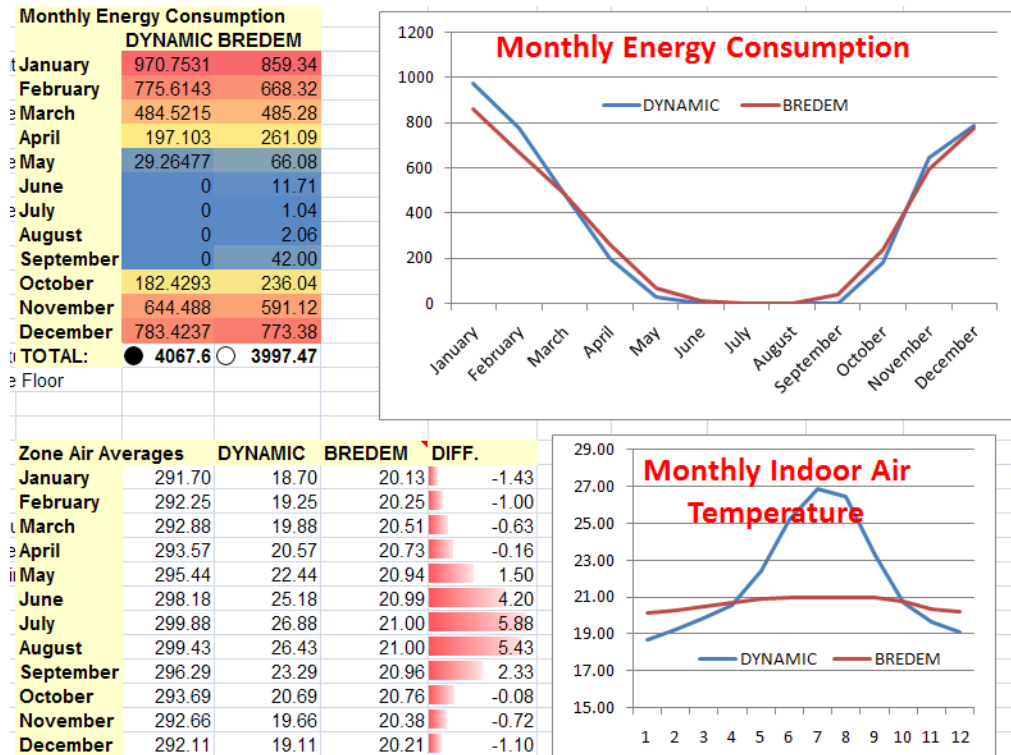
Continuous vs. Digital RIDE Excel Comparison

Monthly Energy Consumption

	DYNAMIC	BREDEM
January	970.7531	859.34
February	775.6143	668.32
March	484.5215	485.28
April	197.103	261.09
May	29.26477	66.08
June	0	11.71
July	0	1.04
August	0	2.06
September	0	42.00
October	182.4293	236.04
November	644.488	591.12
December	783.4237	773.38
TOTAL:	● 4067.6	○ 3997.47
Floor		

Zone Air Averages	DYNAMIC	BREDEM	DIFF.
January	291.70	18.70	20.13	-1.43
February	292.25	19.25	20.25	-1.00
March	292.88	19.88	20.51	-0.63
April	293.57	20.57	20.73	-0.16
May	295.44	22.44	20.94	1.50
June	298.18	25.18	20.99	4.20
July	299.88	26.88	21.00	5.88
August	299.43	26.43	21.00	5.43
September	296.29	23.29	20.96	2.33
October	293.69	20.69	20.76	-0.08
November	292.66	19.66	20.38	-0.72
December	292.11	19.11	20.21	-1.10

Figure T.2 – DIGITAL RIDE comparison with BREDEM; Total IDEAS kWh/year for Energy Consumption = 4067kWh

Monthly Energy Consumption

	DYNAMIC	BREDEM
January	973.6535	859.34
February	777.9172	668.32
March	486.289	485.28
April	198.3528	261.09
May	29.6897	66.08
June	0	11.71
July	0	1.04
August	0	2.06
September	0	42.00
October	183.7217	236.04
November	646.4162	591.12
December	785.7873	773.38
TOTAL:	● 4081.8	○ 3997.47
of the Floor		

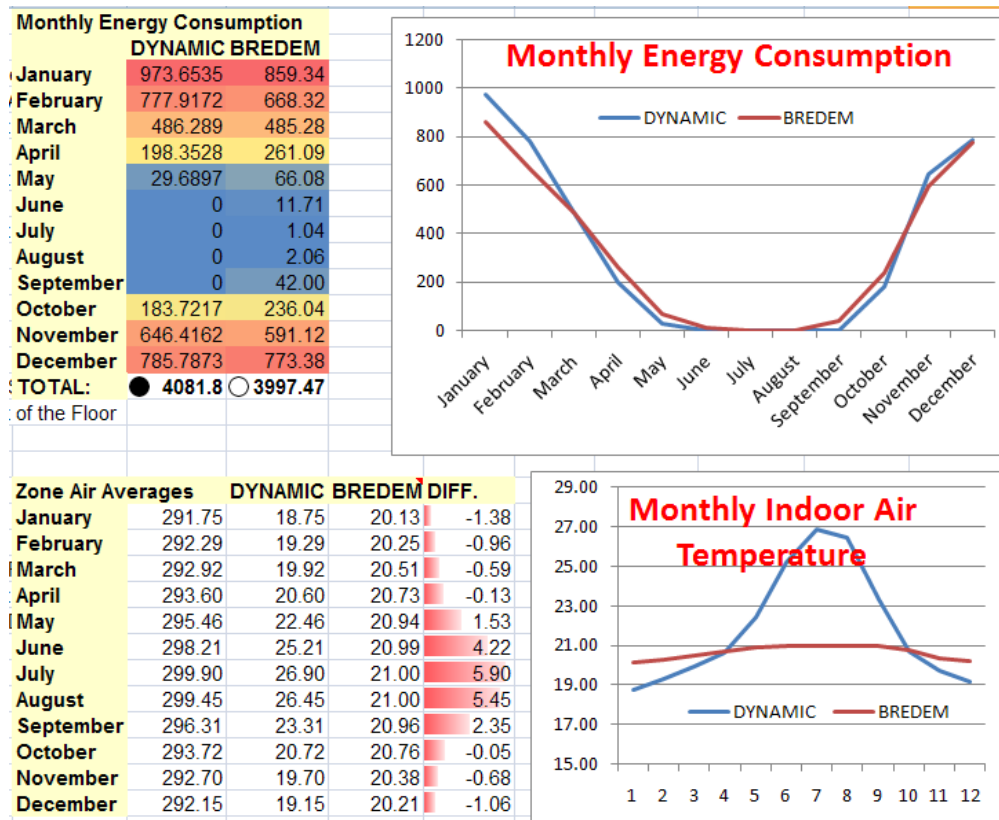| Zone Air Averages	DYNAMIC	BREDEM	DIFF.
January	291.75	18.75	20.13	-1.38
February	292.29	19.29	20.25	-0.96
March	292.92	19.92	20.51	-0.59
April	293.60	20.60	20.73	-0.13
May	295.46	22.46	20.94	1.53
June	298.21	25.21	20.99	4.22
July	299.90	26.90	21.00	5.90
August	299.45	26.45	21.00	5.45
September	296.31	23.31	20.96	2.35
October	293.72	20.72	20.76	-0.05
November	292.70	19.70	20.38	-0.68
December	292.15	19.15	20.21	-1.06

Figure T.3 – CONTINUOUS RIDE comparison with BREDEM; Total IDEAS kWh/year for Energy Consumption = 4081kWh

- New Digital RIDE figure vs Continuous RIDE System:
  - Digital RIDE (4067.6kWh) vs Continuous System (4081.8kWh)
  - Therefore less than 0.5% difference in figures.
  - We can have confidence that the Digital and Continuous RIDE IDEAS models are both generating very similar results to each other
    - The use of Digital RIDE allows for a wider variety of U-Values and inputs to be used than relying on the Continuous RIDE

Seasonal Graphing Comparison between Continuous and Digital Implementations:

Spring (Continuous Screenshot Left / Digital Screenshot Right):
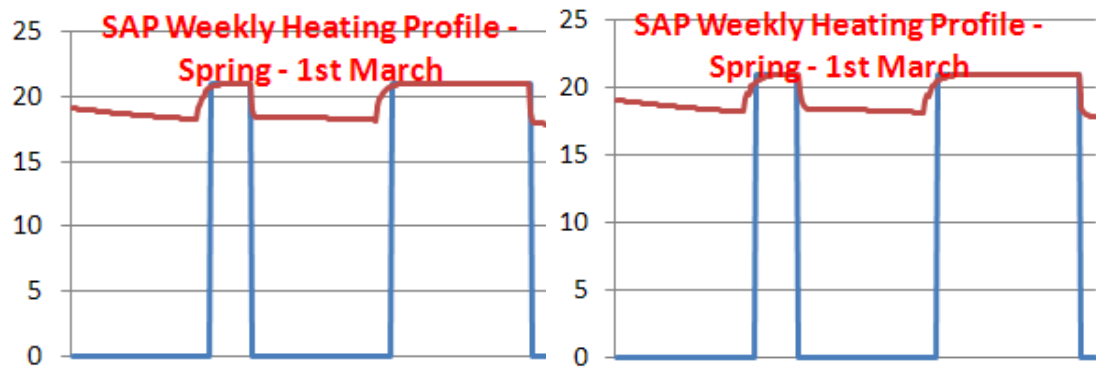
Figure T.4 – Seasonal Graphing Comparison between Continuous and Digital RIDE in Excel: Spring

Summer (Continuous Screenshot Left / Digital Screenshot Right):
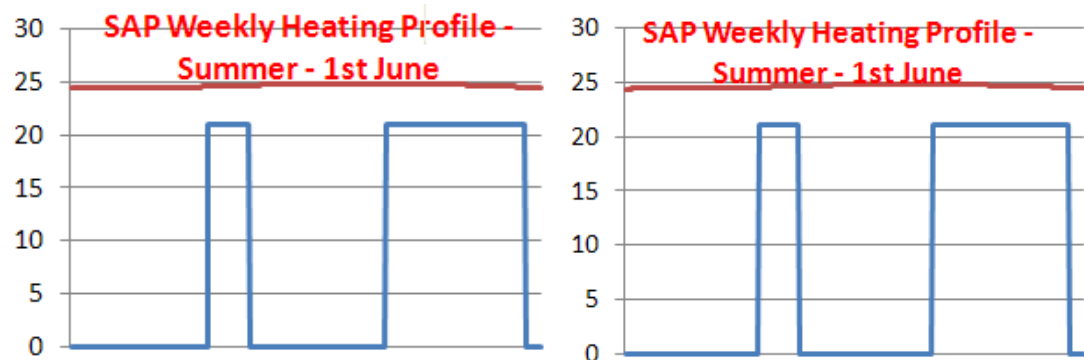
Figure T.5 - Seasonal Graphing Comparison between Continuous and Digital RIDE in Excel: Summer

314

Autumn (Continuous Screenshot Left / Digital Screenshot Right):
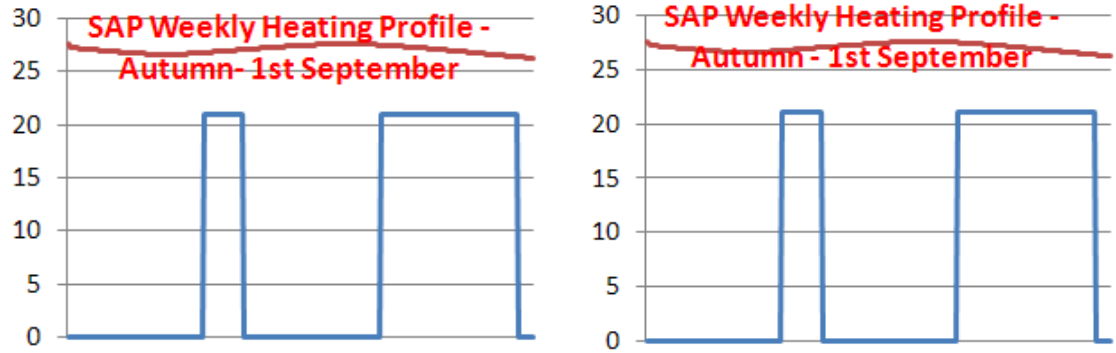

Figure T.6 - Seasonal Graphing Comparison between Continuous and Digital RIDE in Excel: Autumn

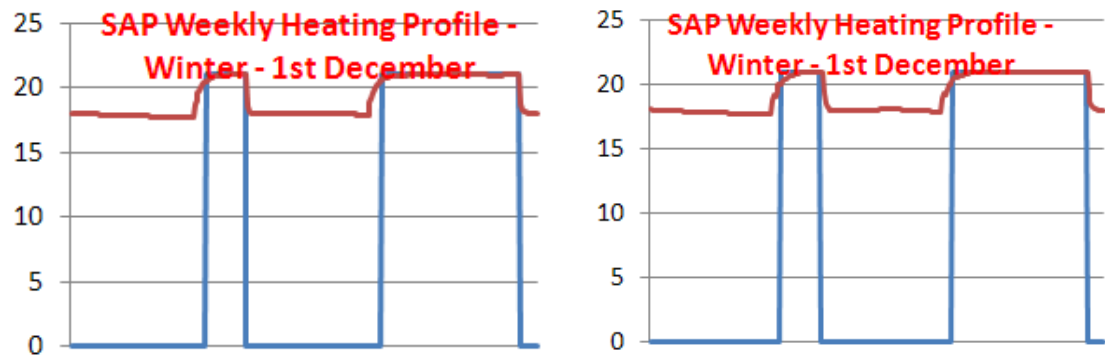*Winter (Continuous Screenshot Left / Digital Screenshot Right):*

Figure T.7 - Seasonal Graphing Comparison between Continuous and Digital RIDE in Excel: Winter

Digital vs. Continuous RIDE comparisons between well and poorly insulated dwellings

As detailed in chapter 4, the IDEAS model was firstly created as a 3rd order model in Microsoft Excel, using the Continuous RIDE control algorithm. A time delay instability was found due to the 5 minute time resolution employed in the Microsoft Excel implementation. The 3rd order model was then updated to use the Digital RIDE Algorithm in Microsoft Excel. The results of the comparison between the two are detailed in the following sections.

IDEAS in Excel: Digital vs. Continuous: Well Insulated Home

Well Insulated Design Parameters:

Table T.1 - Well Insulated Design Parameters for IDEAS Digital vs. Continuous Match

Heat Loss Inputs	U – Value (W/m²K)
Walls (excluding openings)	0.3
Floor	0.2
Roof	0.13
Doors	0.22
Windows	1.5

Free Heat Gains and Outdoor Temperature:

Matched in IDEAS Continuous Model, IDEAS Continuous Model and BREDEM

2009 for benchmarking exercise:

- Total Internal Gains

- Solar

- Metabolic

- Appliances

- Climate Data for Temperature

IDEAS Continuous and Digital RIDE 3rd Order Model Output - Temperature:

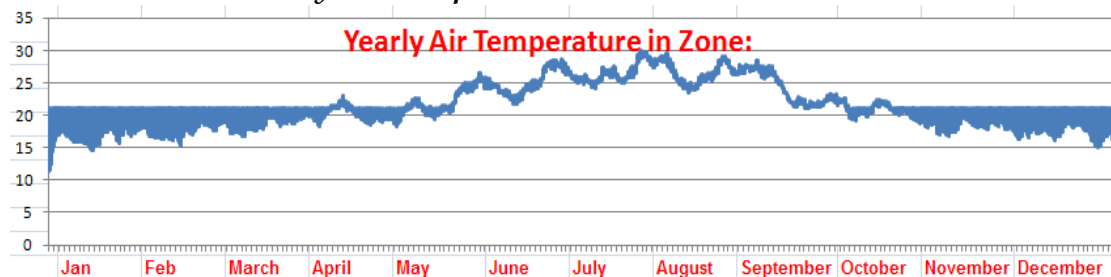*CONTINUOUS: Yearly Air Temperature in Zone:*

Figure T.8 - Continuous RIDE in Microsoft Excel – Yearly Air Temperatures in Dwelling

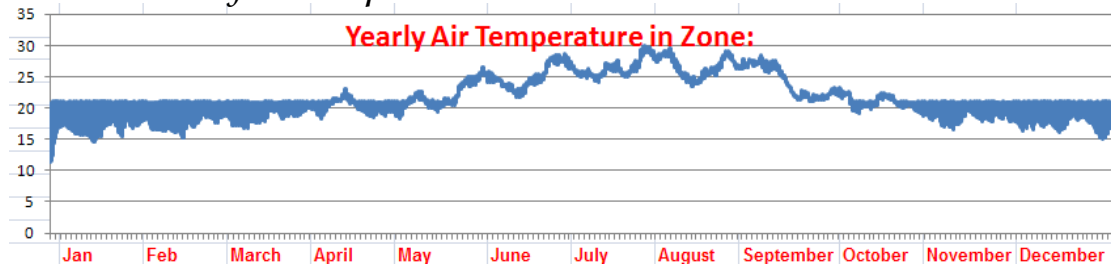*DIGITAL: Yearly Air Temperature in Zone:*

Figure T.9 - DIGITAL RIDE in Microsoft Excel – Yearly Air Temperatures in Dwelling

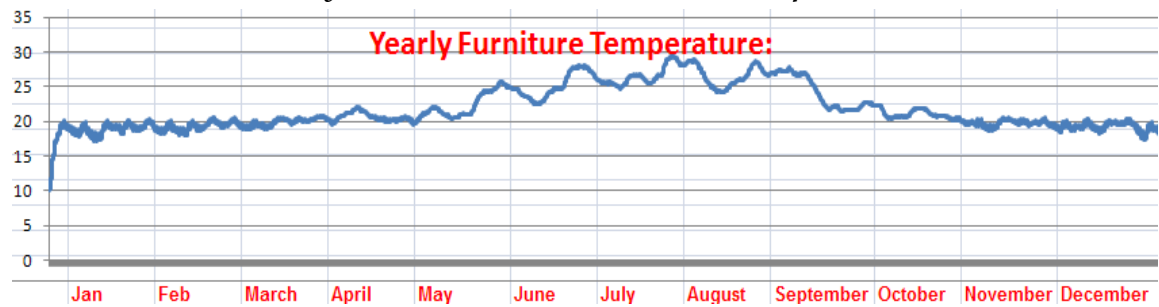## CONTINUOUS: *Yearly Furniture & Internal Mass Temperature:*

Figure T.10 - Continuous RIDE in Microsoft Excel – Yearly Furniture and Internal Mass Temperature in Dwelling

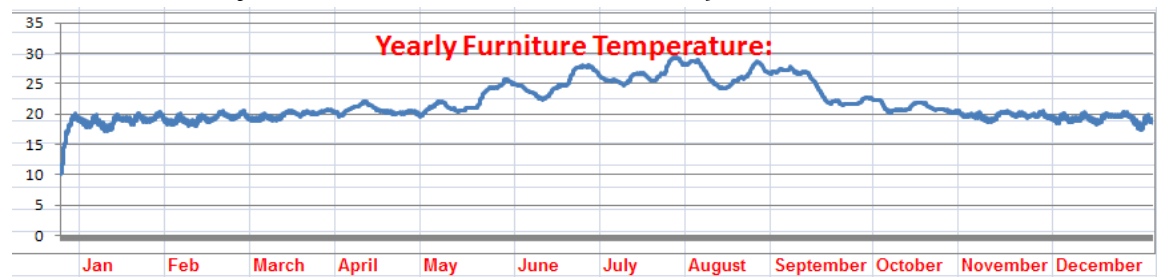## DIGITAL: *Yearly Furniture & Internal Mass Temperature:*

Figure T.11 – Digital RIDE in Microsoft Excel – Yearly Furniture and Internal Mass Temperature in Dwelling

CONTINUOUS: *Yearly Structure Temperature:*
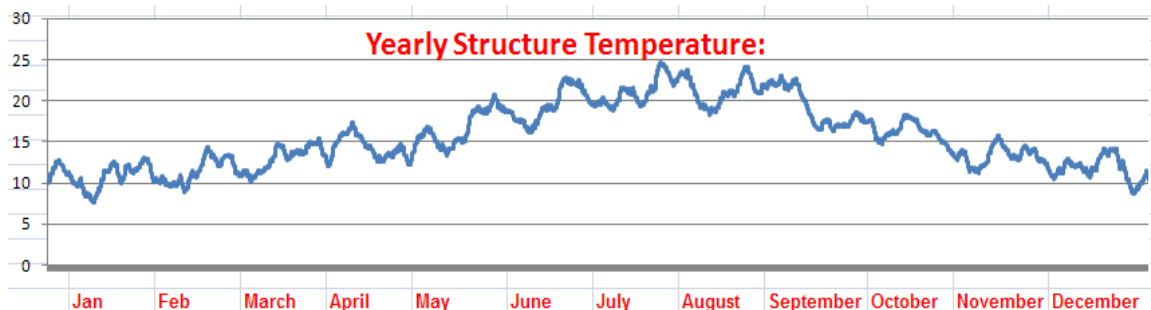

Figure T.12 - Continuous RIDE in Microsoft Excel – Yearly Structure Temperature in Dwelling

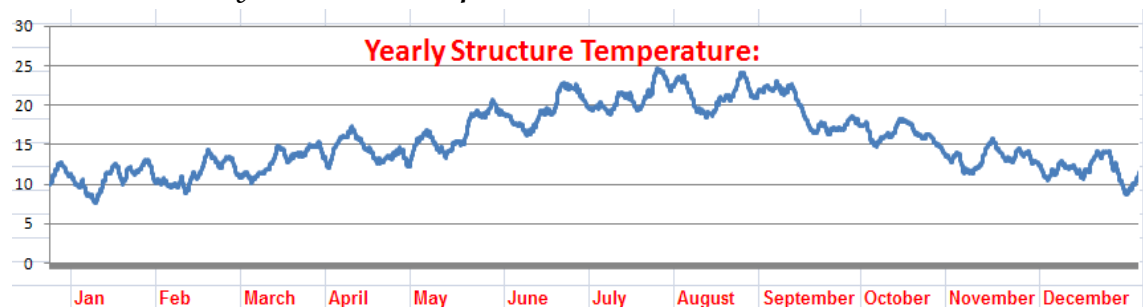## DIGITAL: *Yearly Structure Temperature:*

Figure T.13 - Digital RIDE in Microsoft Excel – Yearly Structure Temperature in Dwelling

IDEAS Continuous and Digital RIDE 3rd Order Models Output

Energy Consumption
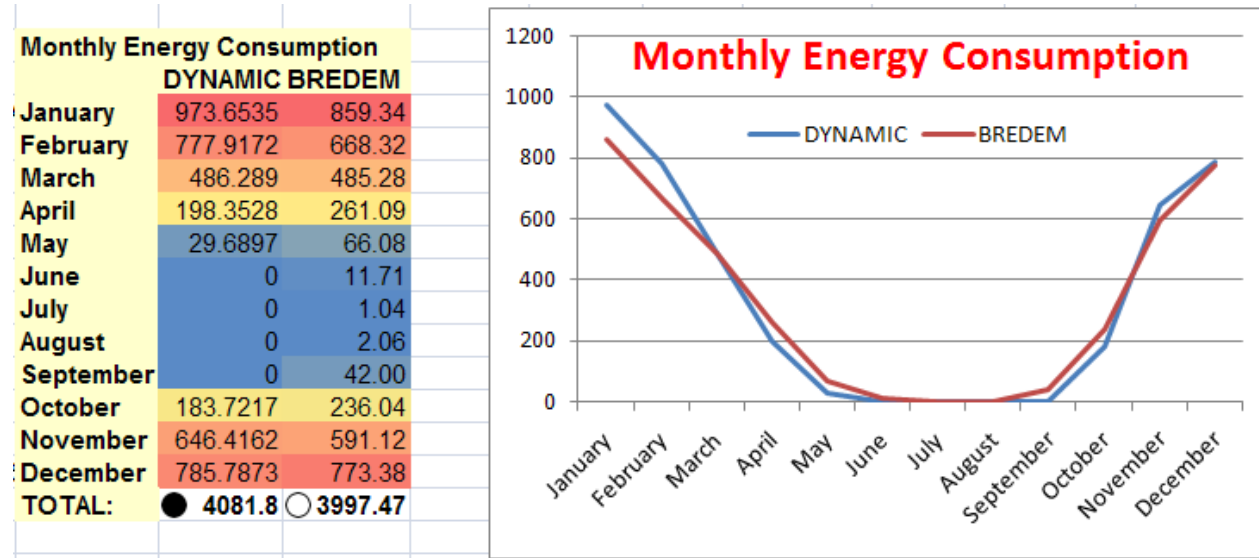
IDEAS CONTINUOUS Monthly Energy Consumption vs. BREDEM:

Monthly Energy Consumption	DYNAMIC	BREDEM
January	973.6535	859.34
February	777.9172	668.32
March	486.289	485.28
April	198.3528	261.09
May	29.6897	66.08
June	0	11.71
July	0	1.04
August	0	2.06
September	0	42.00
October	183.7217	236.04
November	646.4162	591.12
December	785.7873	773.38
TOTAL:	● 4081.8	○ 3997.47

Figure T.14 - IDEAS continuous Monthly Energy Consumption vs. BREDEM

IDEAS DIGITAL Monthly Energy Consumption vs. BREDEM:

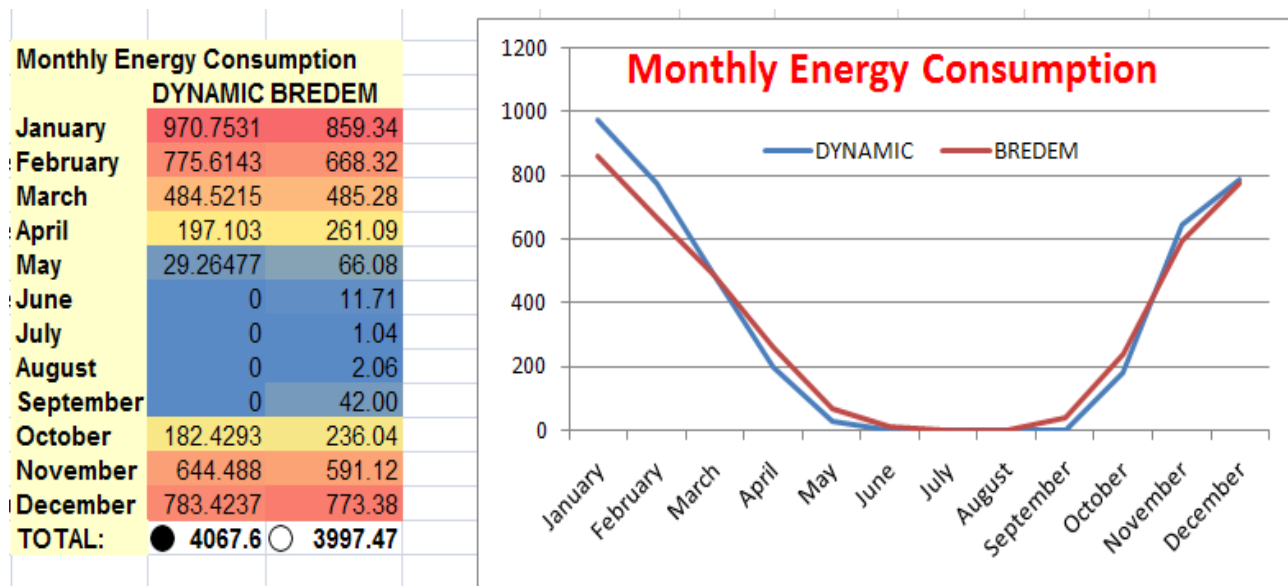| Monthly Energy Consumption	DYNAMIC	BREDEM
January	970.7531	859.34
February	775.6143	668.32
March	484.5215	485.28
April	197.103	261.09
May	29.26477	66.08
June	0	11.71
July	0	1.04
August	0	2.06
September	0	42.00
October	182.4293	236.04
November	644.488	591.12
December	783.4237	773.38
TOTAL:	● 4067.6	○ 3997.47

Figure T.15 - - IDEAS Digital Monthly Energy Consumption vs. BREDEM

Monthly Temperature

IDEAS CONTINUOUS Monthly Temperature vs. BREDEM:
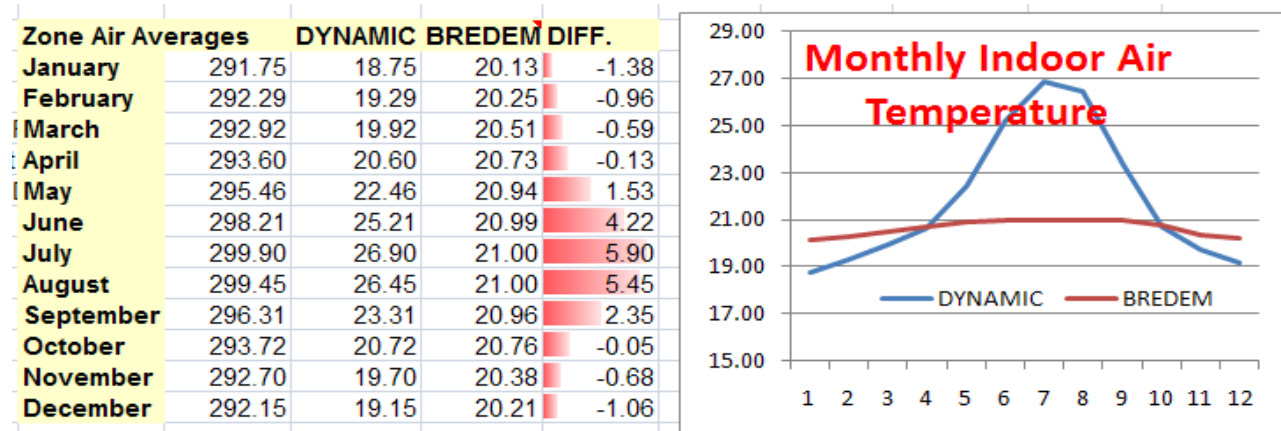
Zone Air Averages	DYNAMIC	BREDEM	DIFF.
January	291.75	18.75	20.13	-1.38
February	292.29	19.29	20.25	-0.96
March	292.92	19.92	20.51	-0.59
April	293.60	20.60	20.73	-0.13
May	295.46	22.46	20.94	1.53
June	298.21	25.21	20.99	4.22
July	299.90	26.90	21.00	5.90
August	299.45	26.45	21.00	5.45
September	296.31	23.31	20.96	2.35
October	293.72	20.72	20.76	-0.05
November	292.70	19.70	20.38	-0.68
December	292.15	19.15	20.21	-1.06

Figure T.16 - IDEAS Continuous Monthly Temperature vs. BREDEM

IDEAS DIGITAL Monthly Temperature vs. BREDEM:

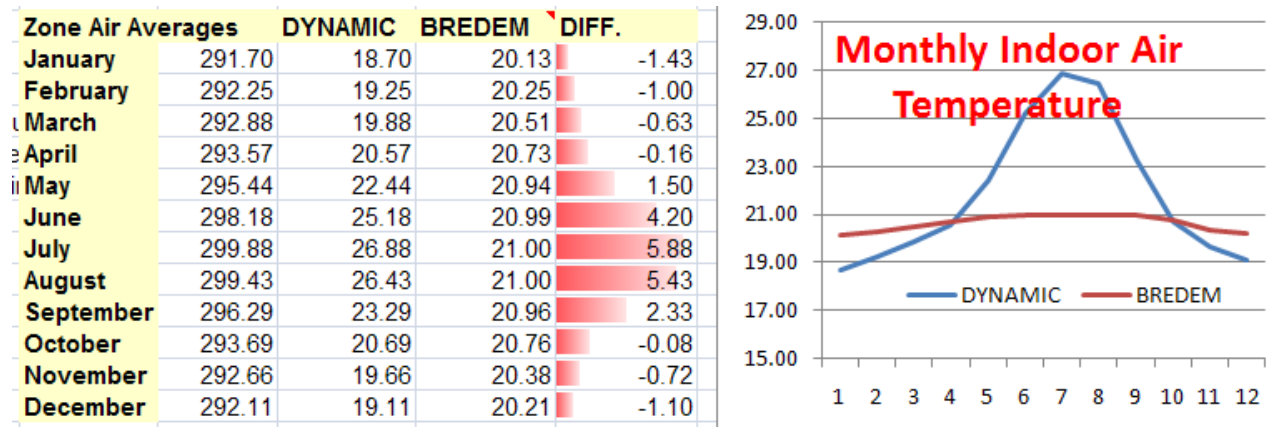| Zone Air Averages	DYNAMIC	BREDEM	DIFF.
January	291.70	18.70	20.13	-1.43
February	292.25	19.25	20.25	-1.00
March	292.88	19.88	20.51	-0.63
April	293.57	20.57	20.73	-0.16
May	295.44	22.44	20.94	1.50
June	298.18	25.18	20.99	4.20
July	299.88	26.88	21.00	5.88
August	299.43	26.43	21.00	5.43
September	296.29	23.29	20.96	2.33
October	293.69	20.69	20.76	-0.08
November	292.66	19.66	20.38	-0.72
December	292.11	19.11	20.21	-1.10

Figure T.17 - IDEAS Digital Monthly Temperature vs. BREDEM

Digital vs. Continuous: Poorly Insulated Home

Poorly Insulated Design Parameters:

Table T.2 - Poorly Insulated Design Parameters

Heat Loss Inputs	U – Value (W/m²K)
Walls (excluding openings)	2.1
Floor	2.3
Roof	0.7
Doors	2.0
Windows	5

IDEAS Model Output - Temperature:

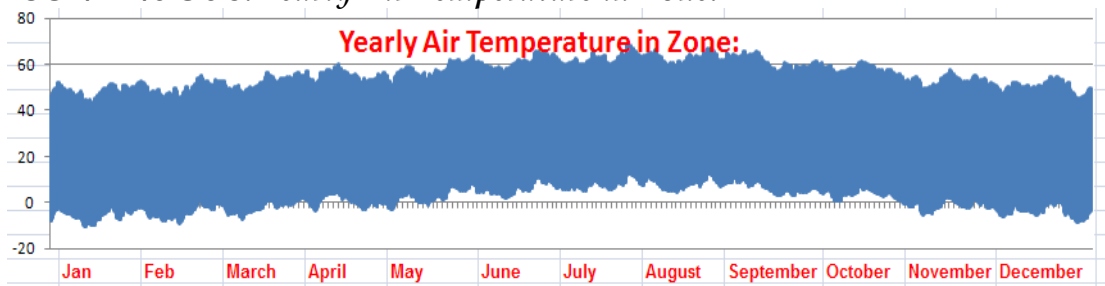*CONTINUOUS: Yearly Air Temperature in Zone:*

Figure T.18 - IDEAS Continuous Yearly Air Temperature – <u>Instability Apparent</u>

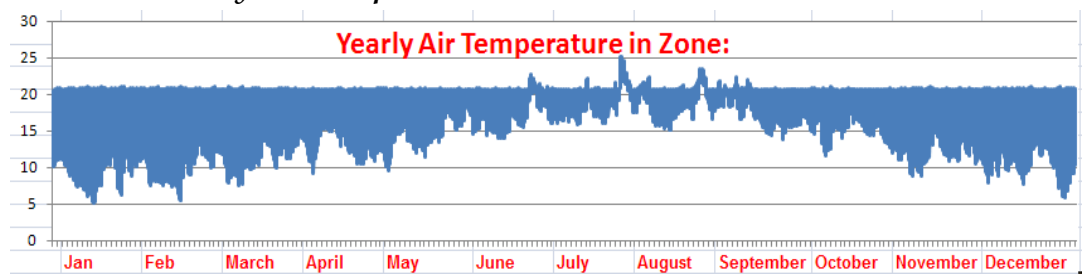*DIGITAL: Yearly Air Temperature in Zone:*

Figure T.19 - IDEAS Continuous Yearly Air Temperature – <u>No Instability Apparent</u>
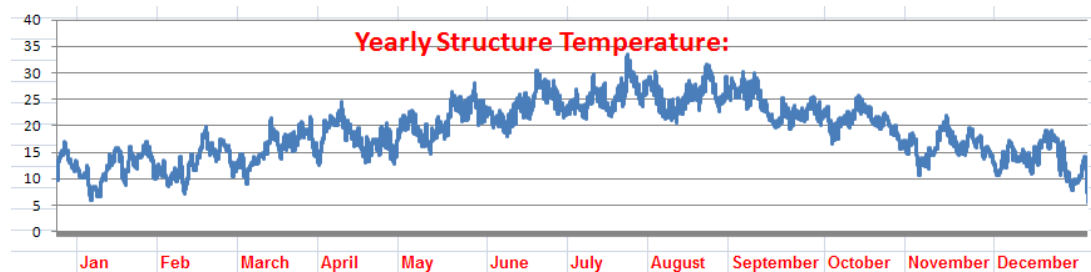
CONTINUOUS: Yearly Furniture Temperature:

Figure T.20 - IDEAS Continuous Yearly Furniture & Internal Mass Temperature
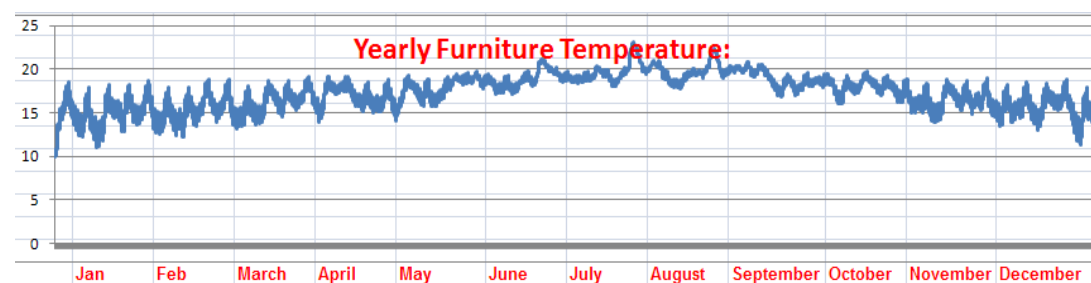
DIGITAL: Yearly Furniture Temperature:

Figure T.21 - IDEAS Continuous Yearly Furniture & Internal Mass Temperature

CONTINUOUS: Yearly Structure Temperature:
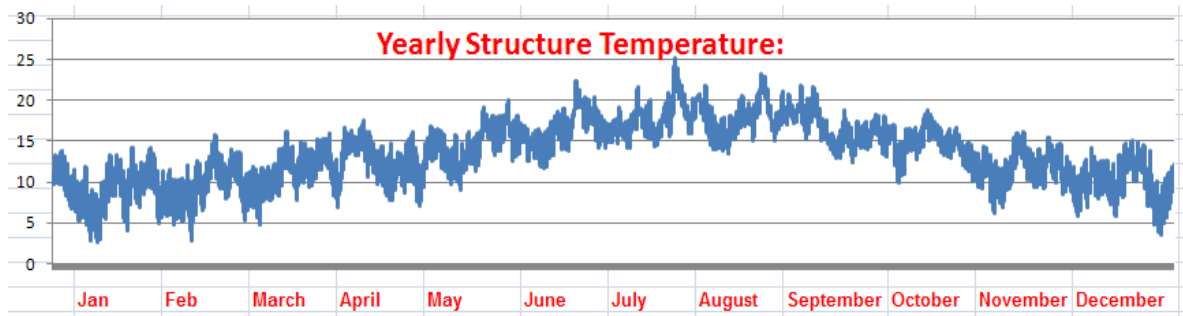

Figure T.22 - IDEAS Continuous Yearly Structure Temperature
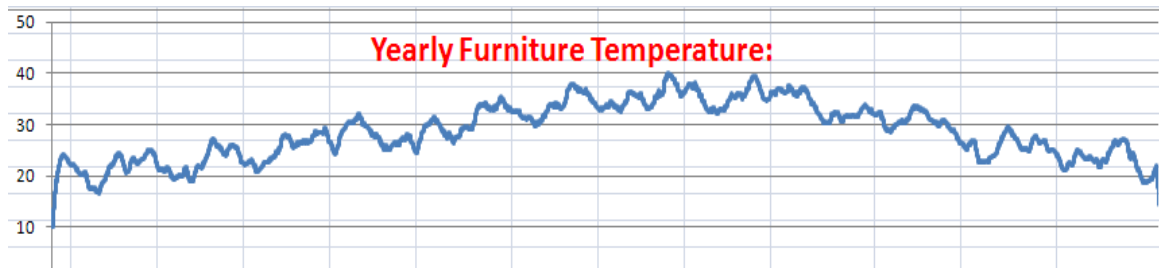
DIGITAL: Yearly Structure Temperature:

Figure T.23 - IDEAS Continuous Yearly Structure Temperature

Conclusion

Instabilities were found with the continuous RIDE control algorithm and methodology when implemented in Excel at a 5 minute time resolution. The instabilities are demonstrated in the figures above when continuous RIDE IDEAS is used to model a dwelling with specific U-Values (see Table T.2). A digital RIDE control algorithm and methodology was required. Digital equivalent matrices were constructed based upon the continuous matrices. A digital RIDE algorithm was then employed. The continuous and digital IDEAS versions were compared to each other and to BREDEM, producing favourable results. The move to digital RIDE now allowed any U-Values to be modelled in Excel at a 5 minute time resolution, with the production of no instability. This can be demonstrated by comparing figures T.18 and T.19.

Fin.