DEVELOPING A SYSTEM DYNAMICS BASED BUILDING PERFORMANCE SIMULATION MODEL – SdSAP to ASSIST RETROFITTING DECISION MAKING

Yangang Xing, Simon Lannon, Malcolm Eames
Low Carbon Research Institute at Welsh School of Architecture, Cardiff University
YXing@Cardiff.ac.uk, xygnet@hotmail.co.uk

ABSTRACT

Retrofitting our current building stock is a vital part of meeting emissions reductions targets, using energy in a more efficient way and creating sustainable lifestyles. However, one of the key barriers identified is a lack of tools to support making retrofitting decisions. In this paper, the creation of a transparent and flexible building energy performance simulation model - SdSAP is reported to assist building owners and investors to make better informed decisions in building retrofitting activities. A case study is provided to demonstrate the benefits of using the SdSAP tool.

INTRODUCTION

The retrofit of buildings has important potential socio-economic impacts, such as reducing energy use, carbon emission and fuel poverty. In the UK recent Government policy has focused upon the development of market mechanisms to incentivise the up take of low carbon building retrofit through its 'flag ship' energy efficiency policy the Green Deal (DECC 2012). The Green Deal is intended to provide householders and businesses with the opportunity to install a wide range of energy efficiency measures at no upfront cost. Instead cost of the measures, with interest charges, are paid for through a levy on the property owner's utility bills over a 25 year period. The scheme's 'Golden Rule' requires that the expected financial savings from installed measures must equal or exceed the cost of repayment over the period of the deal. Nevertheless, to predict future energy end use and cost savings is a very complicated phenomenon. A number of uncertain long term social economic factors might have significant influence over future building energy uses. Building performance and energy savings estimations that can be trusted are therefore central to the successful implementation of market-based incentive schemes such as the Green Deal. However, there is a lack of tools to investigate real impacts of building retrofit when many uncertain factors need to be considered, for example, lifestyles changes, future fuel costs, uncertain weather conditions and future climates.

Conventional simulation is not adequate for this purpose. In this paper, a system dynamics modelling approach is developed using a simulation tool - Vensim® (Ventana 2013) - to analyze building performance. Vensim is a simulation software tool emphasizing connections to data, flexible distribution, instant output with continuous simulation, user friendly graphical interface for model analysis incluing optimizaiton and Monte Carlo simulation. The Vensim-based SdSAP model can be constructed and edited graphically. This model provides a framework for energy users, financers, utilities, energy service companies (ESCOs) and policy makers to carry out more realistic estimations of future energy, cost and carbon emissions savings.

As a simplified building performance predictions tool – SAP (Anderson 2001) is the most commonly used tools to assess performance of domestic buildings in UK. There has been research carried out to investigate the limitations of SAP (Kelly, Crawford-Brown and Pollitt 2012) and how to further improve it (Murphy et al. 2011). Nevertheless, SAP is a generic rating tool; it is used on an individual building to assist owners of the building and contractors in decision makings. The SdSAP model has been created to improve its usability and flexibility to model performance of domestic buildings.

The paper is structured as follows. First, the background to building retrofitting in the UK is briefly introduced. Then the authors' examine building performance programs; especially the SAP for the purpose of this research. The SdSAP model and an analytical process is presented, in section 4. A case study is carried out. Based on simulation results derived from SdSAP, the authors comment on the great uncertainty that can occur with retrofitting actions and usefulness of the SdSAP tool. The final section summarises the usefulness and limitations of the tool SdSAP tool, and how it may be improved.

A BRIEF OVERVIEW OF POLICY INCENTIVES FOR BUILDING RETROFITTING IN THE UK

Building retrofitting is a capital intensive activity. As such policy incentives are essential in improving uptake rates. In the UK, a number of policy measures have been taken to improve the insulations levels, e.g. through Government schemes including Carbon Emissions Reduction Target (CERT), the Community Energy Saving Programme (CESP) and Warm Front (Ofgem 2012). It is estimated that at the start of April 2012, there were 26.7 million homes in Great Britain. Of these 23.4 million have lofts, 19.0 million have cavity walls and some 7.8 million have solid walls (DECC 2012). In those homes, only 14.5 million homes had loft insulation of at least 125mm – 62% of homes with lofts; 11.4 million homes had cavity wall insulation – 60% of homes with cavity walls), and 128,000 homes had solid wall insulation – only 2% of homes with solid walls.

Research has demonstrated that household energy use and associated carbon emissions are both strongly, but not solely, related to income levels. For example the poorest 10% of households use, on average, only 43% of the energy used by the richest 10% of households. Other factors, such as the type of dwelling, tenure, household composition and rural/urban location are also extremely important (Druckman and Jackson 2008).

In the UK previous policy measures (CERT, CESP or Warm Front) were mostly targeted at the public housing sector. However, The Energy Act 2011 (DECC 2011) includes provisions for the 'Green Deal', a new finance framework to enable the provision of improvements to the energy efficiency of private households and non-domestic properties. In the Green Deal, retrofitting activities will be funded by a charge on energy bills that avoids the need for consumers to pay upfront costs. The Act also includes provisions to ensure that from April 2016, private residential landlords will be unable to refuse a tenant's reasonable request for consent to energy efficiency improvements where a finance package, such as the Green Deal and/or the Energy Company Obligation (ECO), is available. Provisions in the Act also provide for powers to ensure that from April 2018, it will be unlawful to rent out a residential or business premise that does not reach a minimum energy efficiency standard (the intention is for this to be set at EPC rating 'E'). The Green Deal financial mechanism eliminates the need to pay upfront for energy efficiency measures and instead is supposed to provide reassurances that the cost of the measures should be covered by savings on the electricity bill. A new Energy Company Obligation is also supposed to integrate with the Green Deal to enable supplier subsidy and Green Deal Finance to come together into a single offer to the consumer.

BUILDING SIMULATION AND SAP

It has been noted that one of the most frequent criticisms of simulation capabilities found in the literature is the lack of consideration for human behaviour and its feedback in simulation programs (Zimmermann, 2006; Crawley et al., 2008; Malkawi, 2004).

Building Performance Simulations (BPS) tools have been developed in order to help architects and researchers to evaluate energy performance of buildings. BPS tools are becoming increasingly advanced, incorporating components from different engineering disciplines, such as lighting, glazing, HVAC services systems, and hydrothermal performances. Much effort has been spent on increasing their prediction accuracy; however some of the limitations are due to the complexity and uncertainties, such as human behaviour (Khotanzad et al., 1995; Mahdavi et al., 2001). Furthermore, ever increasing complexity of the BPS has limited its potential in assisting strategic planning for building design and retrofitting. Logistical limitations due to computational power and data storage have also been noticed (Somaranthne et al., 2005).

SAP is a simplified building physics model and is developed based on Building Research Establishment Domestic Energy Model-12 (Anderson 2001). SAP uses a 2 zone model as defined in BREDEM, with zone 1 being the living area of the home and zone 2 being the bedrooms and rest of house. By default, the heating set points for the two zones are 21°C and 18°C respectively. BREDEM defines two heating profiles, one for weekdays and one for weekends. The BREDEM /

SAP methodology has been validated empirically with favourable comparison found between BREDEM / SAP and real measured data (Shorrock and Dunster 1997).

METHODOLOGY

In order to carry out holistic analyses of building performance to assist decision making on building retrofit, an iterative analytical process (figure 1) can be followed by using the SdSAP model. In the first step (with the solid lines), operation of the building is being surveyed and monitored and with the help of the SdSAP the future performance of building is estimated. In the second step (with the dash lines), the simulation results can be used for two purposes:

1. to provide information to the occupiers of the building to influence behavioural changes (e.g. change of heating set point, heating areas, or retrofitting actions);
2. to provide diagnostic tool with information to the modellers to improve the building models in order to provide better estimations;

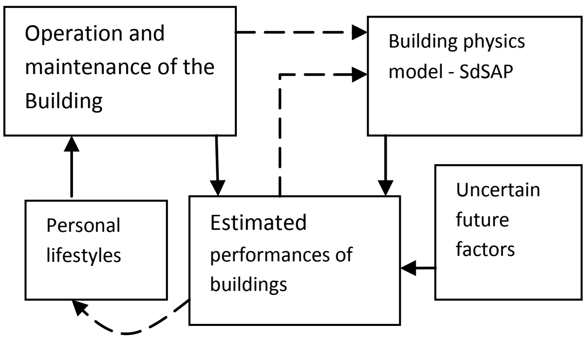

Figure 1. An iterative process to predict energy performance using SdSAP

The SdSAP model is a building physics-based buildings performance predictions tool, which has been developed using a system dynamics methodology. System dynamics is a holistic approach for investigating interactions of linked components over long term horizon (Forrester, Mass and Ryan 1976, Meadows 1972). The system dynamics method has been used in a wide variety of applications, both in the social sciences and in engineering, for examples for building evacuations (Thompson and Bank 2010), urban planning (Yates and Bishop 1998, Fang et al. 2005), island tourism infrastructure planning (Xing and Dangerfield 2010) , hydrological systems modelling (Khan, Luo and Ahmad 2009), and community energy planning (Xing, Hewitt and Griffiths 2010).

The schematic view of the SdSAP model is presented in figure 2. It consists of a set of interlocking differential algebraic equations developed from a broad spectrum of measured field data or experiential estimations based on SAP 2009 (SAP 2009). Unlike other commercial blackbox models, the SdSAP model and user interface are together referenced as a "micorworld" in which the user can interact with a model in a gaming mode to run multiple scenarios. A graphical interface is used to change parameters, such as heating set points, heating periods, fuel costs and weather data in the equation editor pop-out window (figure 3) just by double clicking on the variables. It is easy to use, transparent, flexible to allow for the creation of alternative future scenarios. Highly visual aids can be provided in this model to understand the structure of the model, such in figure 4, the causal relationships for useful gains and figure 5, the strip graphs for heat loss coefficient and heat losses.

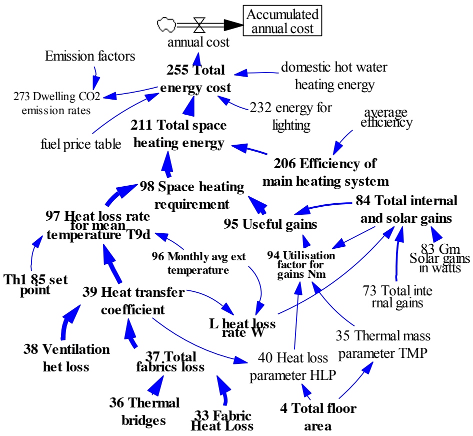

Figure 2: A schematic view of the SdSAP model

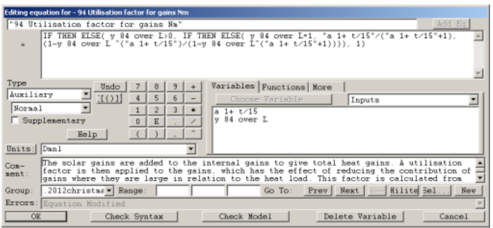

Figure 3: Equation editor

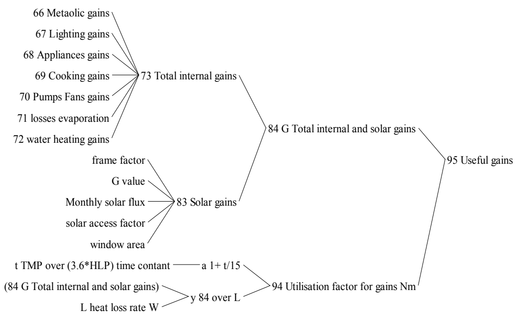

Figure 4: Causal relationship diagram for useful heat gains

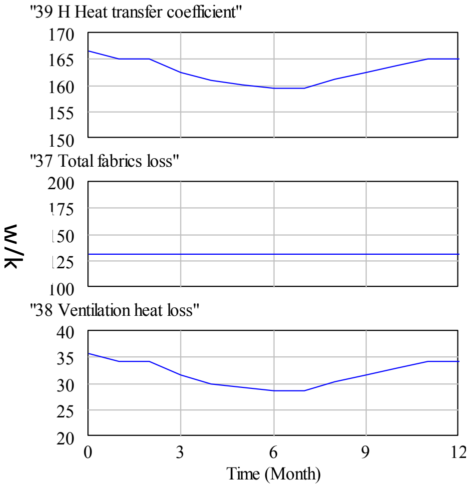

Figure 5: Heat Transfer Coefficient and co-related parameter at set point 22°C in Vensim strip graph

A CASE STUDY

Base scenario – Validation against conventional SAP calculation

A brief review of housing topology in the UK can be found in the paper (Xing, Hewitt and Griffiths 2011). In this research, a typical 1980s UK end terrace house (figure 6) is investigated as a case study. The house is owned by a registered social landlord. The house is located in South Wales, United Kingdom. It is a small two storey house (59.3 m^2 in total) with two bedrooms and a garden. It had un-insulated brick-block cavity walls, concrete slab floor, tile timers truss roof, loft insulation in poor conditions, double glazed windows and gas central heating. Performance of the house is modelled the SdSAP (whole system view in figure 7) which was validated against conventional SAP calculations based on BuildDesk Energy Design® 3.4.2 incorporating SAP 2005 version 9.81 dated January 2008. The base energy consumption is estimated around 9129 kWh/year, with heat losses parameter of 2.760 w/m^2k.

Figure 6: The case study house

In figure 7, the syntheSim view, it can be seen that the SdSAP can be run with considerable interactivity. Changes made (either in the equation editor view on the top left of the view or in graphical sliding bars.) to the model will cause the model to be re-run and simulation results is shown automatically. In SdSAP, the structure and equations can be made available for inspection by non-technical users. This allows model users to investigate in details about the assumptions underlying the model, improving acceptance and preventing the spread of misunderstanding relating to the energy performance predictions.

As learning is considered as an essential goal in building performance simulation by the authors, the highly interactive learning environment (as a workbench-toolbox) created in SdSAP will improve effectiveness in the learning process. It allows users to switch easily between structure, assumptions, available data and predicted results and acquire much better understanding of how those factors interact.

Impacts of variations in future weather conditions and rising fuel costs

Research demonstrates the importance in incorporating climate change, room temperature setting, and energy prices scenarios in helping building owners to understand future building energy costs (de Wilde and Tian 2012) and a case study based in Boston, USA is carried using a dynamic simulation tool (Holmes and Reinhart 2011). In this research, simplified method SdSAP is used to investigate the impacts in variations in future weather conditions, temperature setting, and rising fuel costs in the UK context. Three sets of weather scenarios are investigated, which include 30 years average whether data from (SAP 2009); future weather by 2050 (Eames, Kershaw and Coley 2011), and past weather in UK 1970 to 2012 (DECC 2012) .

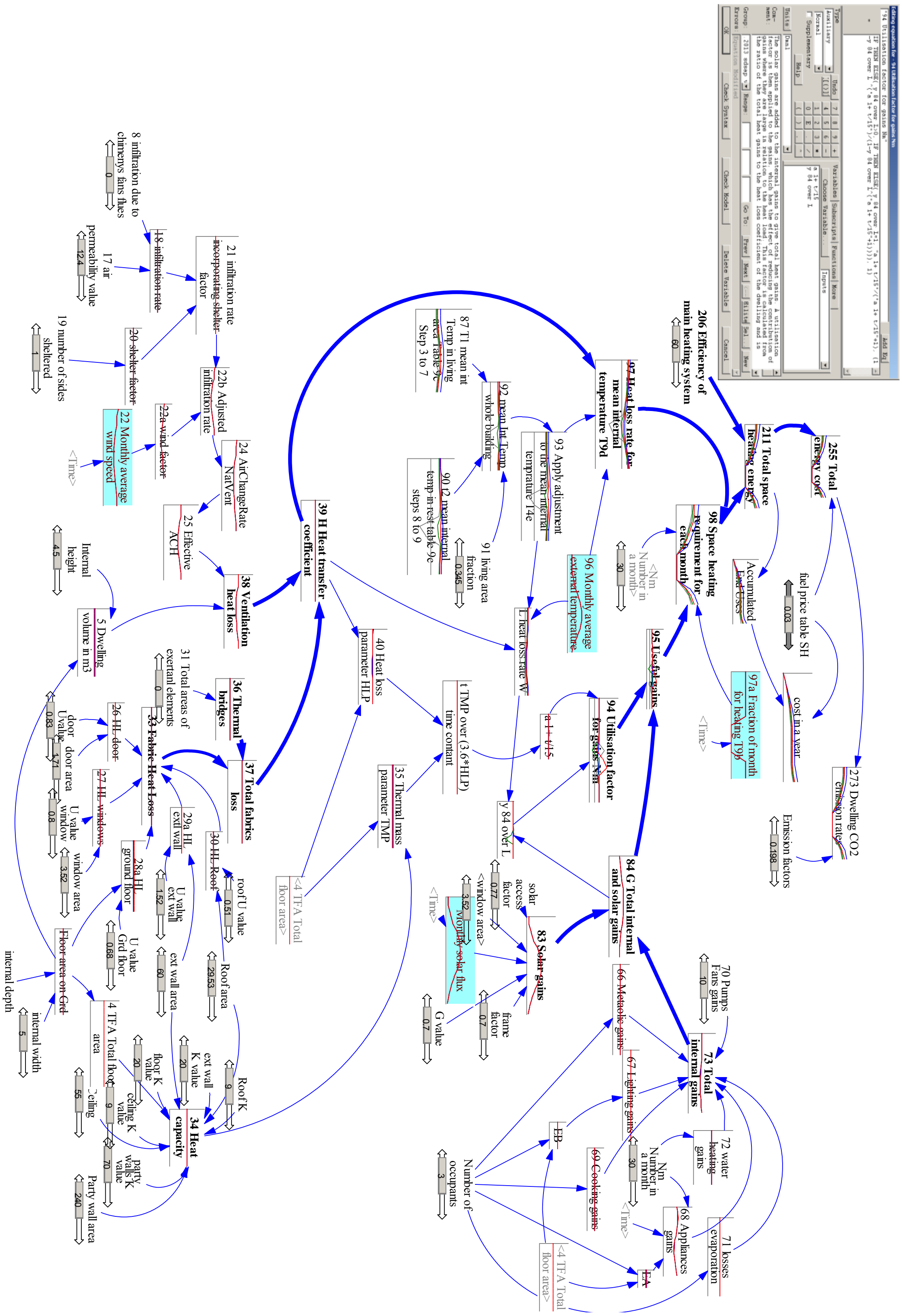

Figure 7: Simulation view of the Whole model view of SdSAP

The total energy cost (with 22 Celsius degree as heating set point) in the coldest year 2010 is 14% more than that of using the typical design year which is the averaged over the past thirty years (SAP 2009). On the other hand, future space heating energy demand can be reduced by 26% if using 2050 the 50% percentile warm year scenarios (figure 8). It is estimated that in the UK, domestic energy bills will increase by between 13% and 26% by 2020 (from 2009 levels) – with the possibility that wholesale price spikes could lead to an increase in domestic energy costs (ofgem 2010). A similar magnitude of increase in fuel prices in the USA and potential impacts on buildings in Boston were investigated (Holmes and Reinhart 2011). In this paper, a 50% increase in fuel costs (red column in figure 10) demonstrate final space energy costs will increase despite warmer climates.

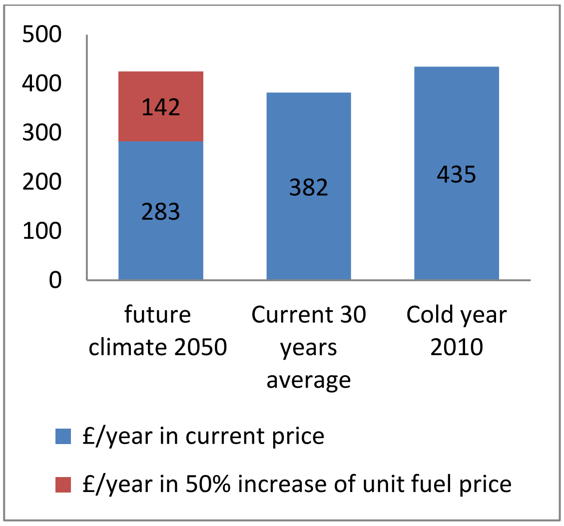

Figure 8: Impacts of weather uncertainty on space heating costs

Impacts of Lifestyle changes

Apart from weather conditions and future fuel prices, there are a number of other factors contributing to an increase in total energy consumptions in buildings. For example, current 'acceptable' level of comfort temperatures combining with increasing heated floor area per capita, which are thought to have risen substantially over the last few decades,. Demand side approaches and lifestyles changes are becoming increasingly important to retrofitting buildings to zero carbon standards (Xing et al. 2011, Lenoir et al. 2011, Tanimoto et al. 2011).

In this paper, we investigate impacts of the following aspects of lifestyles changes: changes in heating set points and changes in heated floor areas.

Based on SdSAP, total space heating energy costs can be estimated by changing heating set points from 20 to 25 Celsius degrees (figure 9). It can be seen that space heating costs can be reduced by £174 (35% reduction) in this house at current fuel price, if the heating set point is reduced from 25^{o}C to 20^{o}C.

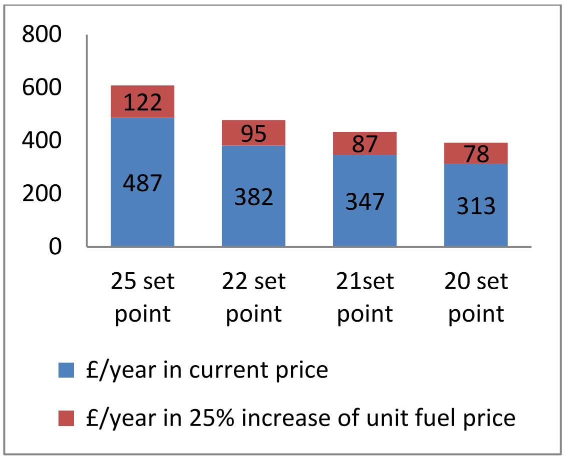

Figure 9: Impacts of heating set points on space heating energy costs

With a future increase of 25% in fuel costs by 2020 (ofgem 2010), if the heating set points adjust to 20^{o}C, the space heating costs will still be less than the space heating costs at 25^{o}C at current fuel price. This diagram can help the owner of the building to choose heating set points accordingly. More radical changes in the life style are presented in the following paragraph by changing heated areas.

It is argued that there is a limitation in central heating systems, which are widely used in the UK today. Central heating has led to the whole house being heated for longer periods, rather than only heating rooms as they were being uses. A number of technologies are explored to reduced space heating energy demand by more manual control of heating and raise or lower on a room by room basis depending on occupancy. In the SdSAP model, we present simulation results showing impacts of smaller volume of heated space on heat energy demand reductions. Initial simulation results (as shown in figure 10) demonstrates the impacts of dramatically changes in heating areas volumes (to one room or one floor only of the existing building) on space heating energy costs - future £235 can be saved in current fuel price scenario.

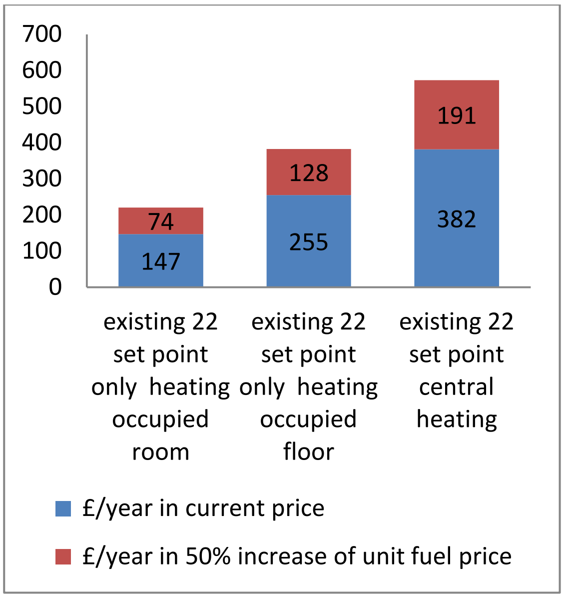

Figure 10: impacts of reducing heating areas on space heating energy costs

CONCLUSIONS

To predict real building energy performance involves many factors. Assessing real costs saving and making investment in retrofitting actions is complicated undertaking. There is a lack of tools to help green deal analysis. SAP is more of a generic rating tool; a more flexible tool is required to deal with individual building, and to assist owners of the building and contractors in decision makings.

Based on BREDEM-12, a system dynamics – based model SdSAP was created to model building performance. The SdSAP is validated against the conventional SAP tool and improved through the a provision of more transparent approach and more flexible control over the inputs. SdSAP can help the users and modellers to investigate energy consumption variations and potential cost savings.

In this paper, uncertainty in energy demand reduction and cost saving are investigated. Based on the case study, it has demonstrated, life styles changes have significant impacts. As with many other types of modelling techniques, if used appropriately, are powerful conceptual aids. However, misapplied they can be more distorting. The model developers and users must be aware of and open about methodological limitations of the tools.

The SdSAP can be further developed by linking social economic feedback loops to investigate interactions of different factors (such as fuel price, fuel poverty, future climate and buildings) over long term. SdSAP can be easily scaled to a neighbourhood or urban size with additional building stock data. This will be dealt with in another subsequent paper.

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http://www.retrofit2050.org.uk/
http://www.lcri.org.uk/
http://www.cardiff.ac.uk/archi/

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