Housing Energy consumption, Social behaviour and Carbon dioxide emissions: A holistic model

Karla Alcantar-Sanchez, Keith Tovey and Andrew Lovett

PhD Student School of Environmental Sciences, University of East Anglia, Norwich, UK

Abstract

Carbon dioxide (CO_2) in the domestic sector is emitted indirectly as a result of energy use. In order to reduce the impacts it is important to determine reliable baseline information against which improvements may be measured. Energy surveys in the UK have traditionally involved an appraisal using the Standard Assessment Procedure (SAP) rating to derive a Target Emissions Ratio (TER). However, such assessments are data intensive as measurements are needed for each property separately. The procedure reported in this paper overcomes this limitation by invoking data reduction techniques, including GIS methods, high-resolution photos and relevant housing survey condition data. To validate the model (Prometheus), energy readings were taken and survey questionnaires were issued to ascertain social attitudes and behaviour. Overall there is good agreement with the predictions and average consumption data, but a wide variation in actual consumption exists for an individual property because of social behavioural patterns.

The project required the development of new computer models and algorithms which incorporate not only the physical condition, but also social behavioural drivers which affect energy consumption and carbon emissions. Finally, the holistic model will provide a robust tool for planners and local authorities to support decisions, report, monitor and improve the energy efficiency. Though the techniques were developed in Norwich, the methods are sufficiently robust for them to be used in other areas within the UK. In addition, they should allow the changes over the time to be visualised and explore the most effective ways to reduce carbon emissions.

Keywords: energy consumption; carbon dioxide emissions; social behaviour.

Introduction

Energy is a necessity for all societies and over the next few decades all countries will have to come to terms with issues of energy security and the impacts energy use has on climate change. Around 70% of the primary energy supply in a country such as the UK occurs in buildings, businesses, industry, and for travelling with the remainder associated with energy conversion and transmission losses. About 31% the final energy used in the UK is used in the domestic sector. Therefore, action is needed to limit the energy consumption in buildings (Department of Trade and Industry, 2005)

Domestic energy consumption represents one area where the links between global environmental problems and individual behaviour are clearly identifiable, even if people do not immediately recognize the connection. Therefore, energy conservation in buildings plays an important role in urban environmental sustainability (Hui, 2001)

The interest in the assessment of energy performance of households is generated by reducing carbon dioxide emissions, providing advice to the consumers, energy labelling of houses and assessing affordable warmth (Boardman *et al.*, 2005; NEA, 2007). Based on this necessity a new energy consumption model has been developed in this research. Known as the Prometheus Model (PROcess Model Emissions Tool for Household Energy Usage Simulation), it provides a holistic approach based around an integrated suite of GIS (Geographic Information System) and Visual Basic programmes. It not only provides the capability of estimating house energy consumption and CO_2 emissions but also provides a means to analyse the impact of social variables on the estimation in overall energy consumption. The predicted consumption was compared with data from actual houses in Norwich when good agreement between the predicted and actual energy consumption was achieved. However, the range in consumption from one household to another is large. Finally, the model can be used as a basis to suggest better end-uses of energy considered as one of the most effective ways to reduce energy consumption in the domestic sector and associated pollutant emissions (Fung *et al.*, 2001)

Energy and CO_2 Emission Models

In the UK there are several models which estimate the energy use in the domestic sector, such as: The UK Domestic Carbon Model (UKDCM) (Boardman et al., 2005), the National Home Energy Rating (NHER-Software) (NHER, 2005) and the Domestic Energy, Carbon Counting and Carbon Reduction model (DECoRuM) developed by Oxford Brookes University in 2006. These models are based on a number of different approaches and offer a variety of applications and have been developed in a number of academic and government departments.

The main problem in energy models is the data collection and each of them address the problem in a different way. The Solar Energy Planning (SEP) and the National Home Energy Rating (NHER-software) are the only ones that allow the energy use to be predicted by different levels of input data. The rest of the models typically require up to 60 data items for data input per house which has considerable resource implications in terms of time and personnel (NHER, 2005). In the worst case, in the high-level version of the NHER-software, no fewer than 250 data items are needed for input of each house.

The Prometheus model approaches the problem from the need to reduce the number of input variables and focuses on new data reduction techniques such as the use of Geographical Information Systems (GIS) to extract much of the architectural dimensions and ascertain ways to support possible default values in an iterative way in order to develop new series of databases. While a GIS approach is also used in the Energy and Environmental Prediction Model (EEP) and SEP models it is only included to display the results in order to highlight the houses according to different ranges of outputs. On the contrary in this research, GIS methods are used as a data reduction technique not only to assess heat losses directly but also display outputs in easy way to understand by the householders and decision makers.

The present work focuses on a holistic study to analyze the relationship between the energy consumption and its social drivers, together with the development of a computer model to determine the values of energy consumption, consequential carbon dioxide emissions and environmental behaviour factors, and through an analysis of a representative questionnaires backed up by validation data to determine the main drivers and interlink them into a final holistic model simulating both technical and social issues.

In the model, an interaction of software tools consists of a collection of software modules, with the main idea to make a system easy to understand, in the sense that people do not have to interact with the system in any laborious manner.

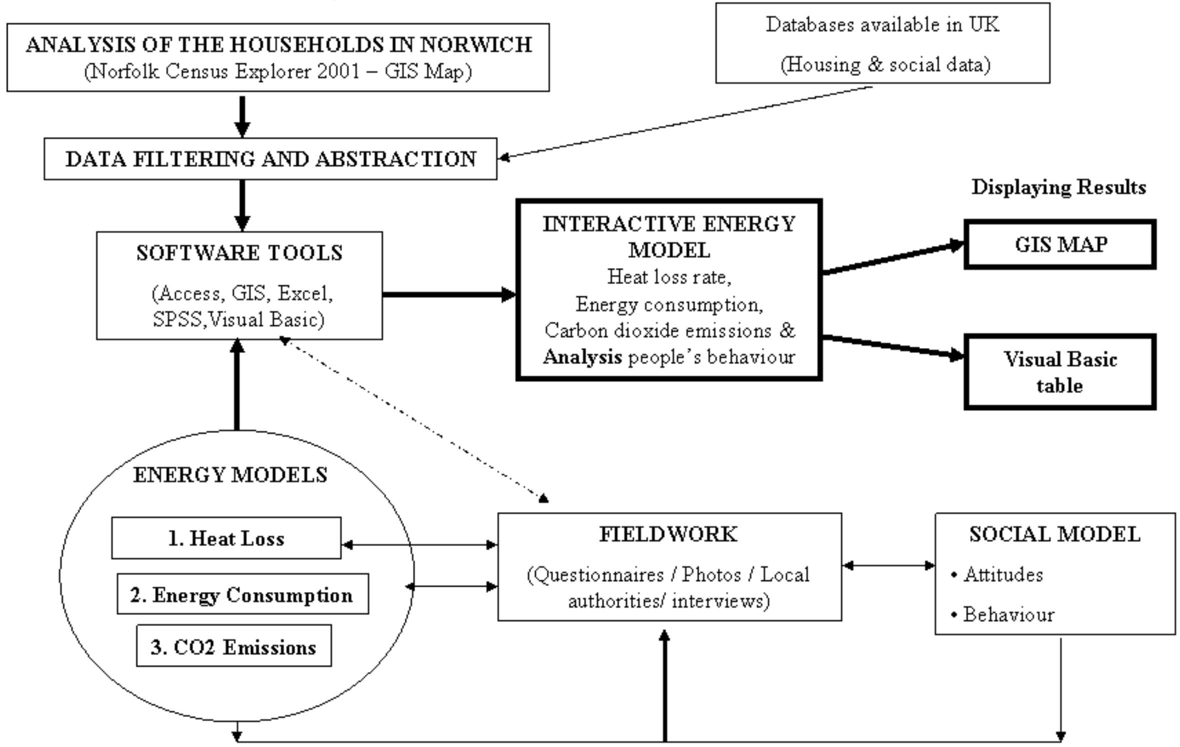
Methodology

A representative target area within Norwich City was chosen to represent a range of housing types and density together. The main parameters needed to develop the models as a basis of reference include estimates of heat loss and consequential energy consumption based on physical estimates of building dimensions from GIS studies and from direct fieldwork supplemented by information from Census Databases (National Statistics, 2001; National Statistics, 2001a) and the English House Condition Survey (EHCS).With the energy consumption data estimated the carbon dioxide emissions may be determined. The general methodology (Figure1) includes the development of three separate energy models:

i) a heat loss model,
ii) an energy consumption and CO_2 emission model, and
iii) a social model

In addition to the development of these models it was necessary to compare and validate the models. There are two separate stages to this validation. Firstly, a comparison between this model and other reported models, and secondly a comparison between the model developed and actual real data. Not all required information for the model was available directly from GIS. Thus improvements to insulation standards of existing properties would not generally be known. This information was extracted on a general basis using information from the relevant Housing Condition information for each area. Such average information can be fed into the relevant models based on averages for the relevant areas. For the purpose of comparison with actual energy consumption data it was necessary to supplement the research with complementary fieldwork to get specific information such as level of insulation, number of occupants etc for each of the properties concerned. This information was mainly obtained from face to face questionnaires in a representative selection of properties and direct measurement in selected houses.

Figure 1 *General Methodology*



Heat Loss Model

Heat loss from houses arises from heat transfer through the fabric of the building itself. The fabric losses include the floors, roof, walls, windows and doors, including both the insulation itself and direct paths of lower thermal resistance called thermal bridges (Larbi, 2004; Boardman et al., 2005). Ventilation losses are also important and arise from the relevant air exchange rate.

To develop the model, the properties were classified according to the age bands, and in the case of unimproved property, the construction type and elemental U-values were derived from the Building Regulations prevailing at the time of construction (Office of the Deputy Prime Minister, 2006). Information from the Housing Condition Surveys facilitated the incorporation of improvements in energy performance in the original buildings while face to face interviews allowed specific comparisons to be made during the data validation stage and also allowed the extent of social behaviour issues to be explored.

The Housing Condition Survey information provided information on the proportion of houses with different levels of insulation improvement within a database for each geographical area and a weighted average of U-value improvements for all properties within the relevant areas were used as default values unless specific detailed information was available from the face to face interviews.

- *Floor and Roof*

Domestic dwellings exhibit a very large variety in shape, form and appearance, and in general there are defined types: detached house, bungalow, semi-detached house, end-terrace, mid-terrace and flat (Chapman, 1994).

New algorithms were developed in GIS to determine the internal floor areas of each property with due allowance being made to exclude non domestic buildings such as garages and large commercial buildings. Physical data checks were made between the GIS evaluations of areas and actual measurements taken of selected properties. For purposes of heat loss estimations, the plan areas of each building were corrected using suitable algorithms to get the internal area directly from the GIS analysis.

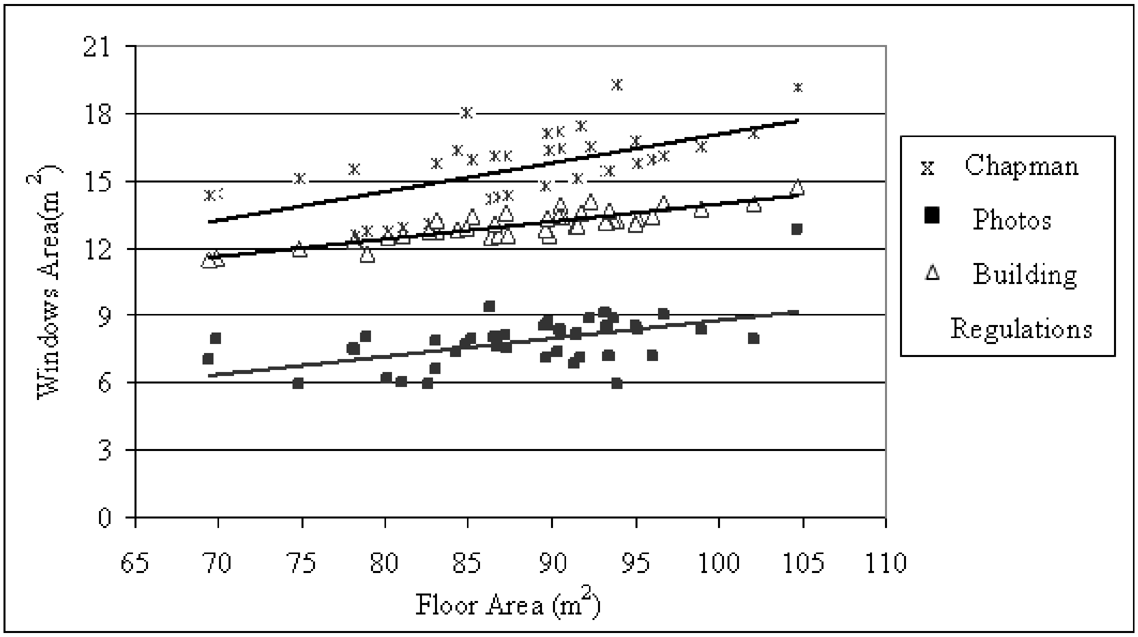
Finally, the total internal floor area was calculated from the internal ground area times the number of storeys while the roof area was assumed to be the same as the ground area. This data reduction technique allows the individual area of each house to be determined automatically and thereby produce accurate results very effectively.

- *Walls and Windows*

To estimate the heat loss from walls it is necessary to know the wall area, and this was calculated from a knowledge of the internal floor dimensions (from GIS) and the dwelling height estimated or measured directly in field work, from photographic evidence or from air-photo interpretation of the area. Use of such photographs is important where single storey extensions may have been added to multi-storey buildings. From fieldwork it was determined that houses built in Norwich have an average storey height of 2.7 m.

In order to estimate the window area, an image analysis of 338 high-resolution photos from houses around Norwich was undertaken to measure the areas of windows in each property. Finally, a general equation was determined based on the floor area which provided coefficients for each age of house and each household type. This approach was validated by comparison with Building Regulation estimations (SAP, 2005) and the Chapman method (Chapman, 1994). Figure 2 shows the results of the comparison between the estimations of window area for middle terrace houses and covering all ages. It is noticeable that both the Chapman and Building Regulation methods for assessing window area from floor area appear to significantly over estimate the actual window area as determined in this research.

Figure 2 *Comparison of different methods for assessing window area*



Energy Consumption Model

For this part of the model the division of the energy uses focused on four essential sections: lighting, appliances, cooking and space heating and water.

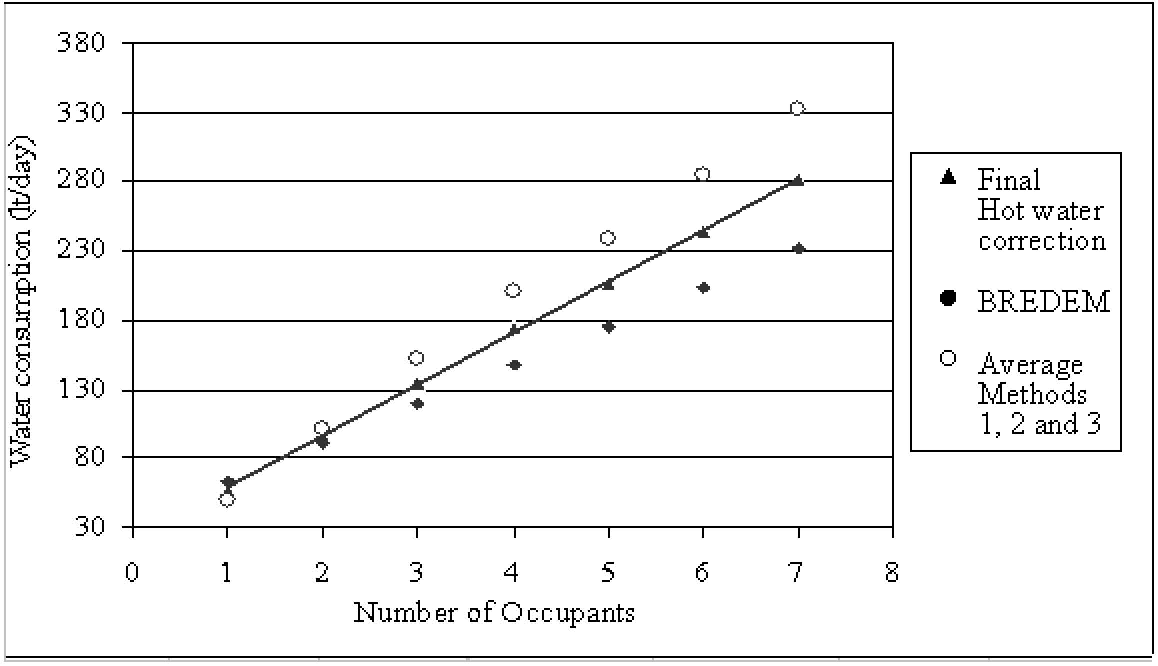
- *Water, Lighting, Appliances and Cooking*

Formulae were developed to estimate energy consumption by electrical appliances, lighting, cooking and water requirements according to the number of people living in the house. There are several different formulae which have been developed previously for estimating the hot water requirements of a household. These different methods are described below; the first three of which were used in the Energy House Condition Energy Follow Up Survey (EFUS, 2005):

a) Method 1. – based on number of appliances. This estimates the amount of water consumed per person by dividing the combined usages of the range of water consuming appliances by the number of people in the household. (BRE, 2005c).
b) Method 2. – based on household composition. (Age of the occupants). This estimates the average amount of water that is used by occupants and apparently varies according to the age of those occupants. (BRE, 2005c).
c) Method 3. – based on household Size. (Number of occupants). This considers the number of occupants in the house and assumes that all comparably sized households have an "average" demand of hot water (BRE, 2005c).
d) Method 4. – BREDEM (Buildings Research Establishment Domestic Energy Mode). This approach is based on the number of occupants (BRE, 2005c).

Generally the estimates from these different models are similar, and in this research estimates based on the trend line of the average of the different methods was used (Figure 3).

Figure 3 *Water requirements estimation*



- *Heating and Hot water requirements*

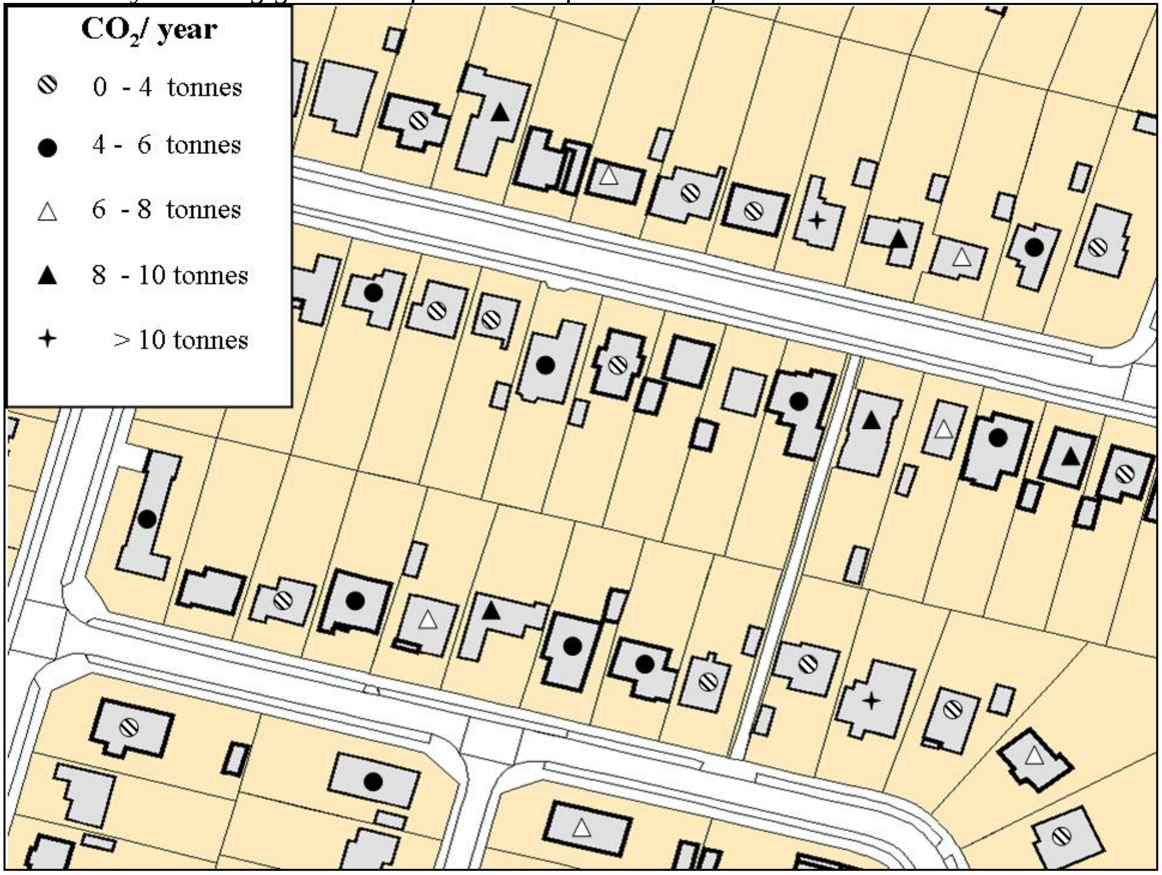
To obtain the space heating requirements, factors such as efficiency of the heating system, free incidental heat gains; climatic variations as measured by degree days and the mean internal temperature of the house were taken in account to get a reliable estimation of energy consumption. Once the general dimensions of the buildings had been obtained, all the subsequent calculations generally followed the approach defined in SAP 2005.

Carbon Dioxide Emissions

The outputs from the Prometheus model represent the energy required by heating systems, hot water, lighting and appliances and cooking, are valuable data, which together with the standard emission conversion factors (e.g. DEFRA's Environmental Reporting Guidelines for Company Reporting on Greenhouse Gas Emissions, 2007) are used to calculate the carbon dioxide emissions associated with the energy consumed in kWh, according to the relevant fuel types.

The results are given in kg CO_2 / year and the mapping process, using GIS is displayed as in Figure 4 where houses with different levels of carbon emissions are shown coded by different symbols. In this particular example, those house not coded were ones where general parameters were used from the Housing Condition Survey whereas the houses coded in Figure 4 were part of the detailed analysis associated with validation.

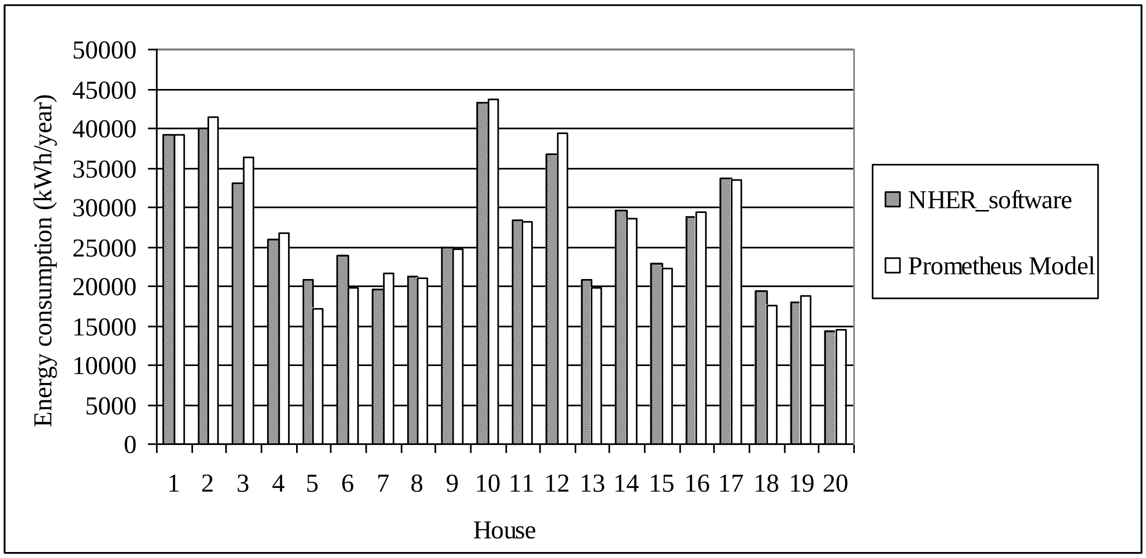
Figure 4 *CO_2 emission displayed in GIS. The houses shown coded in this figure were used as part of the data validation exercise where detailed information was available. Those not coded were analysed using general default values for certain parameters*



Comparison of Prometheus Model with other Models

To test the accuracy of Prometheus model, the outputs were first compared to other models such as the NHER-software. While there are similarities in the approach for basic heat loss calculations, the total energy consumption differs as more emphasis is placed in the present model on estimates of energy such as that for appliances based on the average number of occupants rather than floor area. Furthermore, Prometheus also adjusts lighting requirements according daylight hours at different times of the year, something which is not done in other models. Despite such differences, the predicted total energy consumption in Prometheus Model was within 0.6% of the figures predicted by other models (Figure 5).

Figure 5 *Total Energy consumption validation results between Prometheus and the NHER model*



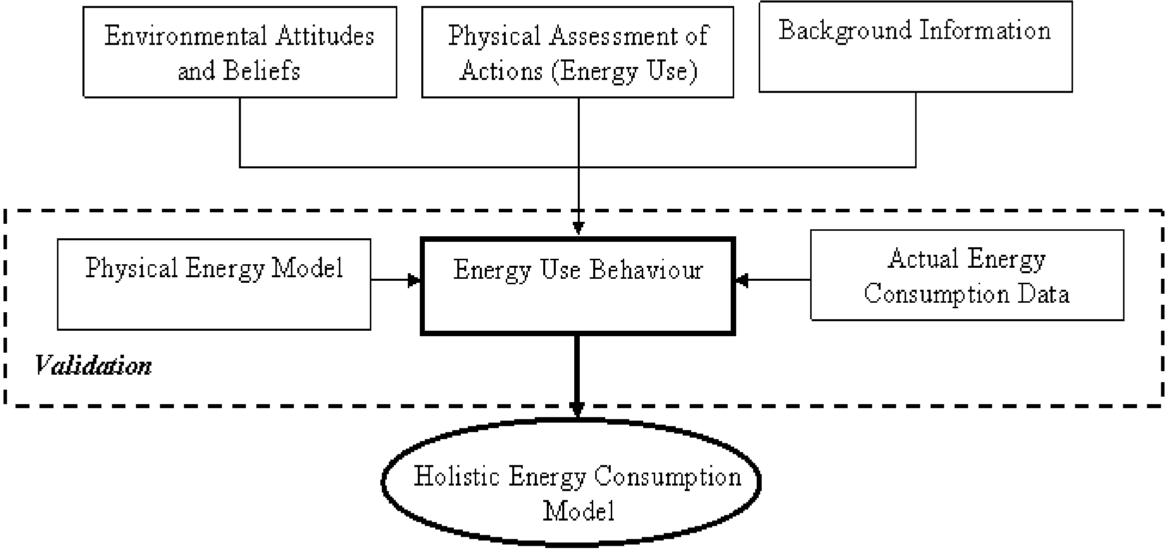
Social Behavioural Issues

The holistic model described in this research includes factors not covered in other models and attempts to address social behaviour aspects such as attitudes of the occupants towards such things as energy and environmental issues, environmental beliefs and also the predicted personal behaviour. This is achieved by integrating the physical model with the behavioural models in a holistic map as shown in Figure. 6. However, before this can be done it is necessary to explore how actual energy consumption differs from predicted physical energy consumption as any difference will be related to the social behavioural patterns of the household.

This technical validation relies on the comparison of actual gas and electricity readings with estimated energy figures calculated by using the Prometheus model based on the technical housing data from the 114 sampled houses in Norwich.

Since one of the aims of the research was to compare the outputs from the Prometheus model with actual consumption figures, the collection of the technical features of each house was necessary. These data were collected from the 114 houses by the use of social questionnaires (attitudinal and behavioural items) and the background information data and technical data by using a second questionnaire. The actual gas and electricity readings were taken directly on-site during the winter season (November 2006 – March 2007) and recorded in a database. After normalizing the data according to the relevant degree days for heating, and the relevant number of lighting hours for lighting, the actual measured consumption values were compared to the Prometheus' outputs in order to estimate the percentage difference between the predictions and actual consumption, a factor which is related to social behavioural patterns.

Figure 6 *Energy holistic map*



Validation of the Physical Energy Model and Actual Energy Consumption

Gas consumption. Before actual comparison was possible it was necessary to evaluate the specific incidental gains for each property so that the corrected base temperature and hence degree-days could be calculated. When averaged over all 114 houses, the error in prediction represented an overall variation of just 4.57 % (i.e. the predicted values were slightly on the low side). Nevertheless the variation for predicted consumption for an individual house could be quite large in the range from +200% of average to -75% of average (see Figure 7).

- *Electricity consumption*. The normalized electricity consumption over the relevant period was compared in a similar manner. In this case, the overall percentage difference between the predicted an actual consumption was just -0.70% or the predicted consumption slightly overestimated the actual consumption.

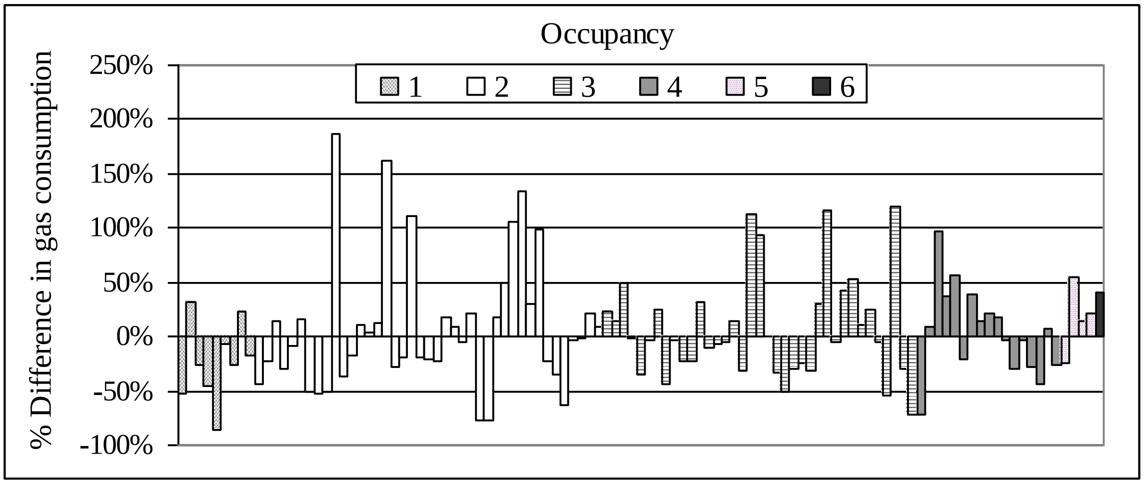
The close agreement between the overall predicted and actual consumption figures gives confidence in the model and allows it now to be used to explore variations in energy consumption associated with social behaviour.

Analysis of Social Data

The first part of the social analysis relates to the study of the relationship between background variables and the difference of the percentage between Prometheus output for gas and electricity consumption and actual figures.

Figure 7 shows that for any one size of household the energy consumption from space heating and hot water varies significantly. Each bar in the figure represents a different house with those plotting above the line reflecting houses where the actual consumption is higher than predicted, and those plotting below the line having actual consumption less than predicted.

Figure 7 *Percentage difference in gas consumption from average as a function of number of occupants*



It is noteworthy that despite the average prediction for all houses being very close indeed, there is considerable variation reflecting differences in social behaviour. According to the literature the variables identified in studies that most frequently affect energy behaviour and energy consumption are income, age, education, home ownership, desire for comfort, and incentives (Neuman, 1986; Guerin *et al.*, 2000; Gatersleben *et al.*, 2002)). The social data collected from the fieldwork was plotted against the percentage of difference between gas estimated by Prometheus model and the actual data for each of several key social variables. The same procedure was also followed for electricity consumption. Figures 8 and 9 show the percentage differences between actual and predicted gas consumption when categorised according to income level and occupancy respectively. As with Figure 6, there is significant variation from one household to another within the same category of income or number of people despite the fact that the analysis has already accounted for the physical differences in size and insulation of the buildings. Moreover, from the same figures there is no evidence of increasing energy consumption with income level (Figure 8) although there is a very weak relationship with number of occupants (Figure 9). This suggests that people who earn more money do not necessarily consume more energy because they can afford it and people with low income may not necessarily saving energy because they are concerned about energy bills. Thus, the stratification of income does not affect the levels of gas consumption. It would be interesting to explore these findings further with larger samples and exploration of other social variables.

Social behaviour effects in energy consumption and CO_2 emissions

The effect of social variables was analyzed by applying statistical methods to collected data: background variables, attitudinal and behavioural items and percentage of difference in gas and electricity consumption from the 114 houses in Norwich.

Figure 8 *Relationship between percentage difference in gas consumption from predicted and income level*

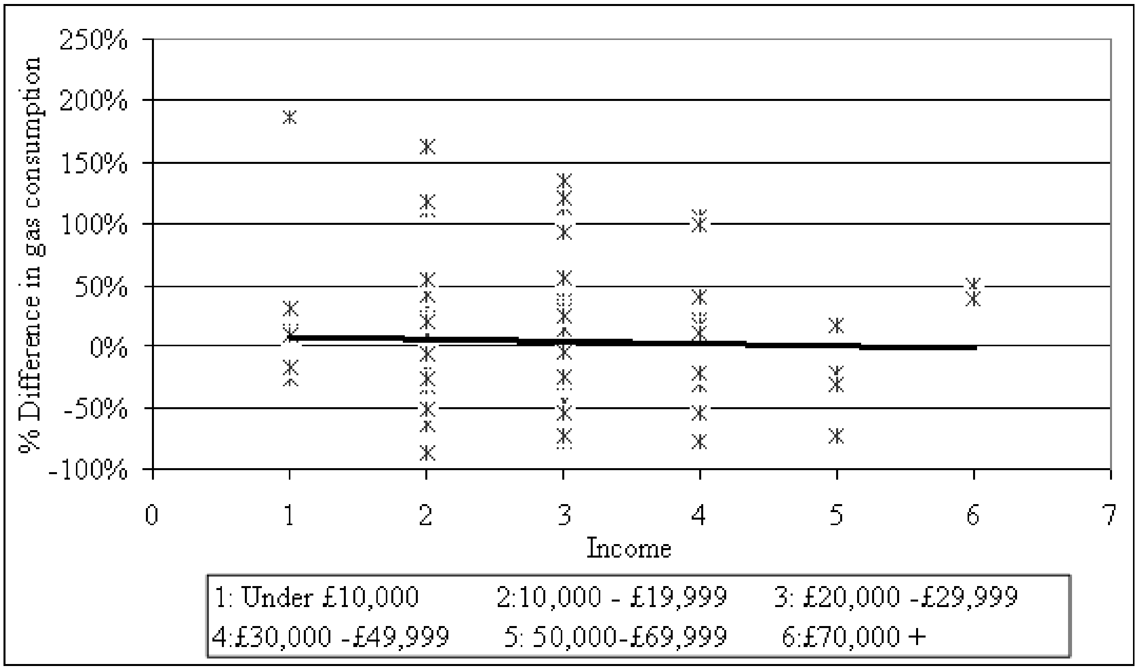
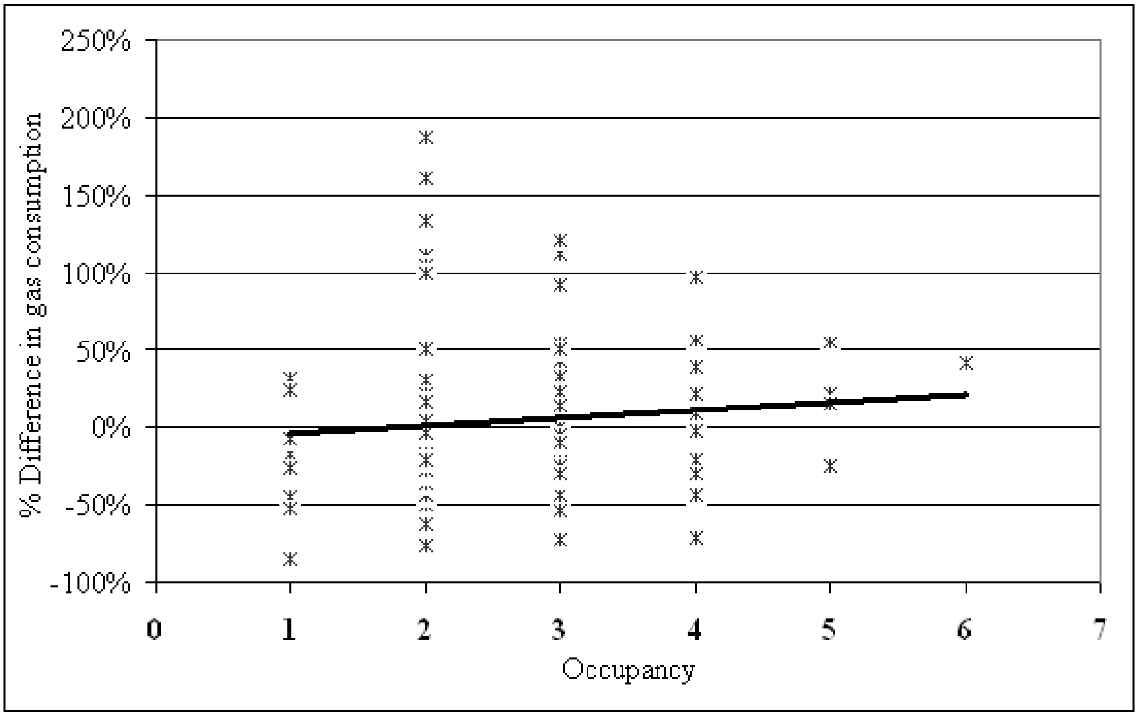


Figure 9 *Relationship between difference in gas consumption and number of occupants*



Firstly, behavioural and attitudinal items were analyzed using Principal Component Analysis (PCA) in order to transform a broad set of variables into substantially smaller sets of uncorrelated data represented by factors or dimensions (Brandon & Lewis, 1999; Reed, 2001; Barr, 2002;

Poortinga et al., 2004). To facilitate the interpretability of the factors, a Varimax rotation was conducted

The introduction of these factors was aimed at finding the most important group of questions which describes the majority of variance in the attitudes and actions responses towards housing energy use.

The social data collected from the questionnaires relating to behaviour issues affecting the physical actions the householders were currently taking have been integrated into five general factors (representing 64% of the variance of the energy use). Of these five factors, the two most important factors are: frequency of wet appliance use representing 18.71 % of total variance in energy use and ‘hot water use’ representing 15.73% of variance. The remaining three general factors each accounted for approximately 10% of variance.

Information on factors relating to attitudes and beliefs were also extracted from the questionnaires using the PCA the two most important of which can be summarised as: ‘health and well-being’ explaining 17.79 % of the total variance, followed by ‘energy efficiency awareness’ which accounted for 14.73% of variance. Much lower down in these categories came beliefs relating to ‘human influence on climate change’ which accounted for only 9.4% of variance.

Conclusions

The Prometheus model described in this paper helps to identify critical areas of carbon dioxide emissions (CO_2) in the existing housing sector. A significant improvement over other models is its ability to make it easier for the user to evaluate the energy use. The model uses remotely sensed information to assess building dimensions and data reduction techniques have been developed to avoid the input of most of the required housing-related data. In general, the data requirement was reduced by 63%, from an average of 40 variables requested by any of the current energy models to 15.

The Prometheus model allows not only strategic assessments of all houses in a region, but has the ability to incorporate more specific information about specific buildings where more information is known. In the former approach assessments of housing energy/CO_2 analysis will take less time as default well-supported values are used which have been backed up by field work.

Part of the study during the development of Prometheus was to validate the model against actual data obtained from 114 houses in Norwich. From validation with actual data it is shown that Prometheus predicts on average, the actual electricity consumption to within 0.7% and actual gas consumption to within 4.57%. Following such validation it has then been possible to explore, both quantitatively and qualitatively the behavioural variations in energy consumption from one household to another. These variations are shown to be large and range over a factor of 9 from the highest to lowest in any household size. On the other hand obvious social variables such as income have no effect on energy consumption whereas occupancy level only shows a very weak trend. These findings emphasize that education is of critical importance if actual energy use is to be reduced.

The accuracy of the carbon emission estimation depends on the type and quality of the data input, and an advantage of the Prometheus model over other models is that it provides consideration of seasonal fluctuations over the course of the year with monthly estimations, and these cover not only climatic conditions covered by variables such as degree days, but also the variation in lighting requirements covered by the darkness hours in different months of a year.

The Prometheus Model allows the user not only to evaluate the potential for domestic CO_2 reductions, but with the provision of a mapping tool provides an additional benefit for local authorities and energy advisers with an ARCMAP (GIS)-based tool to address the barriers of counting and reducing the emissions locally.

A crucial stage of the estimation was the interface and architecture of the Prometheus model which helps to ensure the user can navigate through the model in as a little or as much depth as desired and at the same time, significantly reducing the data requirements. The techniques used to develop this application were based on the premise that the presentation and usability of the Prometheus model affects the user, who will be more likely to return to a computer model because it is well-designed, has accessible information, and is easy to use.

Studying the relationships between energy, CO_2 emissions and environmental behaviour, is important and the Prometheus model will help local government planners to establish the most effective ways to reduce environmental impacts taking account not only of physical factors but also social factors.

Decision-makers will use the Prometheus model to target the most effective technologies and methods for carbon reduction. Prometheus also has the ability to update and enhance databases relating to critical aspects as more data becomes available. In this way, though countrywide defaults may be used initially, the ability to incorporate regionally specific default values is a feature of the model.

References

Barr, S. (2002). *Household Waste in Social Perspective*. Hampshire: Ashgate Publising Limited

Boardman, B., G. Killip, et al. (2005). *40% House Project*. Oxford: Environmental Change Institute, University of Oxford

Brandon, G. & A. Lewis (1999). 'Reducing household energy consumption: a qualitative and quantitative field study.' *Journal of Environmental Psychology*: 75-85.

Chapman, P. F. (1994). 'A geometrical model of dwellings for use in simple energy calculations.' *Energy and Buildings* 21: 83-91.

Department of Trade and Industry (2005). *2004 Energy consumption by final user*. London: DTI Digest of UK Energy Statistics 2005. Available at http://greenenergyworks.org.uk/energy.htm.

Fung, A. S., M. Aydinalp, et al., (2001). 'A residential end-use energy consumption model for Canada.' The Canadian conference on building energy simulation, The CANMET Energy Technology Centre, June 13-14, Ottawa

Gatersleben, B., Steg L., et al. (2002). 'Measurement and determinants of environmentally significant consumer behaviour.' *Environment and Behaviour* 34(3): 335 -362.

Guerin, D., B. Yust, et al. (2000). 'Occupant Predictors of Household Energy Behavior and Consumption Change as Found in Energy Studies Since 1975.' *Family and Consumer Sciences Research Journal* 29(1): 48-80.

Hui, S. C. M. (2001). 'Low energy building design in high density urban cities.' *Renewable Energy* 24(3-4): 627-640.

National Statistics (2001). *Norfolk Census Explorer*. London: Census Explorer: Version 2.6+. Available at http://www.norfolkcensusexplorer.net/censusinside/Census/CensusResults.asp.

National Statistics (2001a). *Census 2001: Housing*. London: Population. Available at http://www.statistics.gov.uk/CCI/nugget.asp?ID=358&Pos=4&ColRank=2&Rank=448.

National Energy Action (2007). *Business Plan 2007-2010*. Newcastle Upon Tyne. Available at http://www.nea.org.uk/Business_Plan_2007-2010/Business_Plan_2007-2010.

Neuman, K. (1986). 'Personal Values and commitment to energy conservation.' *Environment and Behaviour* 18(1): 53.

National Home Energy Rating (2005). *Home Energy Ratings*. London. Available at http://www.nher.co.uk/.

Office of the Deputy Prime Minister (2006). *The Building (Amendment) Regulations (Northern Ireland) 2006*. London. Available at http://www.opsi.gov.uk/Sr/sr2006/20060355.htm.

Poortinga, W., L. Steg, et al. (2004). 'Values, environmental concern and environmental behaviour. A study into household energy use.' *Environmental and Behaviour* 36(1): 70-93.

Reed, R. (2001). 'The significance of social influences and established housing values.' *The Appraisal Journal* 1: 356-361.