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Estimation of Cooling Energy Demand and Carbon Emissions from Urban Buildings using a Quasi-dynamic Model

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ABSTRACT

Global warming and the urban heat island effect in large towns and cities demand new approaches to cooling buildings in an efficient and sustainable way. Modern refrigeration, air conditioning and heat pump (RACHP) systems can achieve a high coefficient of performance and low emissions, but refrigeration technology already accounts for around 15% of worldwide electricity use and up to 10% of all greenhouse gas emissions, so in the context of international agreements to reduce global greenhouse gas emissions by up to 80% RACHP systems alone cannot provide a sustainable cooling solution for cities.

The purpose of the model described in this paper is to provide a simple and easy to use tool to estimate the impact of different heating and cooling technologies, alternative building design and operating parameters and future global warming, on the energy demands and carbon emissions of buildings. Existing software tools for analysis of buildings can provide high quality results for a given scenario, but the determination of an optimal solution demands multiple simulations, which can be time consuming and require post processing to interpret the results. The Excel based tool uses a quasi-dynamic energy balance model and reduced weather data set to generate rapid results, allowing the user to view the building's temperature profile, energy demands and carbon emissions in near real time and to develop an optimum cooling strategy. Results are presented for a single building version of the tool. When fully developed, it will allow the user to model clusters of buildings in an urban environment.

INTRODUCTION

The EU target of achieving an 80% reduction in greenhouse gas emissions by 2050 presents major challenges to producers and users of energy. In the urban environment the challenges are increased by factors such as the urban heat island effect (UHI) and increasing densities of population and buildings. A London study (Mayor of London, 2006) reported that measured night time temperatures in central London during the summer of 2000 were up to 6°C higher than in rural areas, whilst simulations of the impact of global warming predicted temperatures up to 3°C higher by 2050.

The refrigeration, air conditioning and heat pump (RACHP) sector faces additional challenges, because not only will global warming increase the demand for cooling, resulting in increased energy related (indirect) CO_2 emissions, but many refrigerants used in RACHP have high global warming potential (GWP) and refrigerant leakage will add further (direct) emissions. Refrigeration accounts for approximately 15% of all electricity demand in developed countries and refrigerant emissions can amount to as much as 20% of the total global warming impact of RACHP equipment (IIR, 2005). RACHP systems alone cannot provide a sustainable cooling solution for cities.

The model described in this paper provides a simple and easy to use tool for rapid estimation of the energy demand and carbon emissions for alternative building design and cooling (and heating) strategies. Extending the model to simulate

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the performance of large groups or clusters of buildings, in an environment that is subject to the urban heat island effect and climate change, can be used to assess the value of other mitigation measures.

Building design, cooling and comfort levels

Factors that impact on the energy and cooling demand of buildings include: Building design and construction, orientation, glazing and solar control measures (shading); Density of occupation, building occupancy profile; Ventilation, heating, cooling and hot water (DHW) systems; Internal heat gains (people, lighting, IT, small power, catering, machinery etc.); and External environment (daily and seasonal weather), comfort levels and temperature set points. There are frequent opportunities to make improvements during the life of the building, particularly during renovation or refurbishment, as well as to reduce carbon emissions through passive cooling methods or the inclusion of renewable energy technologies.

Comfort levels for building occupants vary with the external environment, as indicated in Figure 1. There is an indoor temperature window of about 5°C where more than 90% of occupants are satisfied, so the use of a cooling system with a temperature set point that tracks the external environment could therefore help to reduce cooling energy demand.

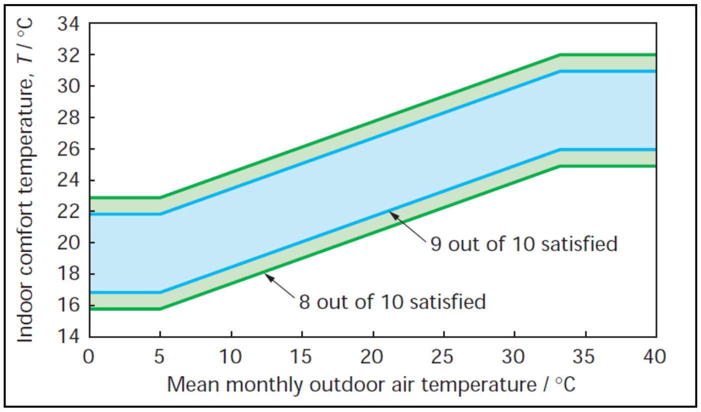


Figure 1. Adaptive comfort model (CIBSE, 2005)

AIMS AND MODELLING STRATEGY

The key aim of developing the model was to provide a high level planning tool that:

- is simple and easy to use, with the data describing the building, occupancy and environment limited to only that which is necessary to achieve acceptable simulation results and accuracy
- provides easy to interpret output data and graphing, with rapid visualization of the impact of changes
- is able to simulate passive ventilation and cooling measures such as night cooling and heat recovery
- calculates the energy related carbon emissions of the building and direct emissions from RACHP equipment
- will assist users to establish optimal high level solutions for building design and operation
- is able to simulate clusters of buildings of different types in an urban environment

The Capabilities and Performance of Existing Building Simulation Tools

Many software tools for thermal analysis of buildings typically use CFD models and 24 hour x 365 day weather data (normally TRY or Test Reference Year data), resulting in the need for a large amount of input data, long computing times and large output data files. Whilst this approach can work well for a building where the design parameters have already been set, it can present significant challenges when trying to optimise the building design or analyse multiple buildings.

A review of software tools for HVAC system design by Trcka and Hensen (2010) concluded that the real performance of buildings usually deviates from predicted performance by a significant margin and that ‘the initial modelling complexity should be the lowest possible complexity that satisfies the simulation objectives in terms of performance indicators’.

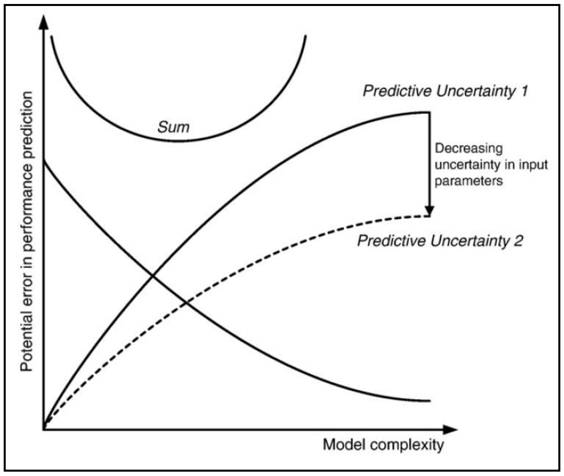


Figure 2. Model uncertainty vs complexity (Trcka and Hensen, 2010)

Trcka and Hensen identified 3 types of error:

- Abstraction error – due to an incomplete model of the physical system
- Input data error – due to uncertainties in the parameters used in the simulation
- Numerical errors (associated with the discretization or step size used in the simulation)

They suggest that there is a trade-off between simplicity and complexity at which the summed errors reach a minimum (Figure 2). They conclude that the capability of most tools is limited to a set of predefined system configurations, but to accelerate innovation in building technology and mitigate climate change, modelling environments should be more flexible.

Kalema et al. (2008) compared the results of 6 building energy simulation packages using the ISO 13790: 2008 methodology and concluded that the ISO method was suitable for estimating annual energy demand for buildings in Nordic climates, also that single zone modelling was acceptable for energy analysis purposes. Crawley et al. (2008) compared the capabilities of several different simulation programmes (including IES-VE which has been used in this work) and concluded there is no common language to describe the capabilities of different tools. Attia (2011) compared 10 tools and found the user input/output interfaces to be complex, providing too much information, making interpretation difficult. Also, few provide good support for carbon emissions evaluation, or simulation of passive or innovative design strategies.

Modelling Strategy

The authors opted to adopt the 'lowest modelling complexity' approach suggested by Trcka and Hensen, developing generic models that could be extended to clusters of buildings. The method broadly follows the guidance in ISO 13790: 2008 (CEN, 2008) using a dynamic heat balance approach, with simulation at hourly intervals. In order to characterise building transient behaviour and the effects of shut-down and start-up following weekends and holidays, the simulations are run over 72 hour periods. The model also simulates the performance of the heating and cooling plant in terms of primary energy demand, distribution and delivery equipment losses and energy related and refrigerant emissions.

As few buildings use sub-metering for heating and cooling plant, it was decided to validate the model against a well established and proven building simulation tool (IES, 2012).

DESCRIPTION OF THE MODEL

The quasi-dynamic model (Figure 3) sums the heat gains and losses associated with the building fabric, solar irradiation, ventilation and internal gains to calculate the energy required from the plant to sustain the required building environment. It calculates the rate of change in building temperature for one hour periods, using the temperature error (from the set points) to determine the required output from the heating and cooling plant over the next one hour period.

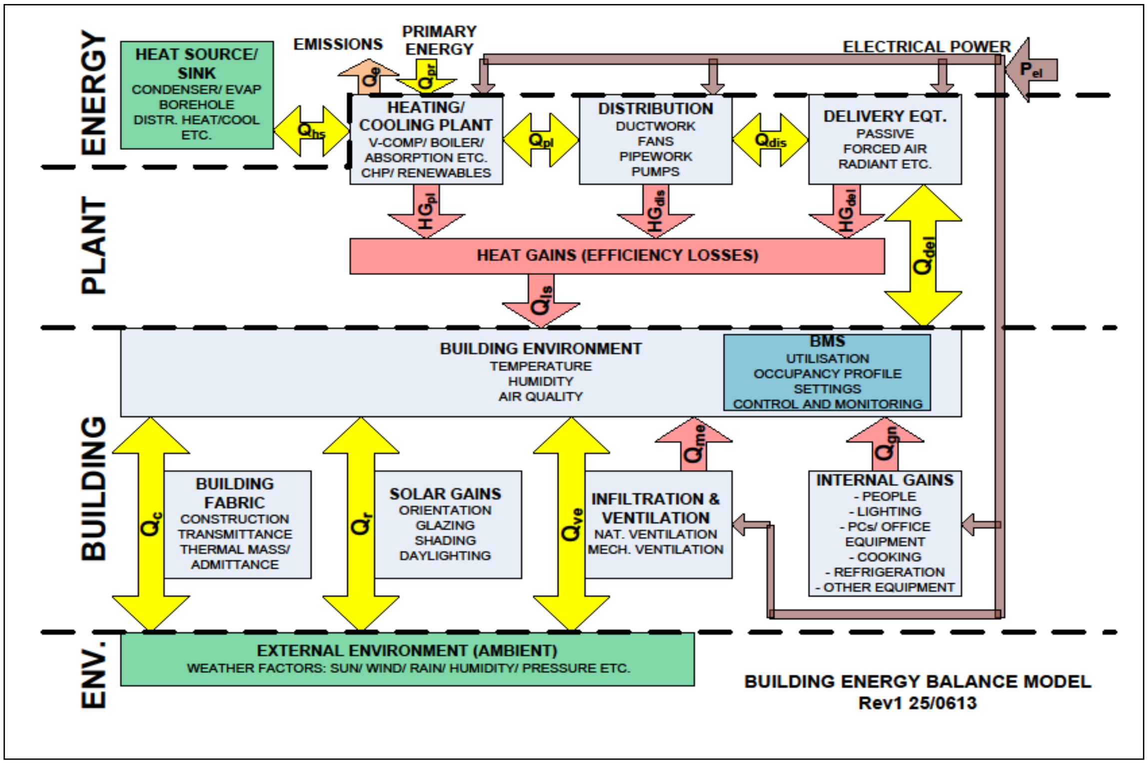


Figure 3: *Energy balance model for building thermal analysis*

The model uses as default the CIBSE (2006) mean hourly air temperature for each month of the year and the 97.5 percentile irradiance data to estimate the solar gain of the building, but other weather data can be used. The primary energy demand and associated carbon emissions for the plant and refrigerant emissions from RACHP systems are also estimated.

Energy Balance Equation

The heating (or cooling) required from the HVAC delivery system to maintain balance is:

$$Q_{del} = -(Q_c + Q_r + Q_{ve} + Q_{me} + Q_{gn} + Q_{ls}) \tag{1}$$

where Q_{del} = heat delivered (or extracted) by the HVAC system
Q_c = heat flow through the building fabric
Q_r = radiative heat flow due to solar gain
Q_{ve} = heat flow due to infiltration and natural or mechanical ventilation
Q_{me} = heat gain associated with natural and mechanical ventilation (actuators and fan power)
Q_{gn} = heat flow due to internal heat gains (people, lighting, equipment etc.)
Q_{ls} = heat gains due to efficiency losses in the HVAC plant, distribution and delivery equipment

Out of Balance Thermal Response

In practice a true steady state is never achieved. In the quasi-dynamic model, building energy balance and temperature calculations are performed at hourly intervals and the temperature error at the end of each hour is used to set the heating (or cooling) level for the next hour. The rate of change of temperature in a one hour period may be approximated as

$$\Delta\theta = (\theta_t - \theta_{(t-1)}) = Q_u/C \quad (°C/h) \tag{2}$$

where θ_t = building internal temperature at time t (°C)

$\theta_{(t-1)}$ = building temperature at time (t-1) (°C)

Q_u = average net heat flow (kW) due to energy unbalance between time (t-1) and time t

C = effective heat capacity of the conditioned space (kWh/K)

The additional heating or cooling necessary to correct the temperature deviation from the desired set point between time t and time (t+1) (the following hour) may be approximated as

$$\Delta Q_{del} = -Q_u = (\theta_{(t-1)} - \theta_t)*C \quad (kW) \tag{3}$$

In the model (and real systems), the maximum heating or cooling capacity of the plant and the modulation control will limit the amount of heating or cooling that can be delivered in any one hour period. The simulation is performed over a 72 hour period; the start temperature is assumed to be mid-way between the external temperature and the desired (set point) temperature. The data for the first 24 hours can be used to demonstrate the recovery from a weekend shutdown (for example) while the day 2 and 3 data indicate the performance when the building is occupied on a daily basis.

Energy Demand and Emissions

The model can estimate the primary energy demand and the carbon emissions from the building. The HVAC system is modelled as 3 separate elements: the plant, a distribution system (ductwork, fans, pipework, pumps etc.) and delivery equipment (fan coil, radiator etc.). The energy balance equation for the HVAC system is

$$Q_{del} + Q_{ls} = Q_{pr} + Q_{hs} - Q_e \tag{4}$$

where Q_{pr} = primary energy input (gas, oil or electricity)

Q_{hs} = heat transfer between any external heat source or heat sink (condenser, evaporator etc.)

Q_e = heat emitted directly from the plant to the external environment (e.g. flue gases)

Q_{ls} = the sum of the losses from the heating (cooling) plant and the distribution and delivery equipment (auxiliary electrical energy used to drive fans etc. is accounted for in this loss term)

The overall coefficient of performance of the HVAC system during any time period is

$$COP = Q_{del}/Q_{pr} \tag{5}$$

The greenhouse gas emissions associated with energy use and refrigerant emissions are calculated as CO_2 equivalents using published conversion factors (GOV.UK, 2013). RACHP direct emissions are predicted by estimating the amount of refrigerant charge in the system and using the refrigerant GWP and typical leakage rate to calculate the emissions as

$$EM_{RACHP} = L_{em}*m*GWP/1000 \quad \text{(tonnes } CO_2\text{(e) per annum)} \tag{6}$$

where EM_{RACHP} = direct emissions from the RACHP system

m = standard refrigerant charge in the RACHP system (kg)

GWP = global warming potential for the specific refrigerant type (expressed as CO_2 equivalent)

L_{em} = refrigerant leakage rate per year (% of the refrigerant charge)

Implementation of the Model

The model has been implemented as a macro enabled Excel workbook, which provides a flexible design environment and allows new and enhanced functionality to be included as the model is developed. The use of multiple windows allows the impact of changes to input parameters to be rapidly assessed in near real time. It comprises multiple worksheets, which include: reference and data input; total building heat energy load; temperature profile; ventilation-aircon load; building fabric heat load; solar gain; hot water load; energy demand; carbon emissions. Output data can be visualised using embedded charts. The impact of making changes can be seen immediately by simultaneously viewing multiple windows.

RESULTS FOR SINGLE BUILDING

The building used for initial validation of the Excel model is a 6 storey office building 60m x 30m in plan, located in London suburbs and constructed to the 2006 UK Building Regulations (ODPM, 2006), with the major axis aligned East-West. The windows on all sides are 40% of the wall area and the low emissivity double glazing has a transmittance of 0.54. An occupation density of 12m^2/ person has been assumed and the building is occupied between the hours of 7 a.m. and 6 p.m. Monday to Friday. The heating and cooling set points are 19°C and 21°C respectively. The building is described in the Excel model by its dimensions, whereas in IES-VE it is represented by a 3D sketch (Figure 4).

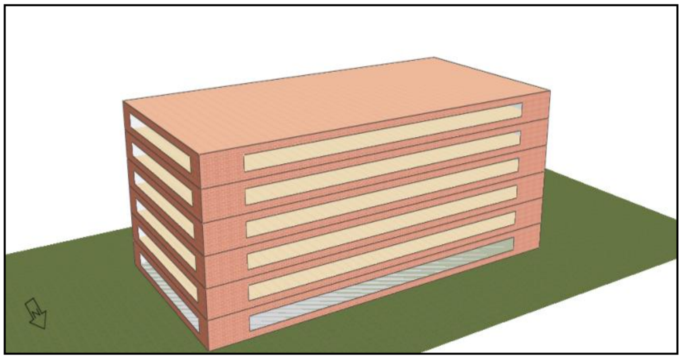
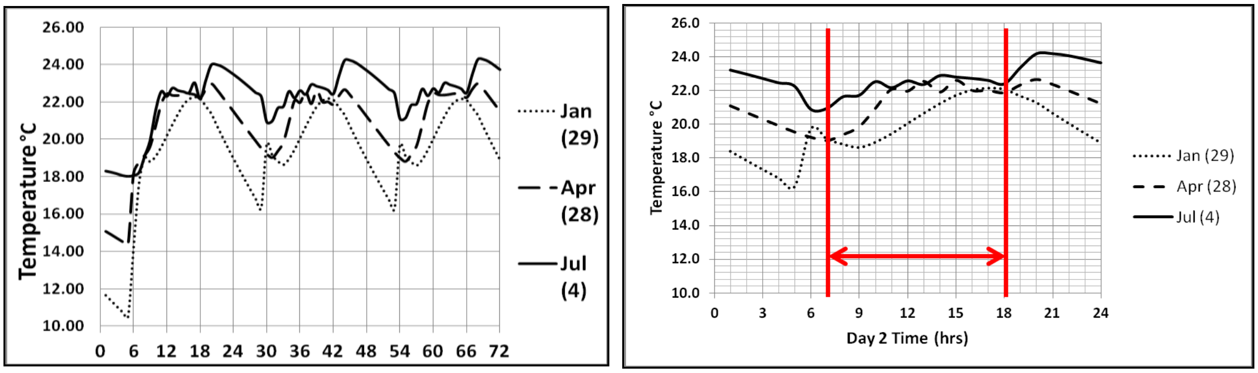


Figure 4. IES-VE 3D representation of the office building used for validation of the model

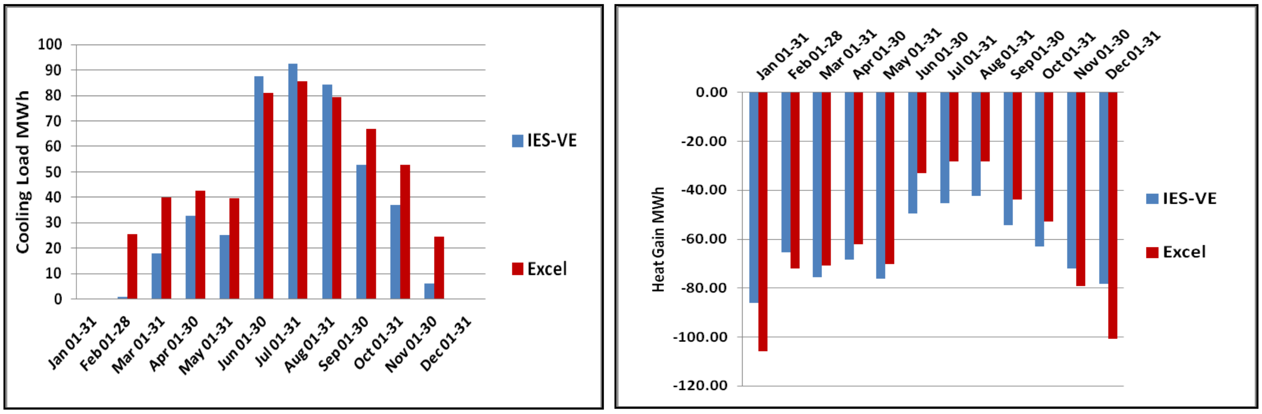


(a) (b)

Figure 5. Simulation of the building temperature profile over 72 hours from cold start (a) and during the occupancy period in day 2 (b)

Figure 5(a) indicates the transient behaviour of the building and how the internal temperature varies over a 72 hours from a cold start. Figure 5(b) shows the temperature profile for day 2 with the occupancy period highlighted (Note: the simulations cover a 12 month period but the charts show only 3 months for clarity). The heating and cooling systems maintain the temperature within a window of approximately 19°C to 23°C when the building is occupied and the pattern of temperature variation over the course of the day indicates that heating is required only during the morning, as internal and solar gains tend to be sufficient to maintain the building internal temperature once the set point has been reached (even in winter). In summer the building temperature continues to rise after the occupants have left and the cooling is switched off.

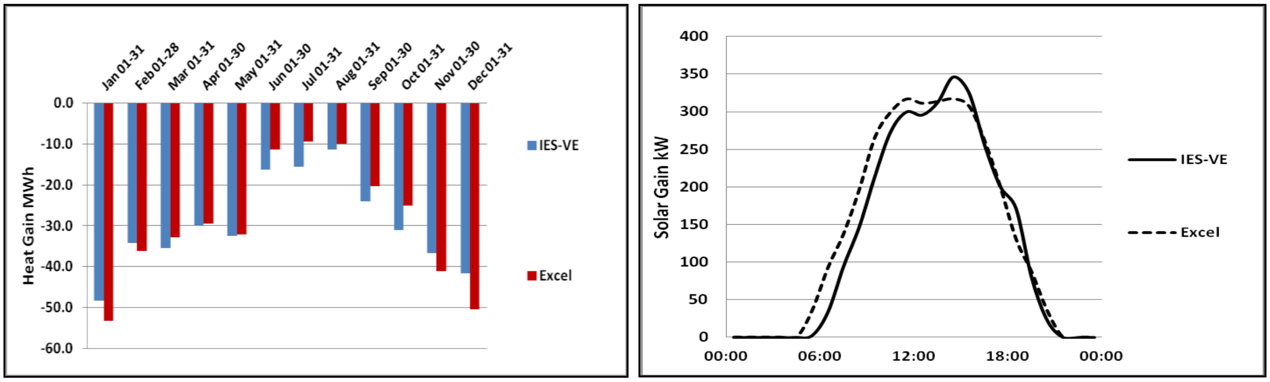
The overall building heating and cooling loads and the heat loads associated with the building fabric, ventilation system, solar gain and internal gains were compared with IES simulations. Figure 6(a) charts the overall cooling load profile for the building for the IES and Excel models, indicating good agreement in summer but less good in winter. Examination of the building fabric heat load profile (Figure 6(b)) and ventilation heat load charts (Figure 7(a)) indicates that the Excel simulation predicts higher heat losses than IES in winter and slightly lower losses in summer.



(a) (b)

Figure 6. Monthly net cooling load (a) and building fabric heat gain (b) for IES and Excel simulations

The peak (cloud free) solar gain profiles match well for IES and Excel simulations (Figure 7(b)). However, since the Excel model uses a more limited weather data set, the daily average illuminance and solar gain in each month are estimated using a 'cloud transmittance' factor which has been derived empirically. Refinements to the model, to include a seasonal cloud cover factor are expected to improve the correlation of monthly gains and the overall heat load for the building.



(a) (b)

Figure 7. Monthly ventilation heat load (a) and 24 hour peak solar gain - 28 April (b) for IES and Excel simulations

DISCUSSION AND CONCLUSIONS

Key Assumptions and Limitations of the Model

In order to simplify the analysis, the model makes several key assumptions:

- For solar gain calculations the alignment of the building's main axis is assumed to be either N-S or E-W
- There are limited options for zoning (it is assumed each building will normally be analysed as a single zone)
- Solar gain is calculated using hourly 97.5 percentile irradiance tables and an empirically derived cloud factor

- Only sensible heat is considered and internal heat gains are proportional to the occupancy of the building
- Hot water used within the building does not contribute to internal heat gain
- The quasi-dynamic model assumes that heat flows are constant during each one hour calculation period

The results of the test model indicate good correlation with IES-VE simulations on an annualized basis, but further work is required to improve the monthly correlation. However, they appear to support the premise that less complex models can achieve an acceptable level of accuracy, especially since many studies have indicated that more complex building simulations often fail to predict the performance of real buildings. The model is intended to be a high level planning tool for estimating the impact of changing building parameters and on the basis of work to date appears to meet that objective.

Future Extension of the Model to Building Clusters

At the time of writing work is under way to extend the model to urban environments. The relative simplicity of the Excel model permits extension for clusters of buildings using a series of linked workbooks/ worksheets. The key parameters for a range of typical building types (office, school, retail etc.), sizes and constructions will be stored in a library sheet with lookup tables and used to build up the cluster model by selecting the relevant quantities of each type and size of building. Demographic data for numbers and types of dwellings and business buildings in a given area are available from the UK Office for National Statistics, so the model can be built and used to compare energy demand with historical data. If the data correlate, the input parameters can be varied to provide a high level projection of the impact of changing demographics, building technology, and climate change on energy demand and carbon emissions.

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