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Regression models for predicting UK office building energy consumption from heating and cooling demands

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ABSTRACT

This paper described the development of regression models which are able to predict office building annual heating, cooling and auxiliary energy requirements for different HVAC systems as a function of office building heating and cooling demands. In order to represent the office building stock, a large number of building parameters were explored such as built forms, fabrics, glazing levels and orientation. Selected parameters were combined into a large set of office building models (3840 in total). As different HVAC systems have different energy requirements when responding to same building demands, each of the 3840 models were further coupled with five HVAC systems: VAV, CAV, fan-coil system with dedicated air (FC), and two chilled ceiling systems with dedicated air, radiator heating and either embedded pipes (EMB) or exposed aluminium panels (ALU). In total 23,040 possible scenarios were created and simulated using EnergyPlus software. The annual heating and cooling demands and their HVAC system's heating, cooling and auxiliary energy requirements were normalised per floor area and fitted to two groups of statistical models. Outputs from the regression analysis were evaluated by inspecting models best fit parameter values and goodness of fit. Based on the described analysis, the specific regression models were recommended.

1. Introduction

The overall environmental impact of any building in terms of Carbon emission depends on the energy consumed by its HVAC system and the fuel type. Energy flow of principal HVAC system within buildings is presented in Fig. 1.

HVAC system is usually divided into two parts, primary HVAC system and secondary HVAC system. Primary HVAC system is composed of equipment such as boilers and chillers, which generates heating/cooling energy (Q_h, Q_c) from primary fuels and electricity. Heating/cooling energy is then distributed in a building by a secondary HVAC system in respond to the building's heating/cooling demand. During this process, secondary HVAC system requires additional energy input, i.e. auxiliary energy (Q_a), to operate mechanical components of the system such as pumps, fans and control gears.

Building heating/cooling demand is the amount of energy required to maintain desired indoor conditions. It is calculated by taking into account its heat gains and heat losses such as transmission heat gains/losses through building envelope elements, solar heat gains through fenestration areas, internal heat gains from occupant, artificial lighting and electrical equipment, infiltration air heat gains/losses, and fresh air ventilation heat gains/losses. Building heating/cooling demand depends on various building parameters such as building fabrics, glazing percentage and glazing properties, occupancy pattern, level of internal gains, etc. Although heating/cooling demand calculation is often used in practice for building's energy performance evaluation, it unnecessarily reflects the actual energy consumption of the building in response to heating/cooling demand. This is because different HVAC systems have different energy requirements when responding to the same building heating/cooling demand. Such behaviour is predominantly affected by the way a particular HVAC system is designed and operated to match the characteristics of the building. In theory, an ideal HVAC system must meet the following criteria [1] in addition to the usual requirement for minimising circulation cost of the heating/cooling media:

1. The system has the ability to minimize outside air load while maintaining minimum fresh air supply to each zone as required by standards.
2. The system has the ability to eliminate simultaneous operation of cooling and heating sources, e.g. cooling at the main deck while

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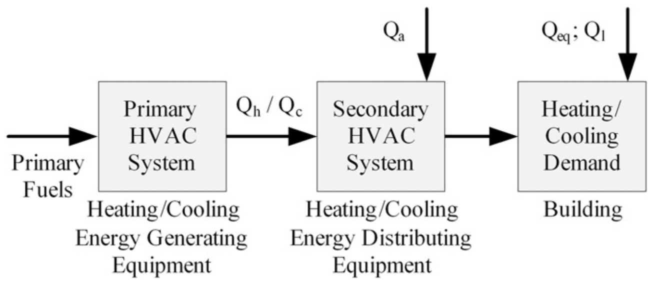

Fig. 1. Energy flow of principal HVAC system within buildings.

reheating at the terminals; and to eliminate the occurrence of heating in the presence of cooling demand and vice versa.

3. The system can take advantage of free cooling when it is available.
4. The system can minimize occurrence of simultaneous heating and cooling demand between different zones, by the means of inter-zonal airflow or heat exchange.

The ability of an HVAC system meeting the above criteria varies in a complex way. For example, systems which cover building demands by using only air as the heating/cooling medium (all-air systems such as VAV and CAV) can benefit from free cooling by allowing increased fresh air intake. However, all-air systems often suffer from simultaneous heating and cooling, and/or the inability for minimising fresh air load. Air–water and all-water systems (e.g. fan-coil based systems), on the other hand, are less prone to simultaneous heating and cooling, but having limited option for free cooling. It is not often possible to tell which HVAC system is a better option for a building without running detailed simulations.

Detailed simulation of HVAC systems is usually complex and requires large numbers of input parameters to be specified in order to calculate the desired outputs. These input parameters include HVAC system components, connections, control system and set points, and operating schedules, amongst others. As a result, the complexity of the existing tools has been identified by Ellis and Mathews [2] as the biggest obstacle to wider adoption of detailed simulation in practice, despite the potential this method offers in achieving better building energy efficiency. Ellis and Mathews further suggested that thermal efficiency of buildings and the selection of HVAC systems are two areas that can benefit from simplified tools, which will simplify input complexity by identifying and focusing on critical parameters and defining them in architectural terms. In achieving these, the simpler tools might be more appropriate for the wide spread use by professionals in built environment especially at the conceptual design stage. Similar views are expressed by others, for example, Trcka and Hensen [3], who suggested that simple HVAC system performance representation can be used "when only load predictions are considered, and/or when energy saving options are investigated" in conceptual design stage.

In addition to the benefit of simplifying modelling process, building models without detailed HVAC system models can simulate mush faster, too. Based on the simulation times of the models used in this research, Fig. 2 shows the ratio of simulation time of buildings with detailed HVAC system models in comparison with buildings without. In average detailed HVAC models take almost twice as long to simulate compared to the same building model. In the worst case, the simulation time can increase by three and a half folds. Simulation time is critical when multiple simulation runs are required in search of a better design solution. In this case, a simple model that can reliably predict HVAC system energy consumption from building demand can be used to accelerate optimisation of building parameters in early design stage.

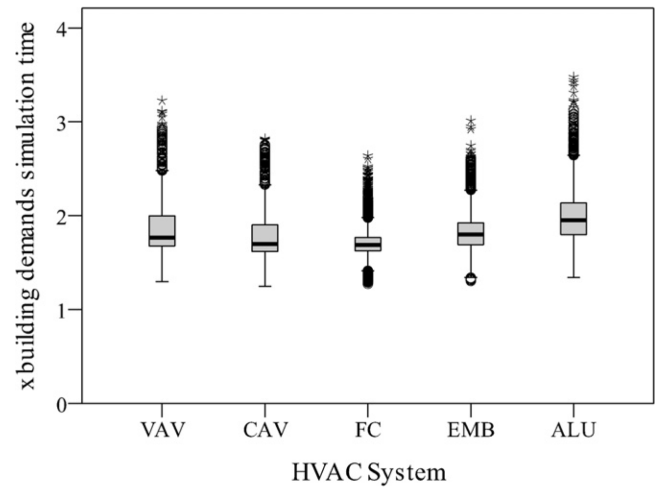

Fig. 2. Simulation time ratio: detailed HVAC system model vs. building heating/cooling demand.

In short, simplified models for predicting secondary HVAC systems heating, cooling and auxiliary energy requirements as a function of building heating and cooling demand can be useful in several situations. For example, during early design stage when decisions, which have high impact on energy performance of a building, have to be made with limited information, simplified models can save time and provide a fast and effective way to explore different HVAC systems and their impact on building energy consumption and greenhouse gas emissions. In addition, simplified model can be also useful in refurbishment projects, especially for HVAC systems refits.

The aim of this paper is to investigate the correlation between buildings' heating and cooling demand and the energy requirement for different (secondary) HVAC systems, in order to create simplified models of HVAC systems. We will show that single or bi-variate regression models will be able to provide prediction of HVAC system energy requirement with sufficient accuracy for typical UK office buildings.

2. Regression models for HVAC systems

Regression models have been widely used to describe performance characteristics of HVAC system components, such as fans and pumps, chillers, coils and so forth. Attempts to using regression models studying building and HVAC systems have also been reported. Sander et al. [4] developed simplified regression models which predict building annual heating and cooling energy requirements for a building equipped with a generic variable air volume (VAV) air-conditioning system based on location, building envelope characteristics and internal gains. The outputs form 5400 building simulations for 25 Canadian locations were used as regression analysis inputs. The accuracy of developed models was quite high with a difference between model predictions and simulation outputs within 10% in most cases, except for buildings with very low either heating or cooling requirements. In order to predict annual energy consumption of high rise fully air conditioned office buildings in Hong Kong [5,6], a generic office building was simulated in the DOE-2 energy simulation software by varying 62 input design parameters related to the building demand, HVAC system and HVAC refrigeration plant. Authors reported that from 62 input parameters, 28 correlate well with the predicted annual energy consumption. After performing a sensitivity analysis, 12 of 28 input parameters were considered to have the most significant impact on