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Stochastic model for electrical loads in Mediterranean residential buildings: Validation and applications

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ABSTRACT

A major issue in modelling the electrical load of residential building is reproducing the variability between dwellings due to the stochastic use of different electrical equipment. In that sense and with the objective to reproduce this variability, a stochastic model to obtain load profiles of household electricity is developed. The model is based on a probabilistic approach and is developed using data from the Mediterranean region of Spain. A detailed validation of the model has been done, analysing and comparing the results with Spanish and European data. The results of the validation show that the model is able to reproduce the most important features of the residential electrical consumption, especially the particularities of the Mediterranean countries. The final part of the paper is focused on the potential applications of the models, and some examples are proposed. The model is useful to simulate a cluster of buildings or individual households. The model allows obtaining synthetic profiles representing the most important characteristics of the mean dwelling, by means of a stochastic approach. The inputs of the proposed model are adapted to energy labelling information of the electric devices. An example case is presented considering a dwelling with high performance equipment.

1. Introduction

The detailed modelling of a household's energy consumption is a complex task that involves different issues and requires different skills. In detail, the main energy consumption sources in a household are: space heating/cooling [1,2], domestic hot water, appliances and lighting. A major issue in modelling is to estimate the uncertainties implicit in the building model. There are many unknown and uncertain parameters that affect directly the results, especially when the model reproduces existing buildings. The uncertainties can be related to the quality of building works, real properties of materials and their performance degradation, real performance of heating and cooling systems and their efficiency reduction, quantification of air infiltrations, subjectivity in comfort condition, and an important group of uncertainties related to the user behaviour (appliances, lighting, set points...). In particular, for modelling the consumption of appliances, a difficult aspect is the quantification of purely stochastic variables, namely the simulation of electrical consumption profiles for appliances and plug loads. In practice, electricity consumption caused by appliances has been often based on fixed profiles derived from statistical data. Although this kind of approach has some strong points (e.g., simple calculations, perfect for first stage analysis), it is not useful when a detailed characterization of the household consumption is needed, as for example in models for studies on the energy interactions of a "prosumer" (producer and consumer) building [3–7]. From this perspective, a good and solid modelling approach should comprise both average and peak value estimation: the first being useful for an early design of the systems, the latter for grid interaction, storage sizing issues and optimization of demand side management strategies. For such applications, transient modelling approaches are used worldwide to represent both building physics and energy generation systems, but it is important to make progress also in the field of user-related energy consumption modelling with models with the same level of detail. In other words, at least hourly time-steps should be adopted to obtain meaningful results and to make comparisons to energy generation data. The modelling of user-related energy consumption is crucial when the focus of

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the study is the residential sector. Residential energy consumption profiles are much more difficult to predict than for e.g., offices, for several reasons: occupant behaviour can vary widely and therefore have notable impacts on energy consumption, privacy issues limit the collection and distribution of energy data related to individual households and usually the detailed metering of end-uses consumption have high costs. The importance of the demand side modelling is particularly high when demand–response studies are being performed: having a detailed insight on how energy use in the households might vary following the designer's input, is of the uttermost importance to develop a solid study.

This paper proposes a model aimed at describing the energy consumption of building clusters and neighbourhoods. The model uses a stochastic approach to simulate more than one household at the same time. The idea behind the model is having a high-resolution tool, dependent on easily modifiable parameters. The model allows a simple and effective customization by the user, keeping it robust. The parameters of the model are also related with energy standards of appliances, making possible an analysis of their effect at neighbourhood level. The modelling environment chosen for the implementation of the model is TRNSYS, in order to complement the simulation of thermal loads in buildings. Considering existing literature, the model could be one of the first implementations in an environment of user-related energy consumption models. The aim of the paper is the analysis of the performance of the model by considering that main inputs and parameters to the model are derived from empirical analysis of real data from existing research projects. A detailed sensitivity analysis of parameters and a comparison of the results with other studies available in the literature are done. Although many household electrical consumption studies are available in the literature, the proposed model is one of the first to be implemented in Mediterranean regions.

1.1. State of the art

Residential energy use modelling is usually very dependent on the level of accuracy of the input data. Therefore, different modelling approaches have been developed in the last decades, with different strengths and weaknesses, as well as different model resolutions and modelling capabilities.

The main techniques used to model residential energy uses can be grouped up into two main categories [8]: "top-down" and "bottom-up". Top-down models underwent a major development during the energy crisis of the late 1970s. The major aim of such research effort was to understand better consumer behaviour with changing supply and pricing. Such models analyse residential sector as a whole and their objective was to determine and to analyse trends of the sector. The strength of "top-down" models is that they do not need very detailed input data to work. They just need widely available energy aggregate data and rely on historic residential sector energy values. The heavy reliance on historical trends and data for these models is also a major drawback, since they are not able to handle discontinuities in the major trends.

Saha and Stephenson [9] developed a "top-down" model for New Zealand, modelling in separate sub-models space heating, domestic hot water and cooking, that are added up to obtain total consumption. The proposed method used historical data to predict future energy use levels as function of stock, ownership, appliance ratings and use factor. Its prediction was excellent during the 1960s, but in 1970s the shifts in home insulation levels caused a major deviation between monitored and simulated data.

The "bottom-up" approach goes beyond the limits of the "top-down" one, accounting in detail for individual houses and energy end-uses. After that, the results of the model may be extrapolated to represent a region or a nation, according to the level of detail of the inputs. Common input data to bottom-up models are dwelling properties, equipment and appliances, climate characteristics, occupancy schedules and use levels of equipment. This detail in characterization is the strength of these methods. It allows a very accurate modelling, but has as drawback the difficulty of obtaining all the needed data. No historical data are required. However, in order to extrapolate the results for a whole region or country, data must be representative of the zone. A peculiar characteristic of these models is the modelling of occupant behaviour. The main modelling approaches in this field may be summarized as: statistical techniques (regression and conditional demand analysis) and neural networks.

Widén and Wäckelgård [10] proposed a Markov–Chains method with a wide use of Time Use Data (TUD) information for Sweden. TUD were used to describe occupancy patterns, obtaining transition probabilities of three states (outside home, active at home, and passive at home). The model is developed in the field of electrical and lighting demand. Widén and Wäckelgård used detailed modelling of the time use for each occupant. The fundamental section of the model is the conversion of the TUD into occupancy levels. Subsequently, the model obtains energy use profiles through the use of different patterns and converting functions for each appliance.

Yamaguchi et al. [11] has developed an occupant behaviour model for estimating high-resolution electricity demand profiles of residential buildings. The occupant behaviour is based on statistical treated data of TUD in Japan. The model is based on a set of probabilities related to different behaviours or activities, which are used to define the behaviour of each occupant and then its electrical consumption. One of the advantages of this model is that not detailed data are needed. Richardson et al. [12] proposed a method having as input the value of natural light entering windows and the activity level of the household residents. The main input of the model is a time-series representing the number of active occupants within a dwelling and is based on Monte-Carlo technique. The statistical information used is from the United Kingdom. Paatero and Lund [13] built a model for generating electricity load profiles for a dwelling using representative data sample and statistical averages from Finland. The randomness has been included using stochastic processes and probability distribution functions (starting probability function based on the seasonal, hourly and social factors). Paatero and Lund use the model to simulate strategies of Demand Side Management (DSM). Another key element is the high influence of the occupancy activity with heating and cooling loads and in consequence, with the size of the systems. Baetens and Saelens [14] simulated in Modelica user behaviour and use of lighting and appliances. The use of appliances has been implemented by a semi-Markov process based on the presence of an occupant and their activity profiles. In a similar way, Neu et al. [15] integrate a Markov Chain Monte-Carlo approach in EnergyPlus platform to simulate multi-zone single-storey detached building. The model is based on TUD of Ireland to obtain disaggregated residential appliances uses profiles, as Widén and Wäckelgård did. The model generates occupancy profiles at a 15-min time resolution, electrical appliances load and lighting load profiles. They relate these profiles with the building models, including the associated heat gains of each element (occupancy, appliances and lighting).

Even though the use of Neural networks methods has been historically limited in this field, they have had some applications to the modelling of electrical consumption in households [16,17] due to their capability of modelling non-linear phenomena with forecasting purposes.

2. Stochastic model description

In the simulation, the energy uses are selected and modelled for each household, through a stochastic approach. Main outputs of the