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An occupant-based energy consumption model for user-focused design of residential buildings

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Abstract

Occupants' behavior exerts a significant influence on the energy performance of residential buildings. Industrial energy simulation tools often account for occupants' as monolithic elements with standard averaged energy consumption profiles. Predictions yielded by these tools can thus deviate dramatically from reality. This paper proposes an activity-based model for forecasting energy and water consumption of households, and discusses how such an occupant-focused model may integrate a user-focused design of residential buildings. A literature review is first presented followed by a brief recall of the proposed modeling methodology and a sample of simulation results. The possible integration of the proposed model into the design and energy management processes of residential buildings is then demonstrated through a number of use cases.

Keywords: Energy modeling, energy management, residential building, performance contract, households, occupant profile, user needs, consumption variability, domestic activity, human behavior, user-focused design.

1 INTRODUCTION

The building stock accounts for between 16 and 50 percent of national energy consumption worldwide [1–3]. Governments around the world are thus rolling out energy directives, national regulations and energy-efficiency labels that set minimum requirements for buildings' performance [4], and promote the construction of green buildings [5]. Buildings' stakeholders have thereby started dealing with buildings as products-with-services rather than just simple products. Services may for instance include energy monitoring or equipments' maintenance during a building's use-phase. Moreover, new market expectations such as the 'energy performance contracts' have started to emerge in a number of countries [6]. Such services and offers require thus a better control of performance's variability during a building's lifecycle. Consequently, a better comprehension and consideration of the key determinants of energy performance has become essential for the design and marketing processes of buildings.
Occupant behavior is a substantial source of uncertainty in energy modeling since. It can impact energy consumption by as much as 100% for a given dwelling [2,7–14]. Industrial energy simulation tools such as Energy Plus and eQUEST propose some simplifications regarding occupants' behavior (among other simplifications), which may lead to unrealistic energy estimates, and may eventually be one of the reasons behind high discrepancies between predicted and real energy consumption values [15–18]. Nowadays, such performance discrepancies are no longer tolerated - especially in the case of green (energy-efficient) buildings. More precise methods are therefore needed to model occupants' influence on buildings' energy performance. Such models should result in more accurate energy estimations, and hence improve building designs and marketing offers.
The authors have proposed an activity-based model of residential energy demand (SABEC[1]) in a doctoral dissertation [19] . The present paper is not intended to detail the model, but it briefly recalls the adopted modeling methodology. The main focus here is to show how a user-focused model, which accounts for occupants' energy-related needs and activities, can be used within the engineering design, energy management processes, and marketing offers of residential buildings.
A literature review is first presented followed by a brief recall of the proposed modeling methodology and a sample of simulation results. The possible integration of the proposed model into the design and energy management processes of residential buildings is then demonstrated through a number of use cases.

2 BACKGROUND AND RELATED WORK

2.1 Occupants' Behaviour and Energy Use Trends in Residential Buildings

According to Ellegård and Palm [20], energy use is embedded in most aspects of households' daily life. People use energy and water to satisfy their daily living needs and activities such as preparing food and supplying heat and light [21,22]. Scientific literature points out the major end-use groups of energy such as space heating, space cooling, domestic hot water, appliances and lighting [3,23,24]. This energy consumption is highly dependent on the behavior of occupants [2,14,25]. Past experience shows that energy usage can vary dramatically from one household to another [12,13,27]. This variation reflects the heterogeneity in occupants' needs and preferences. Literature confirms the presence of high correlations between household attributes on the one hand, and domestic appliances ownership levels, their energy rating, and their use patterns on the other [25,28–34]. This would explain why general assumptions about occupants' behavior imply ambiguities and inevitably lead to significant uncertainties in energy predictions. Therefore, a better modeling of occupant-related energy consumption must merge from a better understanding of their needs, preferences and usage-contexts, and, thus from a better representation of their socio- economic and demographic attributes that influence their energy consumption trends.

[1] SABEC : stands for Stochastic Activity Based Energy Consumption

2.2 Existing Modelling Approaches

Literature reveals the existence of a number of different scientific techniques for modeling energy consumption in residential buildings [11]. Some authors, such as Seryak & Kissock [13] and Yohanis et al. [35], use real sub-metering data in order to derive representational loads (so-called "diversity profiles") of occupants energy use, and thus deduce estimates of buildings' total energy consumption. Other modeling methods are those aiming at simulating occupancy patterns and various energy-load schedules by using stochastic approaches (e.g. Monte Carlo Markov Chains) that are based on national time use surveys (TUS) [18]. Authors such as Tanimoto [36] , Richardson et al. [37,38], Widén and Wäckelgård [39] , Muratori [40] and Subbiah [41] adopted such type of approaches. These modeling approaches yet still have some drawbacks. First, even though they correlate occupancy schedules to appliance use-patterns and consumption, yet to the authors' knowledge, neither of the existing approaches establishes the link between occupants' daily living needs (Maslow's pyramid) and their related energy consumption. Second, they do not generate energy demand profiles based on the activities performed in each household and more particularly by each household member. Therefore, they lack the capability to depict use-situations such as the sharing phenomena of appliances and activities (e.g. Watching TV). Third, the existing models are not exhaustive in representing household attributes (such as the income, age, etc.), where in most cases, the main variable considered for representing households is the number of occupants. Consequently, such models cannot assess energy consumption variability between different population segments and household profiles.

Based on these conclusions, we believe that a user-focused statistically-derived approach which correlates occupants' profiles (socio-economic and demographic) on the one hand, to activities, appliance ownership and use trends, and usage contexts on the other hand, can be very useful for the design process of buildings. The benefits of such a model may not be limited to energy consumption predictions, but it can go further to be used for adapting building design solutions and for energy monitoring and management during the use-phase of buildings for instance.

3 RECALL OF THE SABEC MODEL

SABEC model is developed in the scope of forecasting occupant-related energy consumption in residential buildings, while accounting for variability in consumption patterns due to heterogeneity in occupants' socio-economic and demographic profiles [19]. The model accounts mainly for energy consumption related to domestic activities such as watching TV, washing dishes, and doing laundry. The structure of the proposed Activity-Based Energy Consumption SABEC model is presented in Figure 1, whereas its different objects are very briefly introduced in this section. Occupants' behavior is characterized through a need-activity-action paradigm. We consider that occupants satisfy their daily living needs (e.g. house-caring) by performing a set of daily activities (e.g. washing dishes), which in turn are conducted through a set of actions (e.g. wash dishes by machine, wash dishes by hand). Exhaustive inventories of energy-use needs, activities, actions and appliances are established in accordance with existing literature and related theories (e.g. Maslow's pyramid, activity theory) [19]. An Activity-based model entails that energy consumption of a household is estimated by summing up the energy use of different activities performed (such as cooking, washing clothes, etc.). The model is of a stochastic nature due to the twofold probabilistic mapping (conditional probabilities) established between household attributes (household type, number of occupants, socio-professional category, etc.), as well as the corresponding appliance ownership rates, appliance characteristics and power ratings, and activity quantities. A household model with an exhaustive representation of occupants' attributes is proposed.

Domestic activities are classified according to their nature (shared, additive), and a quantification unit is attributed for each of them (service unit). For a given activity (a given need), the service unit is coupled with appliance's energy rating in order to estimate the resulting energy and water consumption. The proposed model can thus quantify energy consumption per domestic activity at the level of a specific individual or household. We highlight here that the technical and computational aspects of the model are not presented in this paper. For more details, the reader may refer to [19] and [44,45].

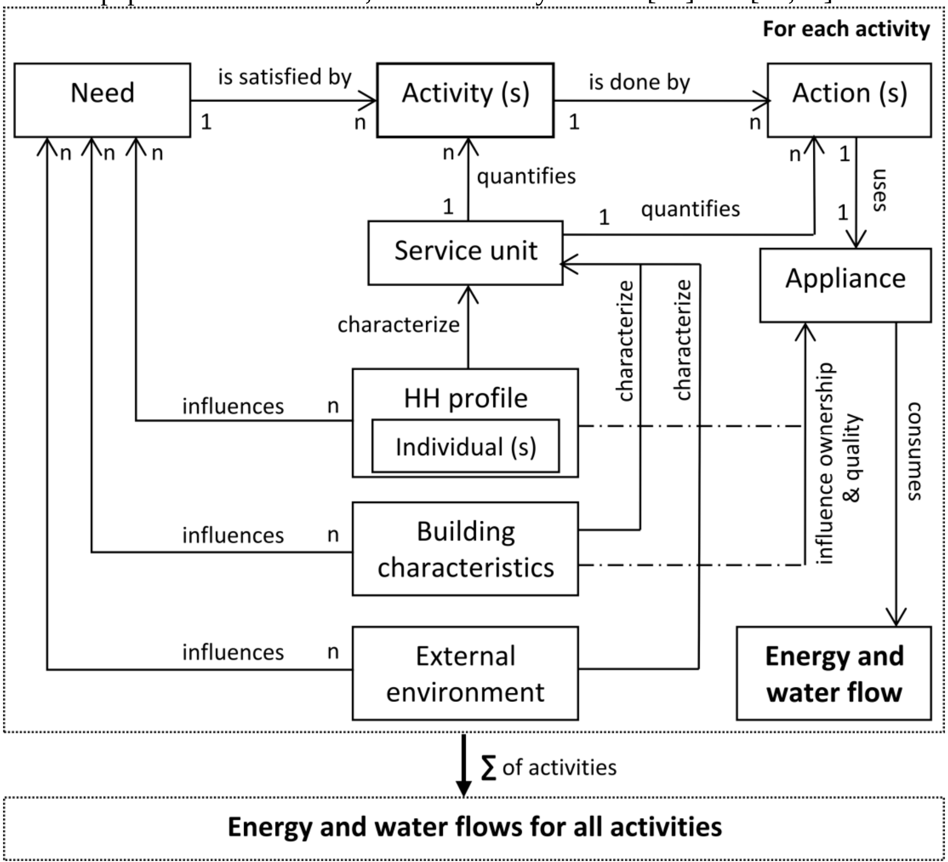

Figure 1: Architecture of SABEC model

4 SAMPLE APPLICATIONS OF THE MODEL

The proposed SABEC model was applied for a number of domestic activities. Only some examples of simulation results are presented here to demonstrate model's utility. A first example is illustrated through Figure 2. The cumulative distribution plot represents electricity consumption of the activity "watching TV" for a sample of 1000 randomly generated households. The plot fits into a normal distribution with an average value of 3.95 KWh/week and a standard deviation of 2.75 KWh/week. The variation in consumption values, which is clearly demonstrated through the distribution, reflects the heterogeneity of household profiles of the sample.

The model also permits to perform energy consumption simulations for specific profiles of households by defining constraints on their attributes. The box plot in Figure 3 shows a sample of electricity consumption results for the activity "watching TV" for four different French household clusters. Each distribution on the box plot corresponds to 10000 simulation runs. The plots show how electricity consumption may vary from one household type to another for the same activity.

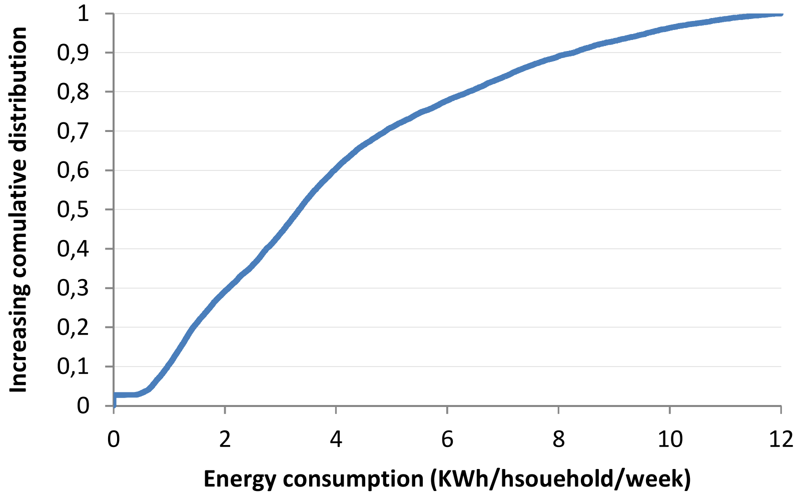

Figure 2: Cumulative distribution of electricity consumption values for the activity "Watching TV" for a sample of 1000 randomly generated households

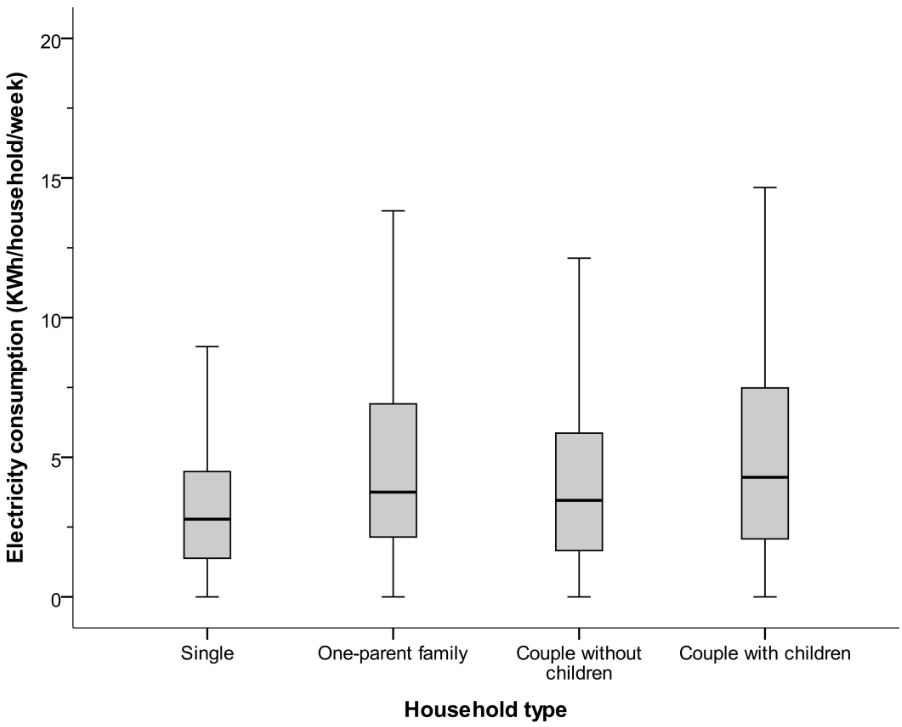

Figure 3: Simulation results of electricity consumption for the activity "Watching TV": Comparison between five household-type clusters of the French population

Another example of simulation results is given in Figure 4. The plots represent electricity consumption distributions of the activity "washing laundry". The households considered have the same household type and same numbers of adults and children, but different income levels. Each of the presented plots corresponds to 1000 simulation runs. The simulation samples presented in this section demonstrate how the SABEC model can be used for assessing energy consumption variability among different household clusters at the level of a domestic activity.

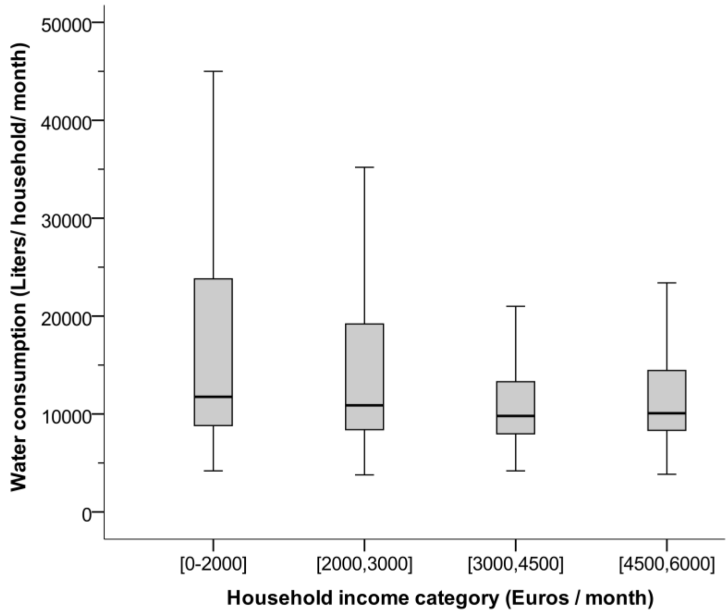

Figure 4: Simulation results of electricity consumption for the activity “Washing laundry”: variability of consumption as a function of the income cluster

5 INTEGRATION OF THE PROPOSED MODELING APPROACH INTO THE DESIGN AND MARKETING PROCESS OF RESIDENTIAL BUILDINGS

As discussed earlier, building experts need to predict the influence of occupants on the overall performance of buildings, as early as possible in the design phase. Even though building contractors and designers do not know the exact profiles of a building’s future occupants, they may still have an abstract image of those profiles. The information about future occupants are used by architects, designers, and engineering consultants to better adapt the building’s design accordingly, and to better propose maintenance and energy management services during buildings’ use-phase. The proposed SABEC model may thus serve in such an industrial context.

5.1 More Accurate Forecasting Of Occupant-Related Energy Consumption

The model presented in this paper may be used as a complementary tool to traditional energy simulators. As pointed out in the second section, industrial simulation tools are not sufficiently granular to account accurately for electricity and water consumptions yielded by domestic activities. A possible advantage of using the SABEC model would thus be to provide more accurate energy estimates at the level of domestic activities and appliances. The model would also be used to assess variability in energy consumption values between different occupant clusters.

5.2 Promoting Design and Construction Solutions

Accurate energy models may enable building designers to get more precise insights about occupants' energy consumption patterns. This would help them promoting design and technical solutions that limit these consumptions by making them more independent of occupants' variability. A possible use of the model may be thus to estimate the usage durations of electro-domestic appliances, which generate 'internal heat gains', and therefore to better forecast cooling and heating loads. The model may also be used to identify major energy-consuming end-uses (activities) in order to guide some design solutions. For instance, the installation of low energy-consuming bulbs can reduce the electricity consumption for lighting, and thus limit the variability that may arise from occupants' personal lighting equipments. We have performed a case study to test a specific design alternative related to the installation of a central laundry room equipped with energy-efficient washing machines in a residential building composed of 54 dwellings of different sizes. Using SABEC model, estimations of energy and water consumption for the "washing laundry" activity are quantified for the two cases (presence and absence of such a central laundry room) and for all of the dwellings. The electricity and water consumption results for each of the 54 households are shown in Figure 5. The results revealed that savings in electricity for the whole building (54 households) can reach up to 206 KWh/month that is a reduction of 37%, where savings in water are about 14139 liters/month that is a reduction of 31% (Table).

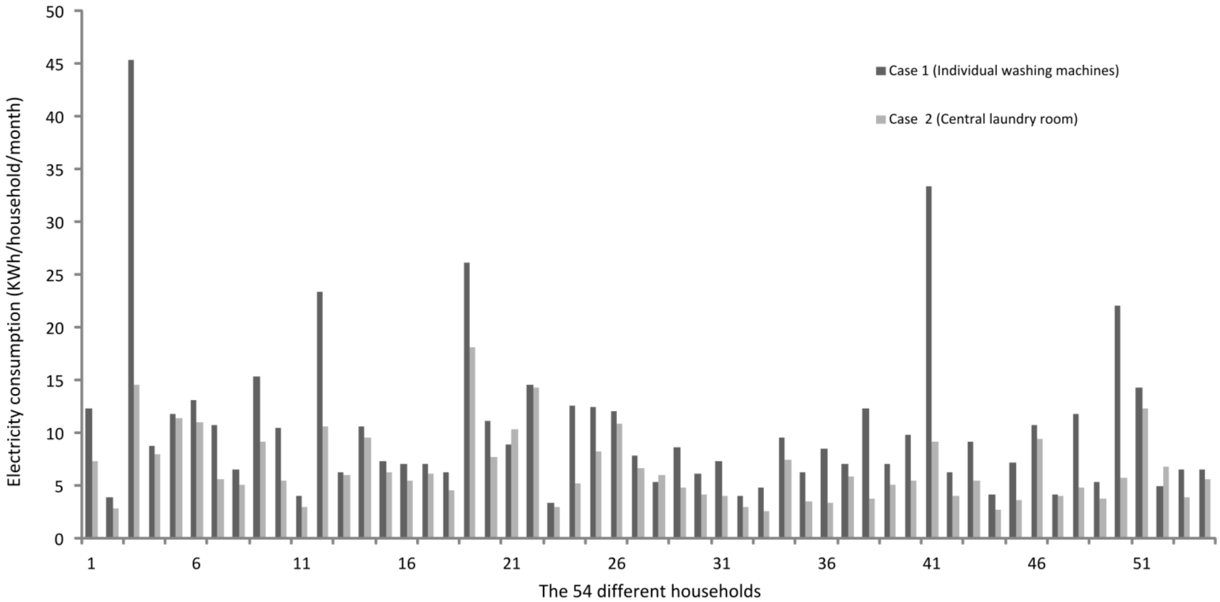

Figure 5: Comparison of electricity consumption for both design alternatives

5.3 Adjusting Energy Performance Guarantees

Energy performance contracts (guarantees) are becoming a powerful marketing offer by which contractors can attract more clients. These contracts can be signed either for a single building or a building stock, and may include energy-efficiency clauses related to the installation, operation and maintenance of energy-consuming systems [6,47]. Experts from our industrial partner confirm that a precise modeling approach, such as the one presented in this paper, would be very beneficial for adjusting energy performance thresholds to be defined in contract clauses.

5.4 Offering and Improving Services

Construction firms have started installing connected tools for the newly constructed green buildings [48]. The installation of these instruments is included in a global offer which also involves information and incitation services for building occupants. Such tools provide real-time information for occupants about their energy consumption levels, yet they do not provide detailed consumption data for all energy end-uses. We believe that an 'activity-based visualization' of energy consumption might be more expressive and more incisive for occupants than nowadays traditionally 'sensor-based monitoring tools'. An 'activity-allocation' model, which consists of assigning physical measuring sensors to a group of appliances belonging to a given activity, could thus be of great interest in this perspective. For instance, personal computer, game console and TV constitute the appliances of the 'entertainment' activity. The authors have already a published work on such a an activity/appliance allocation model in [49]. This concept is being studied now by our industrial partner and may be applied in the near future.

6 DISCUSSION, CONCLUSIONS AND PERSPECTIVES

This paper demonstrates how a user-focused model, which accounts for occupants' energy-related needs and activities, can be used within the engineering design, energy management processes, and marketing offers of residential buildings. An activity-based approach for modeling occupant-related energy consumption is presented and a sample of simulation results is demonstrated. The examples show how the model can be used to assess variability of energy consumption as a function of household profiles' heterogeneity. The possible integration of the proposed model into the industrial context of residential buildings is discussed, and a number of use-cases are identified. First, the model can be used in the design process of buildings: (1) as a complementary tool for energy simulation tools to produce more accurate energy estimates, and (2) to guide and better adapt certain design solutions. Second, the model can be used to better elaborate and finely tune energy performance contracts as a function of occupants' profiles. Third, the model can help improving the visualization features of energy monitoring tools through an activity-allocation decomposition of energy use. Some of the use-cases presented in this paper are still not completed, and are thus presented at an abstract level. The authors highlight that the ongoing work is focused on modeling the complete set of domestic activities, and the next step will be the development of a simulation tool which shall be implemented in the industrial context with our construction partner.

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