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Activity-based simulation of households' energy and water consumptions

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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, standing for *Stochastic Activity Based Energy Consumption*) 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.

BACKGROUND AND RELATED WORK

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.

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.

THE SABEC MODEL

Ontology and principles

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 , 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].

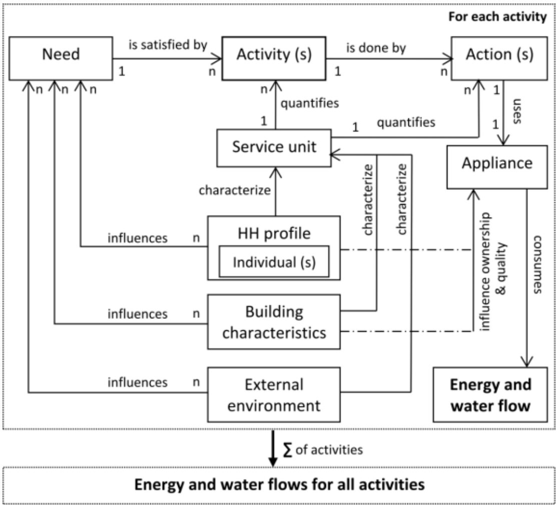

Figure 1: Architecture of SABEC model

Deterministic simulation of energy and water consumptions

This SABEC model has been used for stochastic simulations in [46] of households' energy and water consumptions. The detailed work can be found in [19] (Downloadable here: https://hal.archives-ouvertes.fr/tel-01087894).

In the following, the authors present the deterministic energy and water consumption simulation of a household's whole set of domestic activities.

For summary, it has been proposed a parametric modelling principle of the energy envelope of an activity of a family of occupants according to their characteristics (number, age, sex, occupation and sociological characteristics of family members) by:

- Considering the amount of this activity,
- Correlating the quality and eco-efficiency of equipment brought by the family
- Calculating the consumption by additive summation of individual consumptions and heuristic estimation of the activity sharing
- Fitting of consumption patterns (electricity and water) related to an activity based on national statistical data of consumption.

In total, 28 domestic energy and water consuming activities have been modeled (see the list in Figure 2). These consumption models are expressed with about twenty parameters featuring the household composition.

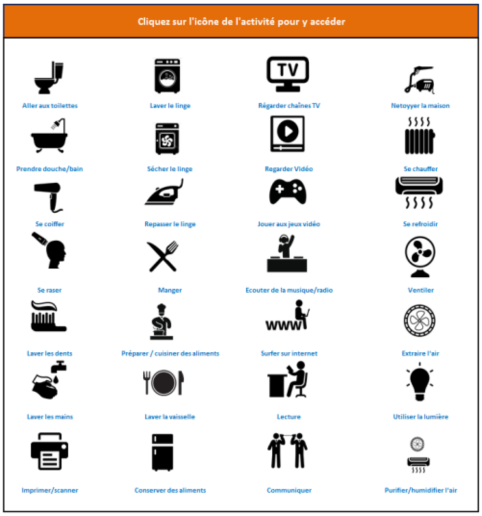

Figure 2: The 28 activities of energy and water consumption

Each activity has been modeled in an Excel spreadsheet by: a subset of influencing households variables, a causal graph of influence starting from these households variables and ending with activity quantities passing through a number of quantitative intermediate variables (e.g. occupation rate, number of weekly meals, laundry weight…), modeling assumptions used, incoming data from statistical databases or national consumptions, and procedures used for model fitting to national consumption data. Figure 3 represents such a data streaming for assessing the final electrical consumption for "Watching TV" activity.

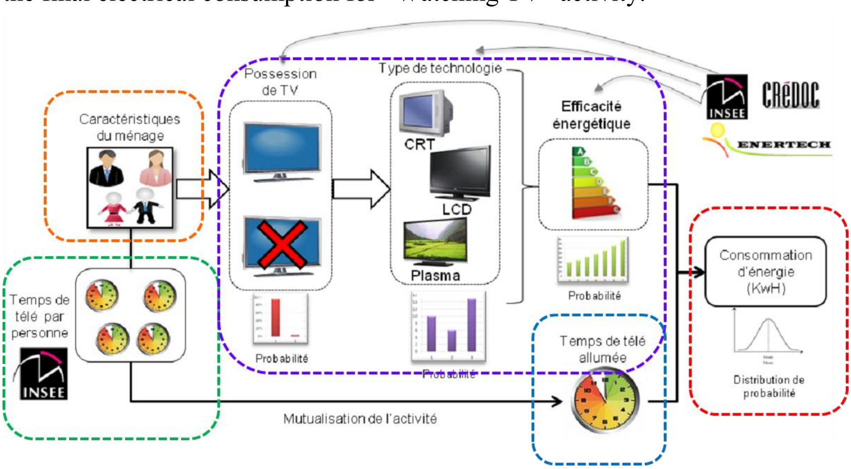

Figure 3: Watching TV electrical consumption model

The household simulation of energy and water consumption is monitored through a dedicated Excel spreadsheet allowing the definition of the household features and of some building physical features (see Figure 4). Some graphical outputs of simulations are provided in Figure 5: for a given dwelling and different households considered: Figure 5.a provides a comparison of both energy and water consumptions, Figure 5.b provides such a comparison under each of the 28 activities.

Figure 4: The SABEC simulation energy and water consumption dashboard for a given household

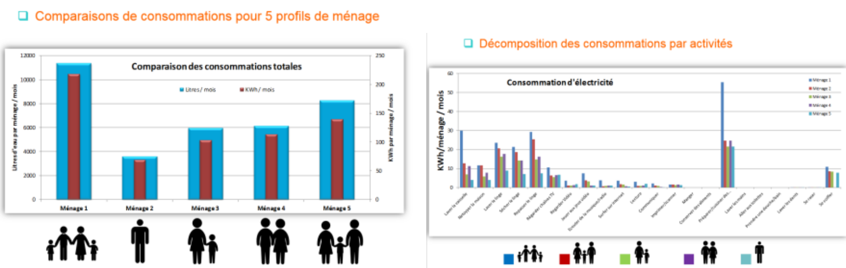

Figure 5: Typical SABEC energy and water consumption of a residence building depending on the household composition

DISCUSSION AND CONCLUSION

Such simulations of energy and water consumptions from different household profiles enable:

- possible refinement or increased accuracy of EPCs (Energy Performance Contracts)
- possible simulations of the influence of certain technical solutions of the frame (e.g. effectiveness or no of pre-installed washing machines)
- to obtain heat gain estimates by activities that are useful inputs for further more accurate dynamic thermal simulations (DTSs).

The originality of our work is the decomposition of electro-domestic consumption by activities. This is of the utmost importance since occupants can and know how to regulate their activities. This model could be central to the development of a connected building approach, to the Internet of Things at the service of information and regulation of consumption. Although to date, we still do not have adequate technical resources for allocating consumption by activities, we can get ahead by calculating consumption by reference activities from the cloud data "for comparable family", develop visualization interfaces and offer occupants means to voluntarily de-consume (incentives, emulation by social network, diagnostic and support to action plan ...).

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