Dynamic Organisation of the Household Activities for Energy Consumption Simulation

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Abstract. Taking into account inhabitants' activities is a necessity for efficient power management, especially in a residential context. In this paper we present an agent-based modelling and simulation framework allowing precise description of the inhabitants behaviour. This framework provides household representation with dynamic organisation capabilities. After introducing the proposed processes, we demonstrate the capabilities of the system to represent coherently the household dynamic organisation in terms of constrained and emergent habits and response to unforeseen event (new electricity tariff and change of the household activities).

Keywords: Agent-Based Modelling, Social Simulation, Electricity Consumption, Inhabitants' Behaviour Adaptation.

1 Introduction

Energy management is becoming an important trend in our society due to greenhouse effect concerns and growing tensions on energy markets. A large amount of the CO_2 emission is due to residential building electricity consumption as it represents around 27% of the final energy used in Europe [2] and 37% in the USA [14]. Power management in the residential sector faces two main challenges: (1) power distribution and balancing and (2) peak consumption reduction. The first is mostly addressed through the development of the smart grids [6] which enables real-time response of electricity production according to the actual demand. In order to meet peak consumption demand, ESCOs (energy supplying company) and DNOs (distribution network operators) are forced to oversize their production and distribution capabilities. Such peaks are short and rare but have a large impact on the overall system. Certainly, the most effective way to limit the peak consumption issue is to change household consumption patterns [13]. Some studies are being conducted to evaluate the efficiency through awareness programs or by the set-up of smart meters allowing inhabitants to track in real-time their electricity cost and the induced carbon emissions [8]. Nevertheless, these field studies are time demanding and costly to conduct, simulation with explicit representation of inhabitants behaviours and how they respond to various incentives would be a solution to such issues.

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We develop the SMACH modelling and simulation framework (see [1] for a complete description) to enable field-experts to investigate inhabitants activities and their relation to the household electricity consumption. In the present paper, we present the organisation processes added to SMACH that allows adaptation of the household activity in response to unforeseen events such as change of electricity tariff or modification of the household constraints.

The rest of the paper is organised as follows. Section 2 briefly presents how household consumption and its change have been modelled so far and then introduces the key elements of the SMACH meta-model. Section 3 describes precisely the two organisation processes proposed in SMACH. Section 4 demonstrates the dynamic organisation of the household with several simulation examples. Section 5 concludes the paper and introduce the current perspectives which are related to improving environment's diversity and complexity and better calibration and validation using upcoming field data.

2 Behavioural Model for Energy Consumption Simulation

Residential electricity consumption has been largely studied from a top-down approach in which the sector is considered as a whole [12]. In contrary, few bottom-up proposals, which consider the household unit, have been made.

2.1 Existing Bottom-Up Approaches

A first class of bottom-up models is the statistical one which use energy consumption data and match them to macroeconomic indicators in order to generate average consumption prediction. The second one, called "engineering method" (EM), uses the dwelling characteristics and appliances' power ratings to generate more individualised prediction. Even though, EM models are clearly more adapted to investigate household energy consumption patterns, we agree with [5] that such models are not sufficient due to their static nature (*i.e.* static consumption profiles).

Whereas more than a few agent-based models have been proposed to study the electricity markets (considering the interactions between ESCOs, DNOs and consumers) [15], limited attempts to represent household inhabitants have been made. In [5], the authors propose to represent explicitly the inhabitants behaviours through a reactive and deliberative decision processes.The authors evaluated numerous deliberative agent architecture and selected the Brahms one [11] as it is similar to the BDI architecture (belief-desire-intention) and its clear definition of thought-frames and work-frames. Nevertheless, we argue that such complex representation of the decision process is not necessary [3] to obtain a model able to tackle our objective: investigating adaptation of household activities to various incentives and events. Moreover, using cognitive-oriented decision are likely to impede the design of experiments by field. In contrary, our activity-oriented model do not require knowledge about human cognition but remains adapted to represent both individual an collective actions.

2.2 SMACH

The key elements of the SMACH meta-model related to the adaptation mechanisms are presented in this section. A more detailed description of the meta-model and the associated simulator can be found in [1].

Metamodel. The environment is limited to the household which is a set of rooms where appliances and inhabitants are located (plus a special location for all outdoor activities). An appliance is characterised by a set of states or a set of programs which defines its electrical consumption. The appliances' electrical consumption are drawn from field measures conducted during the REMODECE european project [1]. In addition, a current date and an electricity tariff are globally defined.

The inhabitants activity is decomposed into generic *tasks* (t) such as *watch TV*, *cook dinner*, etc. The behaviour of each individual is a set of *actions* (a) derived from the generic tasks. A task is a tuple $\langle \tau_{min}, \tau_{max} E_t, E_{tf}, T_{pre} \rangle$ corresponding respectively to minimal and maximal duration to conduct the task, the required and favourable appliances and the pre-conditional tasks. For instance, *ironing* may require the completion of *cleaning clothes*, lasts one to two hours, requires the iron appliance and may be likely to be conducted with the TV switched on.

An action is defined by a tuple $a = \langle t, w, st \rangle$ corresponding respectively to the associated task, rhythm and its conduction state ($done, not_d one$). A *rhythm* (w) is a tuple $\langle per_w, freq_w, var_w, Pp_w \rangle$ corresponding respectively to the base period (day, week, month, year), the frequency, the frequency variability and a set of preferred period (PP). An action example could be as follows: a child may conduct the *watch TV* action according to a weekly rhythm of 10 realisations to be conducted between 7 to 8$a.m$ and/or 5 to 6 $p.m.$

Whereas the rhythm represents inhabitants' habits, the *event* mechanism represents exceptional situation. Concretely, an event replaces the rhythm of several action for a given period. More formally an event q is a couple $([d_{s_q}, d_{e_q}], W_q)$: a period and a set of couples (a, w) (action and new rhythm). For instance, a *sickness* event may prevents an individual to go to work (null frequency rhythm) and force the *resting* action for a few days.

In addition to the individual actions presented, some action can be conducted collectively and/or can benefit the whole household (*prepare dinner* for instance). This is represented by adding a *coll* and a $benef$ parameter to the task characterisation. This collective aspect of the household activity is made possible by a communication protocol based on the speech-act theory [9] allowing agents synchronisation (more details such as the performatives list can be found in [1]).

Action Selection. At any given time-step each inhabitant agent conducts exactly one action which is selected as follows. The agent filters the *possible* actions and then select the one with the highest priority level (resulting in continuing

[1] `http://remodece.isr.uc.pt`

the current actions or starting a new one). An action is considered *possible* if every pre-conditions task have been conducted and all the required appliances are available. The action priority is computed after two types of influence.

- *Agent internal state* influences: commitment to the current action, associated rhythm (*e.g.* is the current date within a preferred period?)
- *Environment* influences: current electricity tariff, other agents invitations (communication) and events

Let us note that only the relative order of the influences values is significant. For instance, an invitation influence higher than the commitment one means that invitations will interrupt current actions *ceterit paribus*. In addition, their initial values have been determined empirically though some of them are subject to an adaptation mechanism, throughout the simulation, that tends to force the conduction of action according to their rhythm. Finally, the priority of an action a can be boosted by another action a' having a as a pre-condition (*e.g.* the *work* action can boost the *take breakfast*'s priority).

3 Dynamic Organisation Process

In this section, we introduce the adaptation mechanisms that complement the previously presented meta-model and enable a dynamical organisation of the household activity. We use the term of organisation to describe the capacity of individuals to coordinate their behaviour in order to achieve a common goal. In our case, the goals of the inhabitants are represented by the rhythms of the actions - frequency and schedule constraints - in other words what people need or want to do every day and every week. This ability needs to be implemented as a continuous process in order to take into account unpredictable events like a new energy pricing or a modification of the household activity. Moreover, because it is continuous, the process has to be light too in order to be able to conduct long term yet precise simulation (*i.e.* our simulation lasts up to several and have a minute time-step). The dynamic organisation process is tow-fold: the first part deals with constrained habits and the second one manages the unscheduled actions.

3.1 Constrained Habits

The organisation process can be seen as a competition between actions for the satisfaction of both constraints. For the frequency constraints (*i.e.* doing what needs to be done), the competition is relative to the duration of a day in which a limited amount of actions can take place. For the schedule constraints (*i.e.* doing it when it should be done), the competition exists when several actions have overlapping PPs (preferred period). The time of realisation of an action is controlled by a specific influence on the action priority. This influence is positive or null during a PP (the bonus) and negative or null outside a PP (the penalty). In other words, the bonus and the penalty govern the likeliness for an action to be triggered inside or outside its PPs. At the end of a day, every action estimates its own satisfaction, and adapts its bonus and penalty according to the following policy :

Bonus increase : increase the probability of realisation during a PP. Used when the action lacks of realisations.

Bonus decrease : decrease the probability of realisation during a PP. Used when the action constraints have been satisfied for a while. It gives the opportunity for other actions to win the competition and thus ensure a slow re-organisation capacity.

Penalty increase : decrease the probability of a realisation outside a PP. Used when realisations happen outside a PP.

Penalty decrease : increase the probability of a realisation outside a PP. Used when bonus increase did not permit to reach the goal frequency, as we give priority to frequency constraint over PP constraints.

Bonus and penalty values are bounded (minimum is zero and maximum is set to respect the influence order see Section 2.2. In case of persistent failure for the realisation of an action, precisely when the bonus is already at its maximum and the penalty at its minimum, the PPs may be slightly extended.

3.2 Emergent Habits

Actions with no initial schedule represent activities that can be conducted at anytime... during the spare time left by scheduled actions. Those mobile actions need to be organised, that is to be given a schedule, for two reasons: scheduling improves the efficiency of the organisation and it is more realistic to give habits to the agents. Nevertheless, those emergent habits should be flexible to adapt themselves to the circumstances. In addition, the modeller is offered the possibility to force an action to remain unscheduled.

The second organisation process aims at creating flexible PPs for mobile actions. Its mechanism relies on the memorisation of the last realisation periods. Those periods are used to update the current schedule of an action. In other words, if one action find the opportunity to be triggered at a given time of the day - wether or not inside a PP, this period will be then favoured as long as it remains in the memory. It is particularly useful for coordinated and exclusive tasks thanks to the emergence of common habits for the first ones (instead of relying on invitations) and differentiated habits for the second ones (resulting in less conflicts.

In order to facilitate the mobile actions to find a first schedule, they receive no PP influence during the first week . Then, from time to time, on a random basis, a given action is *liberated* for a few days (*i.e.* its PP influence is set to zero). Those temporary suppressions of habits gives the action the opportunity to find a more suitable schedule or, another action to take the freed schedules. The frequency and the duration of those *liberations* are some of the factors that control the global mobility of actions, making the routine of a household more or less tight.

Thanks to these adaptation mechanisms, a household can dynamically organises its activities in relation to the current circumstances. The next section demonstrates such ability facing energy pricing changes and major modifications of the household routine.

4 Dynamic Organisation of a Household

In order to evaluate the household organisation capabilities, we introduce the *completion rate* that is the number of actual realisations over the number of realisations specified by the modeller. The difficulty - or even the possibility - to achieve a 100% completion rate depends on several factors including the number of coordinated and exclusive activities, the complexity of the schedule constraints and the *occupation level*: the time needed to achieve all the requested activities over the time available. A second indicator, *PP fulfilment rate* , of the organisation measures the fulfilment of the schedule constraints. In the present case, there is no conflicting schedules situations but such situation is presented and solved in [1].

In this section, 3 situations will be tackled: (1) Initial organisation process (2) Re-organisation in relation with a new energy pricing and (3) Re-organisation following a major change in the household activities. Firstly, let us describe the simulation setting.

4.1 Simulation Setting

The simulation involves a family of 2 parents (John and Mary) and a teenager (Bill). Each one of them receive 3 kind of tasks:

Scheduled tasks : *Sleeping* at night, taking the 3 main meals at the usual time, *Taking a shower* in the morning and *Going to work* or *to school* during the day from monday to friday, with the exception of wednesday for Mary and Bill. In the last simulation, Mary will have a different working schedule.

Mobile tasks : Those tasks have a frequency constraint but can be done at anytime during a a week. In this category, we found housework tasks and leisure tasks. The first ones are shared and can be done indifferently by one of the parents. They include *Cleaning* (using the vacuum cleaner), *Washing clothes* (feeding the washing machine and starting it) and *Ironing* (using the iron). The leisure tasks regroup different types of activities: some of them are coordinated (*Playing chess...*), just more collective than individual (*Watching TV*), free or even exclusive (using the computer for its own purpose.) They can be indoor or outdoor like *Hiking*, and require or not an electrical appliance.

Unconstrained tasks : those tasks have no constraints at all and thus have a low priority. They are triggered when no other tasks is available.

When considering the frequency constraints and the average duration of the actions, we obtain an occupation rate of $\approx 88\%$ per week for each inhabitant. It is sufficiently high to test the organisation abilities of our model.

Let us note that frequency and schedule constraints can be mitigated. For instance, a weak frequency constraint task will receive a lower influence than another one with a strong frequency constraint, thereby creating a hierarchy in the probability of realisation between the tasks. Although, in the following examples, all constraints have been made strong for the sake of clarity.

4.2 Organisation Building and Stability

The first simulation lasts 15 weeks. The figure 1 shows its completion rate by week. It is a typical outline as the completion rate increases during the first 3 or 4 weeks and then is relatively stabilised. The increase stage demonstrates the organisation process: unscheduled tasks find a proper settlement and scheduled tasks adapt their influences too, if necessary.

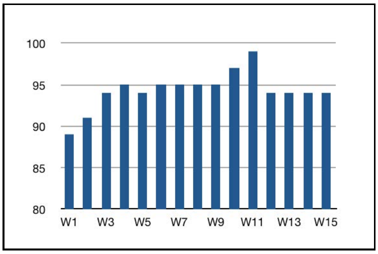

Fig. 1. Completion rate in % by week

In our case, the completion rate stabilises itself around 94% in average. The 6% missing realisation includes uncompleted realisations - started but interrupted before finished - (around 3%) and conflicting tasks. For instance, during 5 weeks, the family goes hiking on sunday around lunch time, thus missing the lunch. Let us precise that the permanent re-organisation process makes the missing realisations to move from one activity to another.

What should we think of the 94% completion rate? On the one hand, considering the occupation rate of 88% and the 6% of time spent in unconstrained activities - a time that could have been dedicated to constrained actions - we can assert that a better organisation, producing a higher completion rate, is possible. On the other hand, optimisation is not our concern: even though people organise their schedule, they do not completely optimise it. The first-weeks increase of the completion rate demonstrates an organisation building process, that is what we need to observe the household adaptation to new situations.

For a more concrete illustration of the organisation process, we will use the long-term activity diagram. This diagram is composed of a succession of coloured columns, one column for one day, and one colour for each task. On the horizontal axe, days are following one another. The long-term diagram offers a synthetic view of habits and change of habits over long periods.

The figure 2(a) shows the long-term diagram for 2 coordinated leisure tasks : *Gaming* in red (4 times a week for Bill and Mary with the use of a computer) and *Hiking* in yellow (2 times a week collectively) and a constrained one: the large purple strips represent *Going to school*. The latter helps us to identify wednesdays and week-ends (no purple stripe).

One can observe that *Going to school* with its strong constraints exhibits a very regular pattern. On the contrary, the 2 leisure tasks settle quickly on some specfici days and times, but move occasionally. This mobility may have several causes:

1. Due to the organisation process, an action may take the place of another one. For instance, at the beginning of the simulation, one of the gaming session takes place on tuesday night and prevents to have dinner (see figure 2(a)). For this reason, *Having diner* adapts its bonus and then, from the third week, it is able to interrupt the gaming session (the 2 separated red stripes).
2. Several stochastic factors intervene during a simulation. One of them is the draw of the number of realisation for an action on a given day. This is why the family who starts to go hiking on saturday afternoon switch from the third week to the morning. The previous weeks, they used to watch TV together. That day, Bill did not draw a realisation for *Watching TV*. Then, the priority of *Hiking* is high enough to be triggered for him and an invitation to hike to his parents is made. The invitation influence positively the parent in favour of this task and thus, they start to do it.
3. Some events like a new pricing or a change in the usual activities may disturb the organisation. We will address those situations in the next sections.

It is worth noticing that the organisation process produces a great deal of variability as shown in figure 2. Indeed, even if two families are very similar in terms of structure and constraints, they are unlikely to come with identical organisation (*i.e.* there are different solutions). Nevertheless, very constrained (*i.e.* scheduled) task, such as work or school, are conducted in a very similar organisation.

4.3 Reorganisation Following a New Energy Pricing

Here, we would like to illustrate a household reorganisation following a new energy pricing. In a simulation with the same settings, the energy price is uniform except in February. During this month, the power company decide to set a new pricing, with a higher price between 6-am and 12-am from monday to saturday. They may want their client to lower their consumption during this period.

As described before, a money saving trend has been added to our model as an action priority influence. More precisely, the energy consuming tasks receive a penalty during the costly periods and a bonus outside. The level of those added influences may vary from one agent to another in order to represent various attitudes in relation with money saving. In this simulation, Bill is less concerned than his parents.

The figure 3 shows the activity diagram for all the energy consuming tasks, with the grey squares indicating the costly periods. One can notice that most

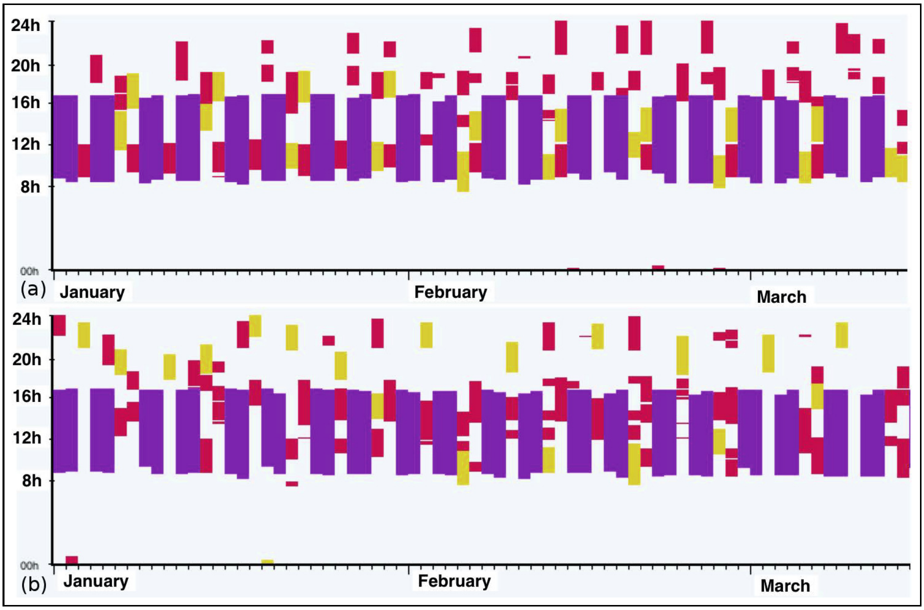

Fig. 2. Activity diagrams of 3 tasks: Going to school (purple), Gaming (red) and Hiking (yellow). (a) and (b) are two different simulation runs.

of the morning consuming tasks migrates to the afternoon and the evening from the beginning of February. Only the sunday morning, when the price is normal, keeps its routine. There is an exception: Bill still uses the computer on wednesday morning; the avoidance of costly periods can be personalised and tuned.

The migration of energy consuming tasks leads, necessarily, to a significant re-organisation of the activities. For instance, the gaming session of wednesday morning is displaced to the wednesday evening. Nevertheless, the disturbance is barely noticeable in term of completion rate: it is decreased by only 1% during the first week of february (week 5).

After the end of february, the price is uniform again. It takes about 3 weeks for the consuming tasks to populate again the morning. This is the time needed to overcome the habits taken during the month of February.

4.4 Reorganisation Following a Change in Household Activity

People have babies, go on holidays, get unemployed, etc.: major changes occurs in a household from time to time and a long term behavioural model have to deal with them. Our last example is a similar simulation, lasting 10 weeks, and with a change in Mary's activities: she starts the simulation unemployed and then, from the 5th week, go to work full time from monday to friday.

The completion rate of this simulation (figure 4(a)) shows a significant drop when Mary starts to work (from 97 to 93%). This drop comes from the time-occupation rate increase caused by the new workload of Mary. Indeed, there

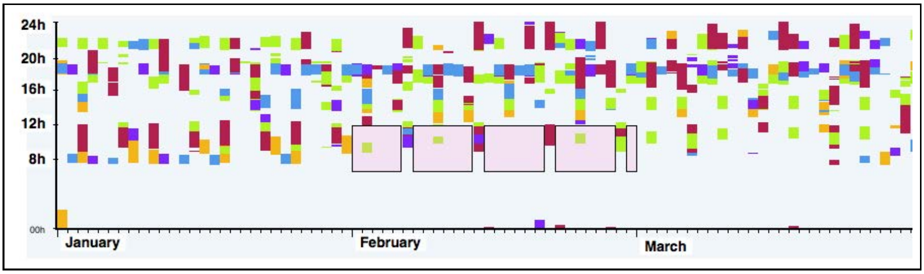

Fig. 3. Activity diagram with the tasks using electrical appliances. Grey squares show periods with higher energy prices.

is a direct link between the time-occupation rate and the difficulties for the household to complete their tasks.

Despite the predictable completion rate drop, one may observe an interesting phenomena in relation with the housework tasks. During the first 4 weeks, Mary perform more than 70% of them because she has more spare time than John as shown on the figure 4(b). Later on, her workload rises thus, a significant part of the housework migrates toward John : Mary having less time to deal with them, those tasks are more likely to be made by John. As we set her working hours longer than his, John then takes the bigger part of the housework, around 60%. Bill, on his side, can participate a bit to the collective tasks making breakfast and lunch, the only housework tasks possible for him.

In the real world, a balanced housework sharing is not a general feature of a household. Anyway, we believe the workload allocation ability of our model to be useful as a general trend and, when necessary, several possibilities to constrain the sharing are offered to the modeller.

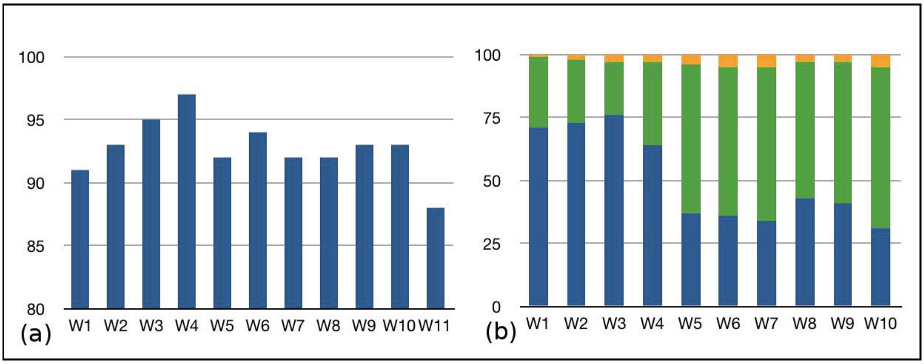

Fig. 4. (a) Completion rate in % by week and (b) Housework tasks sharing in % (Mary in blue, John in green and Bill in yellow)

5 Conclusion and Perspectives

In this paper we have presented a human behaviour meta-model and simulator. This activity-oriented meta-model enable field-experts to represent comprehensively both the routine activities of a household and the unpredictable ones(*i.e.* illness, work schedule change, etc.) that eventually happens. This meta-model is based on the quantitative definition of scheduled tasks (*i.e.* frequency and preferred periods and their degree of imperativeness). We demonstrated the capabilities of our activity model to represent both constrained and flexible habits. Moreover, two continuous processes modify such habits to cope with unforeseen events such as energy consumption incentive and a major constraint change. These features have been demonstrated on several long-term household simulations during which the electricity tariff is dynamic and the work schedule of an occupant is dramatically changed.

Our perspectives are two-fold: (1) better calibration of the current framework and (2) integration of the thermal environment. Our ESCO partner has an ongoing large scale field experiment in which precise household activity schedule are collected. We will use these to calibrate more precisely our model in terms of electricity consumption. In conjunction with participatory simulation experiments (see [10] for previous experiments), it will allow us to validate some of the hypotheses made by field-experts during the development of SMACH. Concurrently, the activity model which allows to simulation end-use consumption will be complemented with a heating model. Indeed, heating may contribute to 50% of household consumption. The under-development model is constituted of two sub-models: a thermodynamic dwelling one introduced in [7] and a thermal environment control model based on the thermal comfort as proposed by Fanger [4]. They allow to represent the thermodynamic of the dwelling, based on both its characteristic and the weather, and the inhabitants responses to the internal environmental, by taking into account the temperature but also the individuals state (*e.g.* clothing, activity, etc.).

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