INTRA-HOUSEHOLD INTERACTIONS OVER TIME: AN ACTIVITY-BASED APPROACH

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ABSTRACT

To jointly predict the dynamic decisions of the household and interactions among members, the household activity-based model is revisited from a time series perspective. A panel nested logit model is proposed with the group decision mechanism, and is calibrated with the data from 2011 Hong Kong Travel Characteristics Survey. In this study, the time dependence of joint activities between household members is empirically discovered. It shows that members who had more joint activities in the past, are likely to have more in the future. In addition, the individual and family taste heterogeneities are also investigated. It was found that the employed household members and students have the largest weights in family decision making. In the households, members of unemployed, retired, and homemakers have the largest extra gain from the joint activities as compared to solo activity participation. Incorporating the time dependence and taste heterogeneity significantly improves the proposed model's goodness-of-fit.

Keywords: social influence, time dependence, discrete choice analysis, demand forecasting, activity-based model

1. INTRODUCTION

Travel behaviors are derived from the activity to be participated. In this regard, activity-based models attract increasing attention in the transportation demand forecasting. Various streams of research focus on modelling individual's activity, in terms of patterns, timing, schedule, and its relationship with the transportation network. However, most models assume that individual's decision is independent across population. To relax this constraint, social influences are considered, particularly, the intra-household interactions (Bhat and Pendyala, 2005; Timmermans and Zhang, 2009; de Palma et al., 2014).

Existing literatures reveal that, household members, as the closest circle of one's social network, have significantly affect one's activity choice. Several promising streams are developed for activity generation. For instance, Fu et al. (2016) analysed the activity-travel scheduling problem considering intra-household interactions, where the scheduling process is based on a supernetwork representation (Liao et al., 2013). Ho and Mulley (2015) used a tour-based style, where the activity patterns are pre-determined, and discrete choice models can be applied to compute the choice probability of each tour. Bhat et al. (2013) developed a discrete-continuous extreme value model, where a group decision mechanism is used, and the number of participated members are precisely forecasted. Various types of intra-household interactions were analyzed. However, it seems that the decisions over time are assumed as independent.

Some researchers focused on the time dependence among activities of individuals. They used the Markov process to consider the time dependence in individual's activities (Xiong and Lam, 2011; Fu et al., 2015; Danalet, 2015), and the temporal correlation was empirically found out. To our knowledge, the extension to intra-household interactions are left for future research. Particularly, the time dependence may reveal the taste and preference of the couple. For instance, a couple have several joint activities in the past, and they are expected to have more in the future. Therefore, the decisions in the past and future are correlated. Ignoring the time dependence of intra-household interactions may cause imprecise forecasting of activity and travel demand. To fill this gap, this paper revisited the intra-household interactions from a time series perspective.

The rest of the paper is as following. Section 2 provides a panel nested logit model, to jointly model individual's dynamic activity choice and intra-household interactions. The individual and household taste heterogeneities are explicitly modelled. In addition, the extra gain from intra-household interactions are elicited. Section 3 is the empirical analysis, where the 2011 Hong Kong Travel Characteristic Survey (TCS) is studied. The last section concludes.

2. METHODOLOGY

A dynamic discrete choice model is developed to capture household members' decisions on: (1) the activity choice; and (2) whether to participate the activity alone or with other members. Without loss of generality, only two members in the household are considered, where the cases with more than two members can be naturally extended. The utility of a household member *n* chooses activity *i* at time *t*, considering the interaction with household member *m*, can be represented as $U_{inmt} = V_{inmt} + \varepsilon_{inmt}$, where V_{inmt} is the deterministic utility and ε_{inmt} is the error term. The characteristics of previous activities are used as lagged variables, entering the utility function via both V_{inmt} and ε_{inmt}. Comparing with the basic model that has ε_{in}, the increased dimensions in the error terms are *m* and *t*. Therefore, the new dimensions of *inm*, *int* and *inmt* in the error terms are analyzed respectively. The utility function is rewritten as

$$U_{inmt} = V_{inmt} + \varepsilon_{in} + \varepsilon_{inm} + \varepsilon_{int} + \varepsilon_{inmt} . \tag{1}$$

Particularly, the distribution of the error terms decides the expression of the model.

2.1 The increased dimension *inm* in the error terms

It is assumed that when members choose an activity, they do not only consider their own utility, but also the other members' utility. Therefore, they will choose the activity that maximizes their perceived household utility. The additive-type household utility function is applied because of its simple expression which can be easily interpreted, and

$$U_{in,jm} = w_n V_{in} + w_m V_{jm} + \varepsilon_{in} + \varepsilon_{inm} , \tag{2}$$

where w_n and w_m are the weights (bargaining powers) of household members, and they are specified as the same as Gliebe and Koppelman (2005), using a logistic regression; ε_{in} is the perception errors of activities, and an i.i.d. (independent and identically distributed) Gumbel is assumed for ε_{in} to capture the unobserved variables across activities; ε_{inm} is the perception error when member *n* evaluates the intra-household interactions with *m*, and another i.i.d. Gumbel is assumed for ε_{inm}, to capture the unobserved differences between solo and joint participation of activity *i*. Therefore, a nested logit model is achieved. Each nest represents an activity, and within each nest there is a binary choice for solo or joint participation. This structure has a behavioral meaning, where a household member's decision is decomposed into a two steps' procedure: firstly, in the upper level, the household member needs to decide which activity to participate; afterwards, in the lower level, the household member needs to decide whether to participate this activity alone or with other members.

2.2 The increased dimensions of *int* and *inmt* in error terms

Firstly, the increased dimension *int* in the error terms is investigated. It is the unobserved correlation of individual's decision at time $t-1$ and *t*. In this regard, ε_{int-1} and ε_{int} are dependent. To decrease the complexity of model, we would like to isolate the correlated part between ε_{int-1} and ε_{int}. Literature on the dynamic choice model pointed out that, the time dependence of choices is rooted from the individual's permanent taste. For example, the individual is a gourmet, so she/he would be observed to have repeated activities of eating out. However, this taste is unobservable to the analyst. In this regard, another error term, α_{in}, representing this unobserved taste is introduced, and it is called "agent effect". Therefore, ε_{int} can be rewritten as

$$\varepsilon_{int} = \alpha_{in} + \varepsilon_{int}^{'} . \tag{3}$$

By isolating α_{in} from ε_{int}, the new error term $\varepsilon_{int}^{'}$ is independent across time, and the complexity of model is decreased.

Secondly, the increased dimension *inmt* in the error terms is investigated. It can be interpreted as the unobserved correlation of the family's decisions at time $t-1$ and *t*. Therefore, ε_{inmt} are dependent across *t*. Similar as the "agent effect", we argue that the temporal correlation sterns from the taste of household. For example, a couple enjoys each other's company, so they are observed to have repeated joint activities. Therefore, the "family effect" α_{inm} is proposed, to capture this unobserved household taste that are persistent over time. By isolating the correlated part α_{inm} from ε_{inmt-1} and ε_{inmt}, the error terms of the household's dynamic choices are independent. ε_{inmt} can be rewritten as

$$\varepsilon_{inmt} = \alpha_{inm} + \varepsilon_{inmt}^{'} , \tag{4}$$

where $\varepsilon_{inmt}^{'}$ is independent across time. α_{in} and α_{inm} can only be consistently estimated if $T \to \infty,\ t \in T$, which is impractical with the household survey data. Therefore, distributions are assumed for α_{in} and α_{inm}, e.g. normal distributions across individuals and families with two variables: mean and standard deviation.

To our knowledge, ε_{inmt} of intra-household interaction is analyzed for the first time. In addition, a solution is proposed to decrease the complexity of the household's dynamic choice model. The proposed model is tractable after revisiting all increased dimensions in the error terms.

The final model: (1) has a nested structure where the intra-household interactions are explicitly captured and the bargaining powers of household members are modeled; (2) is a dynamic model, and at the same time it relaxes the time dependence of the error terms across *t* by considering the agent effect and by proposing the family effect. A panel nested logit model is developed, and the probability of household members *n* and *m* choose activity *i* at time *t* is

$$\Pr_{inmt} = \Pr\left(in,im \middle| i\right)\Pr\left(i\right), \tag{5}$$

where $\Pr\left(in,im \middle| i\right)$ is the conditional probability of joint participation of activity *i*, and

$$\Pr(in,im|i) = \frac{\exp[\mu_i(w_n V_{in} + w_m V_{im} + \alpha_{in} + \alpha_{inm})]}{\exp[\mu_i(w_n V_{in} + w_m V_{im} + \alpha_{in} + \alpha_{inm})] + \exp[\mu_i(w_n V_{in} + w_m V_{jm})]}, i \neq j , \tag{6}$$

where μ_i is the nesting scale that represents the variance of ε_{inm}, and it is to be estimated; the former term in the denominator is the household utility of joint activity, while the latter one represents the solo activities; α_{in} and α_{inm} are only specified in the choice of the joint activity, because only the difference of utility matters. The $\Pr\left(i\right)$ is the marginal probability of choosing activity *i*, and

$$\Pr(in,im|i) = \frac{\frac{1}{\mu_i}\ln\{\exp[\mu_i(w_n V_{in} + w_m V_{im} + \alpha_{in} + \alpha_{inm})] + \exp[\mu_i(w_n V_{in} + w_m V_{jm})]\}}{\sum_{k,l \in C} \frac{1}{\mu_k}\ln\{\exp[\mu_k(w_n V_{kn} + w_m V_{km} + \alpha_{kn} + \alpha_{knm})] + \exp[\mu_l(w_n V_{ln} + w_m V_{lm})]\}}, i \neq j, k \neq l . \tag{7}$$

Different assumptions for α_{in} and α_{inm} lead to different expressions of the model. Without loss of generality, we assume both as i.i.d. normal distributions across alternatives, individuals and households. However, it requires double integrations and leads to a non-closed-form expression. The simulated maximum likelihood estimation is applied for model calibration.

3. EMPIRICAL ANALYSIS

The 2011 Hong Kong Travel Characteristic Survey (TCS) data is applied for model calibration. The survey includes the daily activity diary of 101,384 individuals, which covers approximately 1.5% of the total population in Hong Kong. 35,401 households were surveyed, and totally 122,237 trips were recorded. 9,590 out of 35,402 households have only two members, and among which, only 4,088 households that both members went out of home on the surveyed day. These 4088 households are selected for model calibration. The joint activities of non-mandatory are analyzed, because these activities are more flexible. Therefore, the activities of maintenance, eating out of home and discretionary were analyzed, where the numbers of observations for these three activities are 1,443, 938 and 866. In all, totally 3,247 observations were utilized, which takes up 38.6% of the observed out-of-home activities from the 4,088 households. The respondent is termed as P1, while the other person in the family is termed as P2. All activities analyzed are on weekdays. A correlation analysis is conducted, and results are shown in table 1. It suggests that members who had more joint activities in the past, have higher probability to jointly participate the next activity. It serves as a strong motivation for the proposed research.

Table 1. Correlation between the number of previous joint activities and the next joint activity

# Previous joint activity	Maintenance (shopping, hospital, …)	Eat-out (restaurants, café, …)	Discretionary (KTV, sports…)	Others	Travel
Next activity is joint	0.49	0.24	0.19	0.17	0.27

Four models are specified and calibrated. Model one is specified as Eq. (5) - (7), without lagged variables, α_{in} and α_{inm}, to investigate the bargaining powers and the extra utilities of joint activities. Model two is "model one + lagged variables", to investigate the importance of the lagged variables. Model three is "model one + agent and family effects", to analyze the unobserved taste heterogeneities of individuals and families. Model four is the proposed one, which will be compared with model two and three. Due to space consideration, we will discuss only the most interesting results below.

Model one: the first one is a nested logit model that only considers the increased dimension *inm* in the error terms, namely, the intra-household interactions without time dependence. Particularly, model one does not include the lagged variables, which might be unobtainable in some applications, e.g. the long-term transportation planning. Besides, model two, three and four are built based on the successful estimated parameters of model one. Therefore, we discuss the results of members' bargaining powers, extra utilities of joint activities, time related variables, and nesting parameters in this model.

Bargainging weight of self		The other person				
		Employed	Unemployed	Students	Homemakers	Retired
Slef	Employed	0.500	**0.866**	0.262	0.924	0.921
	Unemployed	0.134	0.500	0.052	0.655	0.645
	Students	0.738	0.948	0.500	0.972	0.971
	Homemakers	0.076	0.345	0.028	0.500	0.489
	Retired	0.079	0.355	0.029	0.511	0.500

Figure 1. Bargaining powers of different roles of household members, based on Eq. (8).

(1) Bargaining powers: members' bargaining powers are presented in figure 1. The number in row one column two, 0.866, indicates that in a family with one worker and one unemployed, the worker has the bargaining power of 0.866, while the unemployed has 0.134. In all, students have the highest bargaining power, followed by the employed members; while homemakers and the retired members have the least bargaining powers.

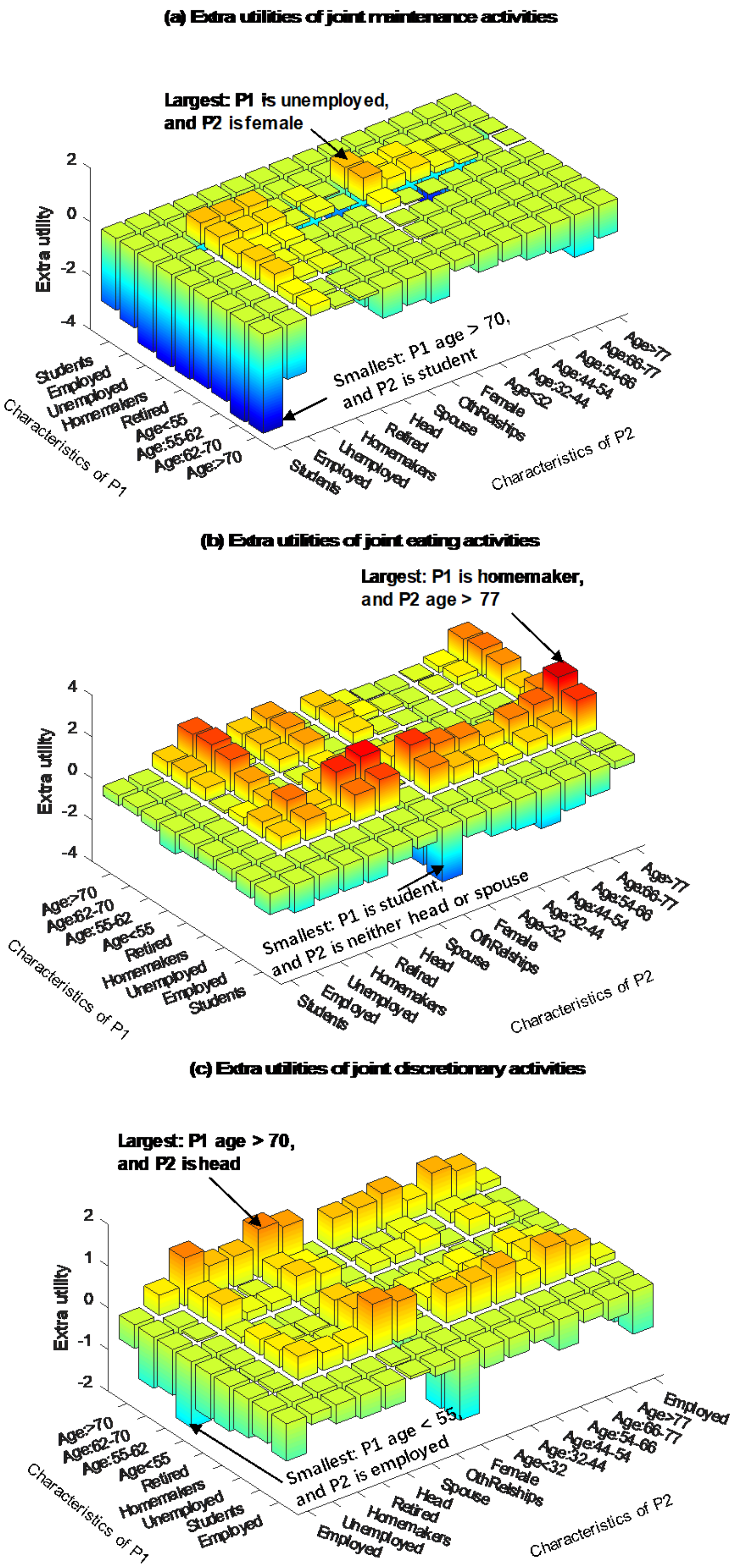

Figure 2 Extra utilities of joint activities. (P1 is the first member, while P2 is the second member)

(2) Extra utilities of participating activities together compared to alone: the extra utility is proposed to measure the extra gain while participating the activity together compared to alone, and it is computed by the difference of utilities between joint and solo activities. Results are visualized in figure 2, where the *x* and *y* axis are the characteristics of the first member (P1) and the second member (P2). The hypothesis of Fu et al. (2016) is validated: activities that require companionship and collaboration among household members have a positive extra utility, such as the joint eat-out and discretionary for the retired; while some routine activities that only need to be undertaken by any one of the individuals are considered as negative, e.g. the joint maintenance activities by the employed on a weekday. Generally, students and the employed do not prefer joint activities on weekdays. It may reveal a fact that the lifestyles for the employed and students in Hong Kong are fast-paced, and during weekdays they do not prefer out-of-home joint-activities after work/school. As for maintenance, if either P1 or P2 is unemployed, homemaker, or retired, then the extra utilities would be positive. If P2 is female, the extra utilities are generally positive. It is as intuitive that female might consider the maintenance activities, e.g. shopping, as fun. The combination of these two members has the largest extra utility in joint maintenance activity; contrarily, if P1 is more than 70 years old and P2 is a student, they have the least extra utility. As for joint eating-out and discretionary activities, it is found out that if one member is older than 70 years old, they have the largest extra utility. This reveals that the senior considers joint non-mandatory activities as companionship. Regarding smallest extra utilities of these two activities, one member is either employed or student, as expected.

(3) Day of week and time of day: results suggest that Friday evening is the most preferable for joint discretionary, which is as expected, because most members are workers. Evening is the least preferable time for joint maintenance. As for the joint eating, a U-shape curve is discovered where morning and evening have the largest values, suggesting the time slots for breakfasts and dinners.

(4) Nesting parameters: only the nesting parameter for the discretionary activity is significantly different from one, suggesting that people would make the joint discretionary decision sequentially: firstly, whether to participate a discretionary activity; then secondly, whether to participate this activity with the household member. As for the maintenance and eating-out, the nesting parameters are not significantly different from one, suggesting the sequential-decision hypothesis might not be valid for these two activities: people would consider participating the activities together as independent as participating them alone.

Model two: the lagged variables, e.g. the types and times of previous joint activities/travels, are considered in this model. The goodness-of-fit improves substantially, where the values of adjusted ρ^2 increases from 0.0843 to 0.367, revealing the time-dependent nature of joint activities. Results suggest that if the last activity is jointly participated, then it is more likely that the next activity is jointly performed as well. It can be interpreted as the "observed family taste" of intra-household interactions, where members who enjoy each other's company, would participate more joint activities.

Model three: the "agent effect" and "family effect" are incorporated in model one to develop model three, without the lagged variables. Particularly, model three is presented to investigate that, if the lagged variables are not obtainable, how the predictive power can be improved via considering ε_{int} and ε_{inmt}. The normal distributions are utilized to represent the individual and family taste heterogeneity, where 300 Halton draws are employed to generate random numbers from the normal distributions. The adjusted ρ^2 is 0.106, although it is better than model one, but it is still worse than model two, suggesting that omitting lagged variables would lead to substantial decrease of model's predictive power.

Model four: it is the proposed model. Table 2 shows the estimates for the agent and family effects, where all estimates are significantly different from zero at the confidence level of 95%, except for the agent effect of joint maintenance. The value of the standard deviation for the family effect of joint maintenance is the largest, suggesting the largest variations in tastes, and the value for family effect of joint eat-out is the smallest. The adjusted ρ^2 is 0.372, which is the largest among models, indicating the need to incorporate both the lagged variables and two types of taste heterogeneity into the model. Because the simulated maximum likelihood estimation is utilized, the estimation is time-consuming: 40.5 minutes for 10 draws, 5.68 hours for 100 draws, and 12.6 hours for 300 draws.

Table 2. Estimations for model four: agent and family effect (300 draws).

Type	Var.	Joint maintenance	Joint eat-out	Joint discretionary
Agent effect	Mean		-0.428	-0.195
	Std. dev.		0.119	0.0501
Family effect	Mean	-7.31	-0.0665	-1.68
	Std. dev.	**1.48**	**0.0171**	0.457

Discussion: firstly, the proposed model has the best goodness-of-fit of four models, suggesting the need to explicitly model the time dependence of intra-household interactions. Secondly, results of model two suggest that, members who had more joint activities in the past, are more likely to have more in the future. As a possible explanation, the temporal correlation may stern from the household's taste, e.g. members' preference for each other's companionship. In addition, model three is proposed to capture the unobserved taste heterogeneity, where estimates are significant, supporting our explanation. Thirdly, the group decision mechanism is empirically investigated, and results suggest that members of employed and students have the largest bargaining weights in household's decision making, while members of homemakers, retired, and unemployed have the least. The extra utility of joint activities is proposed to measure the extra gain from intra-household interactions, and results show that the eat-out and discretionary activities participated by the senior have the largest value. The empirical study reflects a fast-paced lifestyle in Hong Kong during weekdays, where joint activities are not preferred by members of employed and students. It is tractable to explicitly consider the dynamic intra-household interactions, and the empirical study shows that the proposed model is practical.

4. CONCLUSIONS

This paper investigated the household's joint activities with the time series perspective. To represent the time dependence of intra-household interactions, the deterministic and stochastic utilities of the decision maker are modified to capture the observed and unobserved factors, namely, the lagged variables and the taste heterogeneity. It provides us more insights on understanding the intra-household interactions from a dynamic perspective, and thus shed lights on policy implications: ignoring time dependence and taste heterogeneity may lead to biased demand forecasting. Results of this paper contributes to the literature of social influence and group decision, where the impacts from the family members are the influences from the closest circle of one's social network, and family is the basic unit of groups in the society. One drawback of the proposed model is unneglectable: the non-closed form expression and the consequently long computational time. It serves as a motivation for our future research: to achieve a faster way to consider the time dependence of joint activities between household members. Besides, although the extension to cases with three or more household members is not difficult, however when more sophisticated variable distributions are considered for each decision maker, the computation required would be burdensome. The maximum approximate composite marginal likelihood (MACML) estimation method that applied in the spatial correlation could be one of the promising methods for this kind of extension (Bhat, 2011; Bhat et al., 2017).

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