Integration of group decision-mechanisms into activity-based models

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Abstract

Activity-based models (ABMs) have been widely used by transport modellers over the past decades. The dominant approach in activity-based travel behaviour models is based on individual decision-making. However, various interactions exist for individuals making decisions as a member of a household, as well as, different group decision-making mechanisms which can affect the choices of the agents. We investigate the development of integrated models of household group decision-making strategies and activity-travel patterns. We incorporate and operationalise group decision-making mechanisms into household scheduling model, building on the Optimisation-based Activity Scheduling Integrating Simultaneous choice dimensions (OASIS) framework with intra-household interactions. Household-level OASIS simulates multiple intra-household interaction dimensions within the same framework and the coordination of the activity scheduling decisions among all household members is captured. We then showcase how different decision-making mechanisms and relative power of agents in a household can cause variations in the activity scheduling and travel patterns of agents in a household.

Keywords : Group decision-making, intra-housheold interactions, daily scheduling, activity-based models

1. Introduction

ABMs consider the demand for travel to be driven by participation in spatially and temporally distributed activities. By including personal and environmental influential factors, they try to replicate the actual decisions of travellers with more behavioural realism compared to the traditional trip-based models.

In practice, most ABMs are based on individual decision-making. However, ignoring the mutual dependence of household members' decisions limit the behavioural realism of the models as individuals do not plan their day in isolation from other members of the household. This will induce bias in the estimation of activity demand, as well as, travel patterns. Various decisions in a group are derived through group consensus (Zhang et al. 2006; Rose et al. 2004; Corfman et al. 1993). Different members within a household have different relative influences in joint decision-making (Zhang et al. 2006; McGrath et al. 1982). The involvement of household members in the decision-making process differs according to the decision types (e.g., choices of residential location, family holidays, or children's education) (Kirchler 1988; Davis 1976). The members' involvement varies across stages in the household life cycle, as well (Zhang et al. 2006; Kirchler 1988; Cosenza et al. 1981).

Moreover, group decision mechanisms can vary within different households. It can be either consensual; meaning satisfying the minimum level of expectations of all members, or accommodative where strategies like bargaining, persuasion, or role structure may be used to reach a decision (Davis 1976; Spiro 1983). Thus, household decision-making strategies can be affected by socio-demographic and attitudinal variables such as family ideology. These strategies affect not only the relative influence of members in the decision-making process, but also the ways of conducting decision-making. Therefore, there exist diverse general household decision-making mechanisms, which are crucial to explicitly integrate them to realistically model activity-travel behaviour. This can contribute to a better understanding of household decision-making behaviour in transportation. Although group decision-making models are still limited in transportation, there have been advances in this matter in other fields such as economics and marketing.

In this paper, we review studies on group decision-making strategies and explore integrating them into ABMs. We then incorporate and operationalise example group decision-making mechanisms into household scheduling model. We build on the household-level OASIS framework (Rezvany et al. 2023). The household-level OASIS is a scheduling framework which simulates multiple intra-household interaction dimensions within the same model and captures the coordination of the activity scheduling decisions among all household members. Using an example, we then showcase diverse decision-making mechanisms and their varying influence on household members' activity and travel scheduling decisions. Finally, we suggest avenues to be explored in future research including methodological extension contributions.

The remainder of this manuscript is structured as follows. In Section 2. we discuss relevant literature on group-decisions and interactions. In Section 3., we explore incorporating different group decision-making mechanisms into household scheduling model, operationalising the model, and an illustrative example. An analysis of the results is then discussed. Finally, the concluding remarks and opportunities for future research are presented in Section 4..

2. Relevant literature

Most of the conventional activity-based models in transportation research are based on individual decision-making process where the individuals are treated as isolated agents whose choices are independent of other decision-makers (Habib et al. 2017; Bhat 2005). However, the schedule of household members are mutually dependent and thus, ignoring the interdependence between household members causes a biased simulation of activity-travel schedules.

The intra-household interaction models can be either based on statistically-oriented or behavioural-oriented approaches. For instance, the activity participation models developed by Thomas F Golob et al. (1997a) and Lu et al. (1997) which incorporate household interactions based on the LISREL model (Karl G. Jöreskog et al. 1989), are examples of the first category. These models identify intra-household interactions based on statistical significance rather than the behavioural mechanisms underlying them.

Traditionally, economic studies primarily relied on unitary models, in which households are perceived as single units driven by a unique decision-maker acting on behalf of all. In unitary models, the decision-making process is treated as a black box. The possible transactions and diverging interests among family members are disregarded, and the decision-making mechanism is neglected. Unitary models presume inherently aligned goals for the members, leading to poor understanding of decision-making process and thus allocation of resources within the household.

Household-level models consider group decision-making either at the top-level of activity generation, time allocation, or household-level activity pattern generation rather than explicitly modelling interactions among the members (Arentze et al. 2009; Bradley et al. 2005; Zhang et al. 2006; Bhat et al. 2013). In earlier activity-based studies, intra-household interactions were either disregarded (Srinivasan et al. 2005), or addressed implicitly by using household characteristics as explanatory variables for individual decisions (H. J. Timmermans et al. 2009; Thomas F. Golob et al. 1997b).

In reality, many decisions in households are made by not just a single decision-maker. Even in cases where a single individual appears to be the primary decision-maker, their choices may still be impacted, either directly or indirectly, by the preferences or decisions of other members (Hensher et al. 2017). A significant shift occurred in the field of Economics of Family, where non-unitary, called collective models, were introduced by Chiappori (1988). Collective models are more realistic than unitary models explaining households behaviour as they are not based on assumptions such as income pooling, which are typically empirically dubbed (Apps et al. 2009). Collective models acknowledge different preferences among household members and aim to elucidate the collaborative decision-making dynamics within households (Bhat et al. 2005; H. Timmermans et al. 1992). Household decisions are determined by some process of aggregating or resolving heterogeneous preferences. Non-unitary models feature concepts specific to within-family interactions such as bargaining, altruism, and Pareto optimality. Collective models are general framework which can accommodate various bargaining processes and degrees of intra-household caring (De Palma et al. 2021).

The collective models have been in the first place applied in studies exploring consumption behaviour. Household consumption behaviour is regarded as the outcome of an intra-household bargaining process to achieve the Pareto optimal outcome for the household. This strategy can be applied in the household activity-travel demand problems as well (Cherchye et al. 2017). Household activity-travel models with inter-personal dependencies can be broadly categorised as micro-simulation, rule-based, and utility-maximising models. Timmermans (2006) divides the utility-maximizing models, into models that use the discrete choice approach based on random utility models, and models that use the time allocation approach.

One research stream on household time allocation is the multi-linear group utility function models (Zhang et al. 2002; Zhang et al. 2004; Zhang et al. 2005). The multi-linear group utility function comprises individual-specific terms and interaction terms that capture interactions between individuals in a multiplicative form. The multi-linear specification has the advantage of ease of estimation. Zhang et al. (2006) argue that the ability of multi-linear models to be theoretically limited to represent diverse intra-household interactions such as Nash-type household functions. Zhang et al. (2006) develop a time allocation model based on the iso-elastic class of social welfare function, which can include different types of household utility functions as special cases. Unlike the multi-linear function, this is a general function which is more flexible representing various group decisions-making mechanisms. It is notable that there is no clear a priori choice criterion among these alternative Household utility function (HUF) specifications, and the choice depends on the considered problem and relevant empirical evidence.

There still remains room for integrating household decision-making into operational ABMs (De Palma et al. 2021; Vo et al. 2020). Moreover, there is still a lack of consensus on how household interactions should be modelled and the form of household utility functions. The modelling approach can vary depending on the time-frame of the decisions. The non-unitary models have been applied on long-term decisions such as household residential location, workplace location, and vehicle ownership. Applying them to short-term decisions such as daily activity scheduling should be looked into further.

3. Incorporating group decision mechanisms into household ABM

In this paper, we investigate the development of integrated models of household decision-making and activity-travel patterns. We integrate and operationalise cases of group decision-making strategies into a household scheduling model. We build on the household-level OASIS scheduling framework which captures intra-household interactions (Rezvany et al. 2023). In the remainder of this section, first a brief synopsis of the household-level OASIS model is given. Then, a set of alternative specifications for HUF are presented. Finally, using an example, we showcase how different household decision-making strategies can cause variations in the schedules of agents in a household.

3.1 Scheduling model structure: OASIS framework with intra-household interactions

We briefly introduce the OASIS framework with interactions in this subsection. A detailed explanation of the framework together with the definitions and mathematical specifications can be found in Rezvany et al. (2023).

We have proposed a modelling framework to simulate the joint scheduling process of a household, comprising several household members (called agents) over a time period. It accounts for both individuals' constraints and the constraints that appear due to interpersonal dependencies within household members. We treat activity scheduling as a mixed integer optimisation problem based on random utility theory, considering multiple scheduling decisions simultaneously. This adopt the approach proposed by Pougala et al. (2022a). The simultaneous simulation of choice dimensions allow explicit capturing trade-offs between choices. We assume that the agents in the household schedule their day such that the household utility is maximised. Thus, the objective function in the household scheduling problem is as follows:

$$\max HUF \tag{1}$$

where HUF is a function of utilities of household agents $n_1, n_2, \dots, N_m$:

$$HUF = f(U_{n_1}, U_{n_2}, \dots, U_{N_m}) \tag{2}$$

The schedule of each agent is a sequence of activities over a time horizon T, resulting from the agent's choices such as activity participation, activity duration, activity timing, activity location, activity participation mode (solo/joint), and transportation mode.

In our framework, we first ensure that the possible interaction aspects are captured in the utility function by incorporating terms capturing the utility/disutility of joint activity participation and escorting. We further define the constraints such that it ensures the validity of the schedules under both individual- and household-level constraints due to interactions. The within-household interactions lead to more complex constraints, thus, we define household-level constraints to explicitly capture the interplays. Resource constraints and allocation of resources to household members, sharing household maintenance responsibilities, joint participation of household members in activities, joint travels, and escorting are examples of intra-household interactions, which add to the complexity of the constraints in the household scheduling model and captured in the model.

The framework takes as input the household composition, scheduling preferences, activity flexibilities, household resources and their associated events sets, as well as, a considered activity set including their associated locations, transport modes, and participation modes for each agent in the household. They are utilized to define a distribution over possible schedules from which random realisations can be generated. The outcome of the model is a realisation from the distributions of valid schedules, presenting the schedules of the agents in the same household under both individual- and household-level constraints and preferences.

3.2 Representing group decision-making mechanisms

To derive the total utility for the household, the utility of individual household agents should be combined, depending on the nature of the group decision-making strategy. We investigate different specifications for HUF in the OASIS framework with interactions. The multi-linear group utility function proposed by Zhang et al. (2002) is presented in Equation 3. The multi-linear group utility formulation has its theoretical roots in group decision theory. The household utility is defined such that the utility of the agents are added and weighted based on the relative influence of the agents. The specification allows for some multiplicative terms representing the weighted interaction effects. The multiplicative form implies that household members negotiate to balance their own preferences for all shared activities such that the loss of utility from one of the shared activities can be compensated by the benefit from the decision about another shared or allocated activity.

$$HUF = \sum_{n=1}^{N_m} w_n U_n + \sum_{n_1} \sum_{n_2 > n_1} (w_{n_1 n_2} U_{n_1} U_{n_2}) + \sum_{n_1} \sum_{n_2 > n_1} \sum_{n_3 > n_2} (w_{n_1 n_2 n_3} U_{n_1} U_{n_2} U_{n_3}) + \dots \tag{3}$$

where w_n is the agent n's weight parameter, capturing the relative power of each individual in the household-oriented decisions. U_n is the utility that agent n gains from her/his schedule. The interaction parameters $w_{n_1 n_2}, w_{n_1 n_2 n_3}, \dots$ moderate the power effect and reflect the agents' concern for achieving equality in agents' utilities. The larger the interaction parameters, the higher the households' collective desire to choose a activity-time allocation so that the utilities of all agents are more or less equal. The value of the weights can be estimated from preference data, that could be collected from stated preference surveys, for instance. If not available, the weights can be defined based on individual characteristics, determined using the literature, or combining educated guess and trial-and-errors.

The group decision-making formulation proposed by Zhang et al. (2006), presented in Equation 4, is theoretically more flexible to represent diverse group decision-making mechanisms, compared to the multi-linear model. The iso-elastic class of social welfare function (Atkinson 1970) is adopted as the household utility function.

$$HUF = \frac{1}{1-\alpha} \sum_{n=1}^{n=N_m} w_n \, {U_n}^{1-\alpha} \tag{4}$$

where w_n is the agent's weight parameter reflecting their influence in the decision-making process, and α is the Atkinson's measure of aversion to inequality, which describes the household preferences in trading off utilities between its members. Different values of w_n and α represent different decision-making mechanisms. Some special cases of presented generic functions are presented below:

- *Utilitarianism/Additive-type household:* If the group is to behave in a Bayesian rational manner, assuming that the agents first average their separate utility functions and then maximize the resulting mixture function.

$$HUF = \sum_{n=1}^{N_m} w_n U_n \tag{5}$$

If the household members have equal weights, Equation 5 will be the special case of Compromise-type group utility function (Curry et al. 1979):

$$HUF = \sum_{n=1}^{N_m} U_n / N_m \tag{6}$$

- *Nash-type household:* each agent first identifies his/her most preferred outcome. The household then compromises by averaging along the resulting negotiation frontier.

$$HUF = \prod_{n=1}^{N_m} {U_n}^{w_n} \tag{7}$$

- *Minimum-type of household:* the household regards the utility of its weakest agent as the household utility and maximizes it.

$$HUF = \min_{n=1,\ldots,N_m} U_n \tag{8}$$

- *Autocratic-type of household:* the household regards the utility of its strongest agent as the household utility and maximizes it.

$$HUF = \max_{n=1,\ldots,N_m} U_n \tag{9}$$

3.3 Simulation results

We showcase how different group decision-making mechanisms and relative power of agents in a household can cause variations in the schedules of agents using an example. For this purpose, we consider 4 special group decision-making strategy cases:

- A Utilitarianism-type household with equal power within its agents (Compromise-type),
- A Utilitarianism-type household with unequal power within its agents, with one agent having a double influence of the other agent,
- An Autocratic-type household, and
- A Minimum-type household.

For each considered example, we run 500 iterations of the model. We then aggregate the model outcomes generated from several iterations of the model and present the distribution of schedule frequencies over a day.

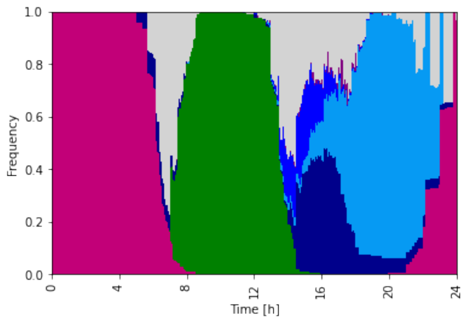
Activity	Desired timings		Average simulated timings							
			Equal Utilitarianism		non-equal Utilitarianism		Autocratic-type		Minimum-type	
	Start time	Duration	Start time	Duration	Start time	Duration	Start time	Duration	Start time	Duration
Adult 1										
Sleep_morn	0	6.50	0	6.33	0	6.48	0	7.51	0	7.25
Sleep_night	22.17	1.83	22.93	1.07	22.98	1.02	21.88	2.12	22.33	1.67
Work	8.50	6	7.60	5.94	7.77	6.01	9.71	6.04	8.88	5.88
Homecare	14.50	7.67	13.73	1.79	14.65	3.55	12.70	3.87	13.81	3.22
Leisure	19	1	17.19	5.06	17.68	4.76	17.19	5.18	17.13	5.11
Maintenance	14.67	1.17	14.08	1.11	14.09	1.40	13.81	1.64	13.94	1.46
Adult 2										
Sleep_morn	0	7.33	0	6.21	0	6.32	0	7.20	0	7.27
Sleep_night	22	2	22.88	1.12	22.78	1.22	21.01	1.99	22.01	1.98
Work	7.83	8.67	7.44	8.22	7.57	8.50	8.95	7.19	9.17	7.01
Personal care	7.33	0.5	6.35	0.5	6.46	0.42	11.08	1.61	10.74	1.66
Leisure	18.17	4.83	17.02	4.98	16.65	4.23	15.75	4.62	15.91	4.30
Maintenance	14.67	1.17	15.40	0.74	15.64	0.91	15.60	1.37	15.14	1.27

Table 1: Desired and simulated activity patterns for considered household decision-making mechanism examples

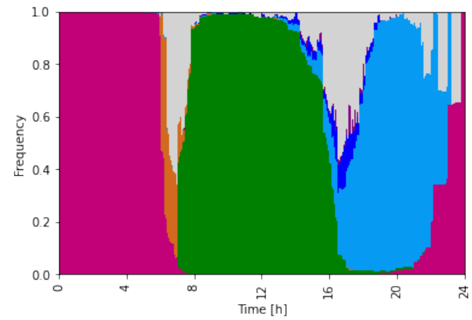
In order to obtain the required inputs, we rely on a real-world daily diary dataset. The data from the United Kingdom (UK) Time use survey (TUS) (Gershuny et al. 2021) is used for this purpose. It includes information on respondents' socio-economic characteristics and those of their household, as well as detailed diary information on activity, location, and accompaniment. We consider an example of household of 2 adult agents. Two adult individuals are randomly chosen from the dataset and their reported activity schedules are used for activity choice set generation and scheduling preferences. It should be noted that the data shows only realised schedules, and not desired start times and durations. We deal with this in this case by assuming that the realised timings of activities are an indicator of the scheduling preferences. Another way to address this would be to collect stated preference data on desired times, though this is out of the scope of this paper.

The schedule frequency for Adult 1 and Adult 2 with model calibrations as members of a 2-member household are presented in Figures 1 to 3. We can observe that, in the simulated examples, the schedule of flexible activities (eg. personal care, homecare, leisure) are more spread over time in the case of Minimum- and Autocratic-type household compared to the Utilitarianism-type household.

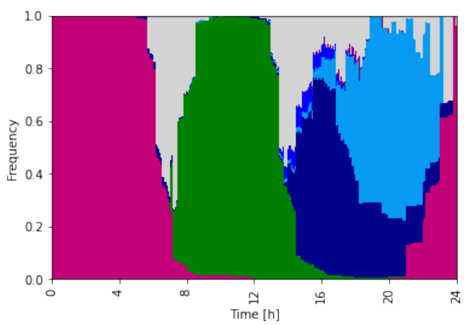
Table 1 summarises the activity patterns for the simulated schedules in the considered examples. On average, in the Utilitarianism-type households, the agents' schedules are closer to their personal desired timings, compared to Autocratic- and Minimum-type households. The deviation is less for the agent with a higher influence in a Utilitarianism-type household with unequal-powered agents. For personal care activities, the divergence in start time is more substantial in Autocratic households than preference. Whereas the deviations in simulated durations for personal care are higher in Minimum-type households. The work pattern of the members is also affected as the household decision-making mechanism changes. Broadly, the agents start work later in the morning and work longer into the evening in the Autocratic- and Minimum-type households. This implies changes in their travel patterns which can thus, affect the peak traffic times.



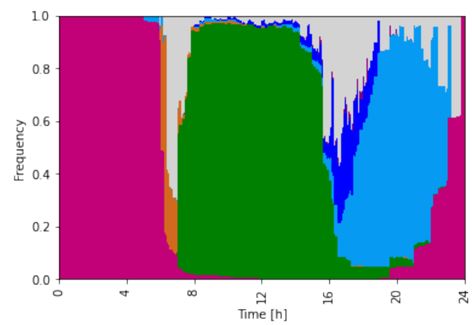
(a) Simulated distribution of activities for Adult 1 in the example of Utilitarianism–type household (case of agents with equal power)



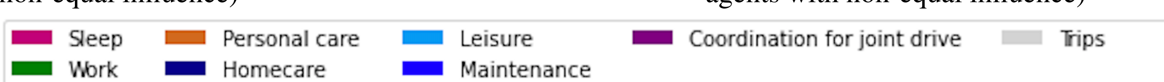
(b) Simulated distribution of activities for Adult 2 in the example of Utilitarianism–type household (case of agents with equal power)



(c) Simulated distribution of activities for Adult 1 in the example of Utilitarianism–type household (case of agents with non-equal influence)

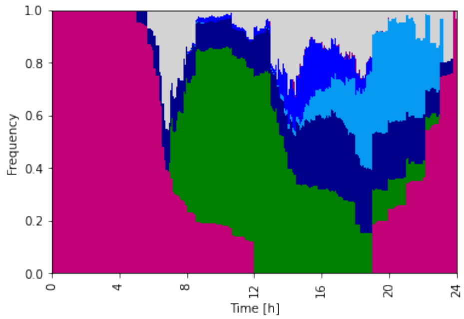


(d) Simulated distribution of activities for Adult 2 an agent in the example of Utilitarianism–type household (case of agents with non-equal influence)

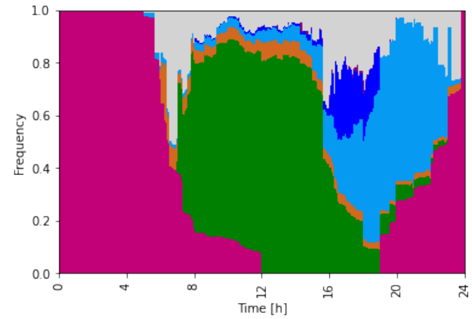


(e) Bar plot color guide

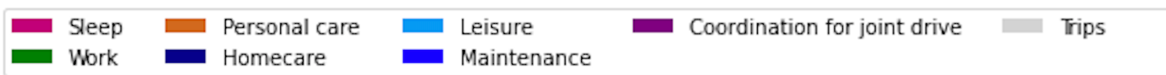
Figure 1: Distribution of simulated activity schedules for Adult 1 and Adult 2 in the example of Utilitarianism–type household



(a) Simulated distribution of activities for Adult 1 in the example of Autocratic type household

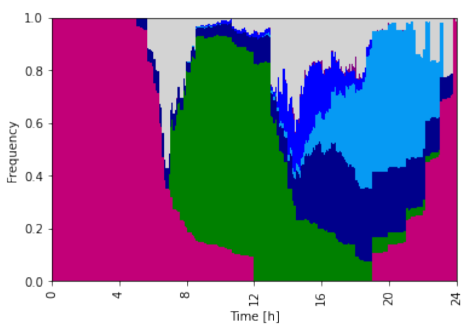


(b) Simulated distribution of activities for Adult 2 in the example of Autocratic-type household

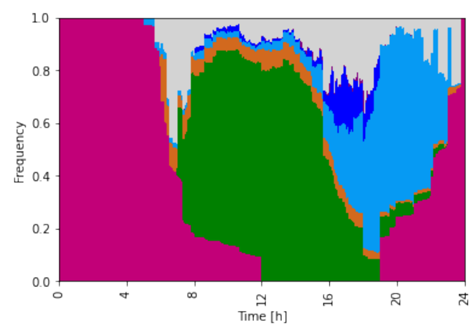


(c) Bar plot color guide

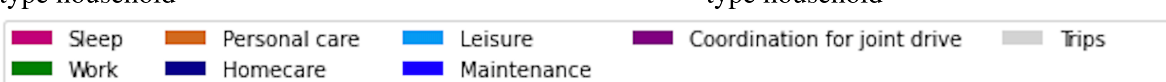
Figure 2: Distribution of simulated activity schedules for Adult 1 and Adult 2 in the example of Autocratic-type household



(a) Simulated distribution of activities for Adult 1 in the example of Minimum-type household



(b) Simulated distribution of activities for Adult 2 in the example of Minimum-type household



(c) Bar plot color guide

Figure 3: Distribution of simulated activity schedules for Adult 1 and Adult 2 in the example of Minimum type household

4. Conclusion and future work

This paper reviews key studies on group decision-making strategies and investigates integrated activity-based models with household decision-making strategies. We incorporate example group-decision mechanisms into a household scheduling model called OASIS (Rezvany et al. 2023). This is an optimisation-based scheduling framework that reconstructs the daily activity schedules of individuals in a household, explicitly considering both the individual- and household-level needs, preferences, and constraints such as the allocation of the private vehicle to household members, escort duties, joint participation in activities, and sharing rides.

There have been advances in group decision-making strategies in other fields such as economics. However, studies in transportation are still limited. The decisions of individuals in a household are affected, directly or indirectly, by other members of the household. This can include long-term decisions such as residential location, as well as, short-term decisions such as daily scheduling decisions. There are example studies on group-decision mechanisms in long-term decisions, however, there is still room for integrating them into short-term decisions such as daily activity scheduling. Household decision-making mechanisms should be explicitly incorporated into ABMs in order to realistically model the activity-travel behaviour. Different group decision-making strategies affect the activity timings and travel patterns of household members.

This paper presents a preliminary investigation and operationalisation of integrating group-decision models into ABMs. There are further work and improvements of the current study, suggesting paths for future research. In future work, we will work on household-level choice set generation, as well as, parameter estimation for OASIS. Building on the estimation procedure using the maximum likelihood estimation technique proposed by Pougala et al. 2022b, aspect of household-level scheduling which lead to further validity constraints in choice set generation, should be considered. Using household-based diary data, the model parameters and weights are estimated. Moreover, in this phase of the research, the operationalised model has not been scaled up. The matter of scaling-up the method is on our agenda to investigate in further research.

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