# Simulating multiple intra-household interactions

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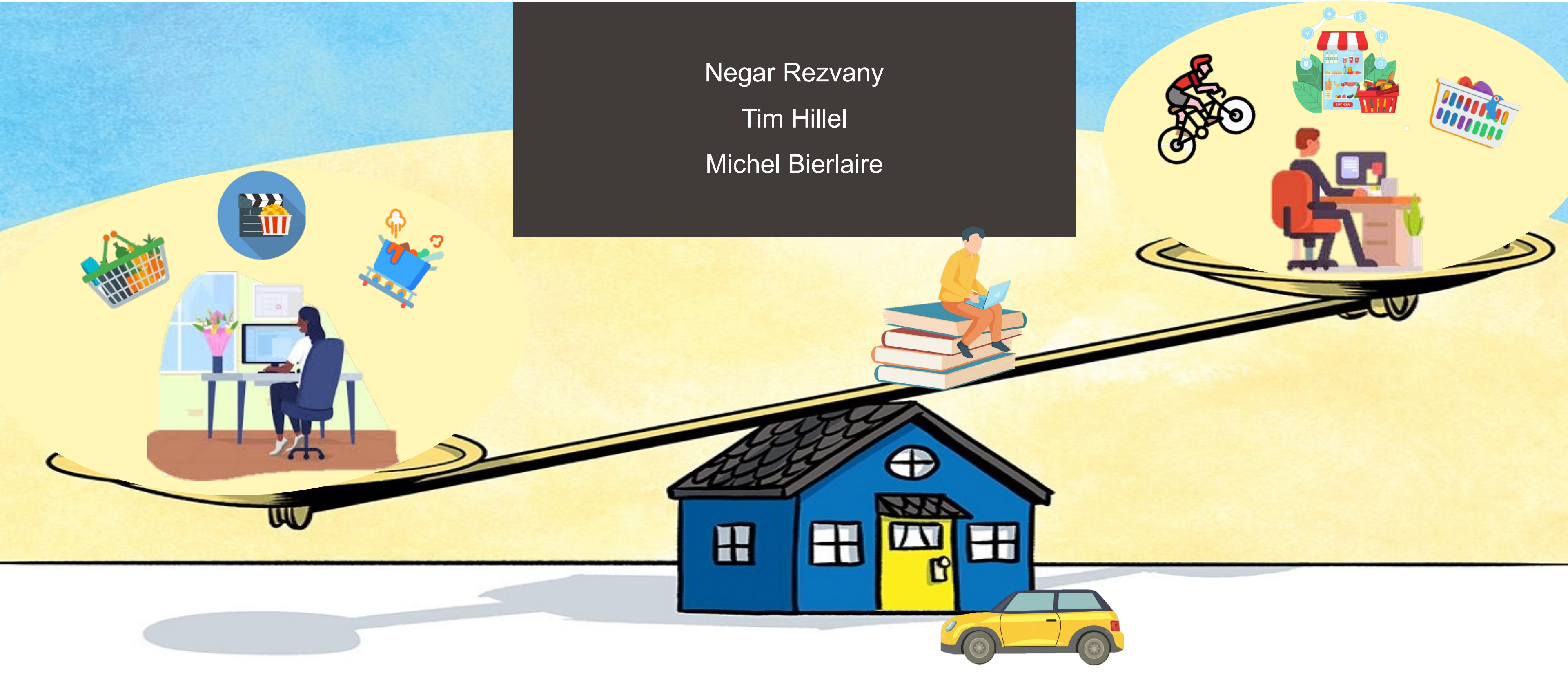


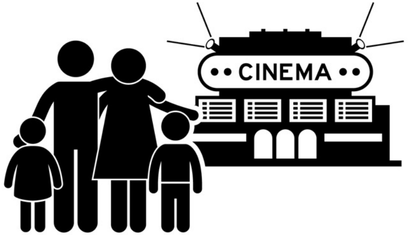
# Outline

# Introduction: Motivation

- Individuals do **not** plan their day in **isolation** from other members of the household.
- Various **interactions**, **time arrangements**, and **constraints** affect the **in-home** as well as **out-of-home** activity schedules of individuals.

# Introduction: Motivation

- **What are some examples of intra-household interactions?**
  - Individuals in a household synchronize their schedules to create time window overlaps for **joint activities**.




Joint participation in a recreational activity

A family dinner at home

# Introduction: Motivation



- **What are some examples of intra-household interactions?**
  - Household members **coordinate their travels** as well.

Escorting children

Sharing a ride

# Introduction: Motivation



- **What are some examples of intra-household interactions?**
  - The members of a household also **share responsibilities and resources** with each other to satisfy household needs.

Sharing household maintenance responsibilities

Sharing resources

# Introduction: Motivation



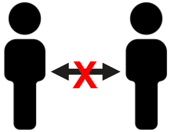
- Why is it important to capture intra-household interactions in activity-based models?
- How can intra-household interactions affect the schedule of individuals?
  - Policies directly affecting the activity and travel patterns of an individual, such as earlier school starting times, can affect the schedule of multiple household members.
  - Joint activities require coordination between the schedules of participating individuals.
  - Resource constraints affect the scheduling choices of individuals.
  - The escorting duty affects the schedule and travel patterns of the adult members as they should accommodate the pick-up and drop-off activities into their schedule.

➡ Considering the interpersonal dependencies in a household, the activity schedule should be addressed from a **group decision-making point-of-view** rather than isolated agents in order to reflect reality.

# What is the current state of the research in activity-based modeling?

- Activity scheduling process has been of interest to transportation activity-based modelers in the last decades (e.g. *Hilgert et al. 2017, Bhat et al. 2004, Bowman & Ben-Akiva 2001, Adler and Ben-Akiva 1979*) as the **demand for travel** is assumed to be driven by **participation in activities distributed in space and time**.

- 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.



- However, **ignoring** the **interdependence** between household members causes a **biased** simulation of activity-travel schedules as the schedule of household members are **mutually dependent**.

- In spite of the recognition of the importance of incorporating **group decision-making** paradigm into household travel behavior in 1980s (*Jones et al. 1987*), studies on group choice models are **relatively new** and thus, **limited** due to **methodological difficulties** and **data availability**.

# How have the activity-based modelers studied interactions?

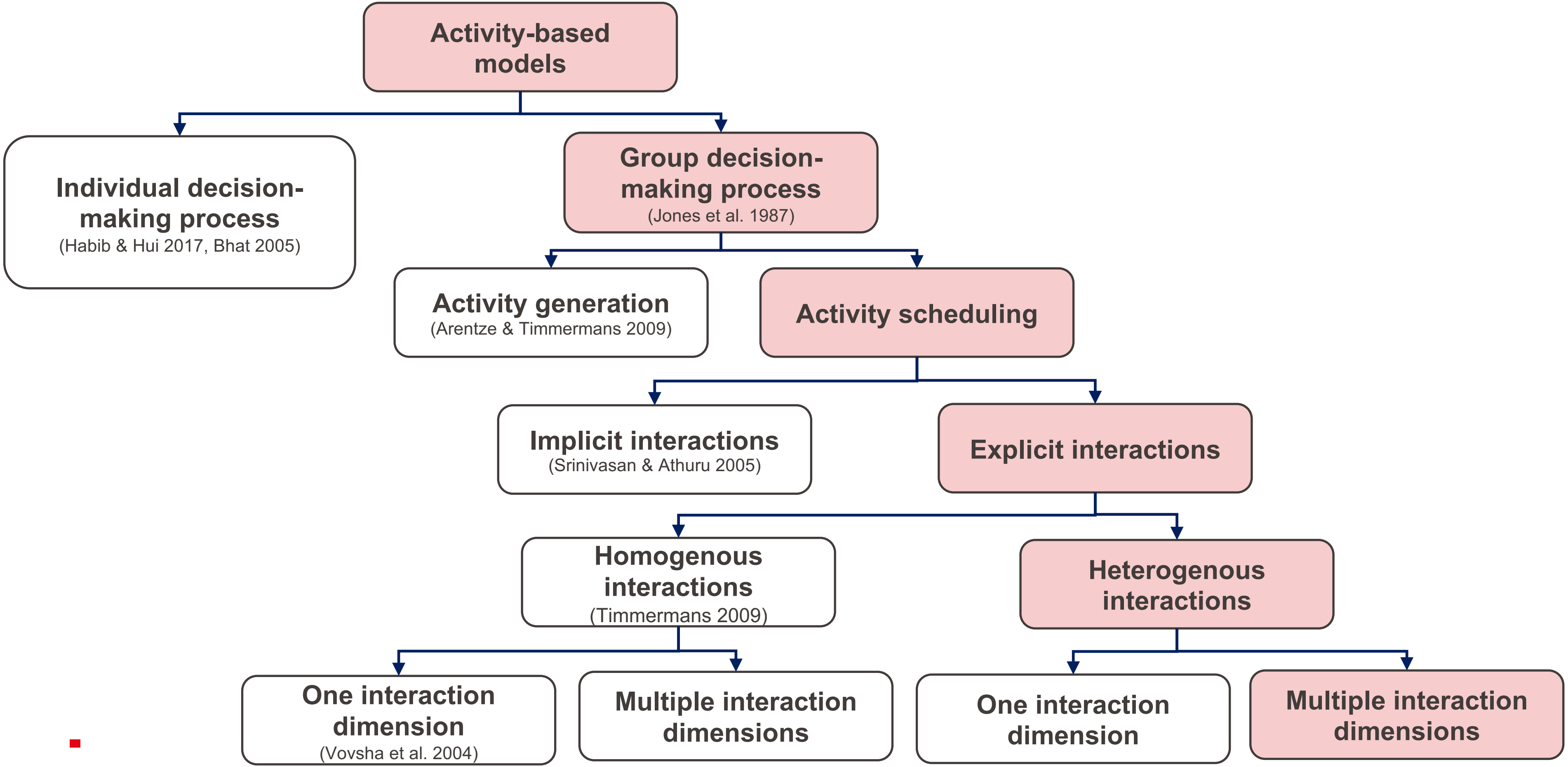
- Only a **limited** number of studies examine **household decision-making perspectives** and consider the **effect of intra-household interactions** in their activity-based models.
- The intra-household dependencies in activity-travel behavior have mostly been explored at the **top-level** of **activity generation** and much less at the level of household activity scheduling process (*Bhat et al. 2013, Arentze & Timmermans 2009*).
- Early activity-based studies address inter-household interactions **implicitly** such as by using household characteristics as explanatory variables for individual decisions (*Srinivasan & Athuru 2005*).
- This, however, does **not ensure** the **consistency of the choices**.
- These models **cannot explicitly evaluate** the impact of intra-household interactions on the schedule of individuals.

➡ Therefore, capturing the inter-personal effects of household members on their daily schedules needs **explicit modeling of household interactions**.

# How have the activity-based modelers studied interactions?

- Most of the studies that consider the interactions explicitly, assume the intra-household interplays to be **homogeneous**.
- Thus, they do **not** consider the **heterogeneous** and **context-dependent** influence of members on household decisions.
- Existing research address only **one or few aspects** of household **interactions** within their studies such as resource allocation and usage decisions, task allocation, joint activity participation, or travel arrangements.
- In addition, current activity-based models **only** focus on **out-of-home activities** and do **not** contain any information on **activities performed at home**.

# Gaps in the current literature



# Contributions and scope



- A framework to **simulate** the **daily activity schedules of individuals in a household**, **explicitly** accommodating **multiple interactions**:
  - **Group decision-making** paradigm
  - **Simultaneous simulation** of different **choice** dimensions
    - More behavioral realism compared to conventional sequential models.
    - Captures complex trade-offs between different choice dimensions.
  - **Explicit** interactions
    - Ensures consistency of choices.
  - **Multiple interaction** dimensions
  - High level of **flexibility**
    - Based on an optimization-based framework.
    - Interactions and dependencies can be comfortably incorporated by modifying the constraints and/or terms of the objective function of the optimization problem.
  - **Heterogenous** decision-making
  - Both **in-** and **out-of-home** scheduling are simulated within the same framework
    - Allows modelers to capture the trade-offs between in- and out-of-home activities (e.g. in- and out-of-home activity location choices).
    - Understanding behavior and interactions throughout the day is the key to better demand-side management and adapting infrastructure systems (e.g. transportation, energy) to deliver critical services that meet the needs of society.

# Methodology

- We build on the **Optimisation-based Activity Scheduling Integrating Simultaneous choice dimensions** (**OASIS**) framework *(Pougala et al. 2022)*:
  - A mixed-integer utility optimization approach
  - Utilizes a simulation technique to solve the stochastic optimization problem
  - Explicitly captures **trade-offs** between choices
  - At the level of **isolated** individuals
  - Focuses on **out-of-home activity** schedules
  - Is defined under a set of **constraints** that determines the **validity** of the schedules at an **individual level** such as:
    - Time budget constraints,
    - Time window constraints,
    - Boundary conditions,
    - No duplicates,
    - Activity succession constraints, and
    - Time consistency between two consecutive activities: each activity starts when the trip following the previous activity is finished.

# Base OASIS Formulation



- Objective: $\Omega_n = \max U_n$
- Utility of a schedule: $\mathrm{U_n} = \sum_{a_n} \omega_{a_n} U_{a_n}$
    - For individual $n$, considering activity $a_n$:

Utility purely associated with participation in activity, irrespective of timing and trips

Duration deviations

Error term

$$U_{a_n} = U_{a_n}^{partic} + U_{a_n}^{start} + U_{a_n}^{duration} + \sum_{b_n \in A^n} U_{a_n,b_n}^{travel} + \varepsilon_{a_n}$$

Start time deviations

Travel from activity $a_n$ to $b_n$

# Extensions to OASIS framework

- We extend the base model to:
  - Accommodate **interactions** among members of the same household, and
  - **Jointly** simulate **in-** and **out-of-home** activities.

# Modeling framework



- **Fundamental assumption**: individuals do not plan their day in isolation from other members of the household.
- The framework considers the **household** as a **single decision-making unit** while encompassing the activity scheduling behavior of all agents through the utility that each agent derives from their schedules.
- Agents schedule their day to **maximize the total combined utility** of the **household**.

$$\Omega = max \sum_{n=1}^{n=N_m} \boxed{w_n} U_n$$

agent priority parameter

- It accounts for **both individuals' constraints** and the **constraints** that appear due to **interpersonal dependencies** within household members.

# Utility

- The utility specifications have been modified to accommodate interactions.
  - A term capturing the reward of joint activity participation with other member(s) of the household, compared to solo participation in the activity.

$$U_{a_n}^{partic} = \boxed{U_{a_n}^{joint}} + U_{a_n}^{escort} + U_{a_n}^{social}$$

Joint activity participation

$$\alpha^{jnt} p_{a_n} \tau_{a_n}$$

*Joint activity engagement Parameter* ($\alpha^{jnt}$)

*Joint participation mode indicator (0/1)* ($p_{a_n}$)

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# Utility

- The utility specifications have been modified to accommodate interactions.
  - a term capturing the penalty of escorting other agent(s).

$$U_{a_n}^{partic} = U_{a_n}^{joint} + U_{a_n}^{escort} + U_{a_n}^{social}$$

escort

$$\theta_s^{esc} \lambda_{a_n} \tau_{a_n}$$

*Escort penalty parameter*

*Escort indicator (0/1)*

# Utility



- The utility specifications have been modified to accommodate interactions.
  - The reward that social interactions can have at out-of-home locations is added to the utility specification.

$$U_{a_n}^{partic} = U_{a_n}^{joint} + U_{a_n}^{escort} + \boxed{U_{a_n}^{social}}$$

Social interactions

$$\alpha_{l_{a_n}}^{socl} l_{a_n} \tau_{a_n}$$

*Social interaction reward parameter*

*location indicator (0/1)*

# Utility



- Agents in the household solve an optimization problem with the objective to maximize the household utility:

$$max \sum_{n=1}^{n=N_m} \sum_{a_n \epsilon A^n} w_n U_{a_n}$$

$$max \sum_{n=1}^{n=N_m} \sum_{a_n \epsilon A^n} w_n \left(U_{a_n}^{partic} + U_{a_n}^{start} + U_{a_n}^{duration} + \sum_{b_n \epsilon A^n} U_{a_n,b_n}^{travel} + \varepsilon_{a_n}\right)$$

# Constraints



- Firstly, the model constraints are revisited and modified if needed to allow the **integration of in-home activities** into the framework.
- Secondly, **within-household interactions** lead to **additional and more complex** constraints.
  - Resource constraints,
  - Allocation of the private vehicle to household members,
  - Sharing household maintenance responsibilities,
  - Joint participation of household members in activities,
  - Joint travels, and
  - Escorting children.

# Examples of household-level constraints

- **Household private vehicle ownership:**

$$\boldsymbol{\omega_{a_n}} + \boldsymbol{m^V_{a_n}} \leq \boldsymbol{N_V} + \mathbf{1} \qquad \forall \boldsymbol{a_n} \boldsymbol{\epsilon} \boldsymbol{A^n}, \forall \boldsymbol{n} \in \boldsymbol{N_m}$$

- $\boldsymbol{\omega_{a_n}}$: activity participation.
- $\boldsymbol{N_V}$: number of household private vehicles.
- $\boldsymbol{N_m}$: number of agents in the household.
- $\boldsymbol{A^n}$: activity choice set.
- $\boldsymbol{m^V_{a_n}}$: indicator variable that is 1 if a private mode is chosen for activity $a_n$, and 0 otherwise.

# Examples of household-level constraints



- **Allocation of private vehicle to household members:** The availability and allocation of private vehicle is necessary in auto-deficient households.
- We treat the private vehicle like an agent which has a schedule and cannot schedule more than one activity at each time-step.
- The schedule of the private vehicle is constrained to that of the other agents such that the private vehicle can schedule an activity only if it is **accompanied by an adult agent throughout the tour**.
- The only exemption from this constraint is staying in the parking at home.
- This approach can be used for modeling any resource constraints.
- This approach for modeling the resource constraints provides valuable information such as the location and occupancy of the private vehicle at each time step.

# Examples of household-level constraints

- **Allocation of private vehicle to household members:**

**Algorithm : Allocation of private vehicle to household members**

**for** $n : n \in \mathit{Adults}$ **do**
    **for** $a : a_n \in A^n$ and $a_V \in A^V$ **do**
        $\omega_{a_V} = \omega_{a_n}$;
        **if** $\ell_{a_n} \in \{\mathit{Home}\}$ **then**
            $x_{a_V} = x_{a_n} + \tau_{a_n}$;
            $\tau_{a_V} = \sum_{b_n \in A^n} (z_{a_n b_n} \rho(\ell_{a_n}, \ell_{b_n}, \text{Driving}))$;
        **else if** $\ell_{a_n} \notin \{\mathit{Home}\}$ **then**
            $x_{a_V} = x_{a_n}$;
            $\tau_{a_V} = \tau_{a_n} + \sum_{b_n \in A^n} (z_{a_n b_n} \rho(\ell_{a_n}, \ell_{b_n}, \text{Driving}))$;
        **end**
    **end**
**end**

# Examples of household-level constraints

- **Sharing household maintenance responsibilities:**
  - Household maintenance activities are for satisfying the needs of the entire household rather than solely the needs of the agent who implements them.
  - Therefore, the maintenance activities are associated with a significant degree of intra-household coordination, substitution, and allocation.

$$\sum_{n \in Adults} \omega_{maintenance_n} = 1$$

# Examples of household-level constraints



- **Escort:** a trip chauffeured by one of the adults in the household with a private vehicle.
  - Pick-up and drop-off
  - Escort and stay

**Algorithm : Escort**

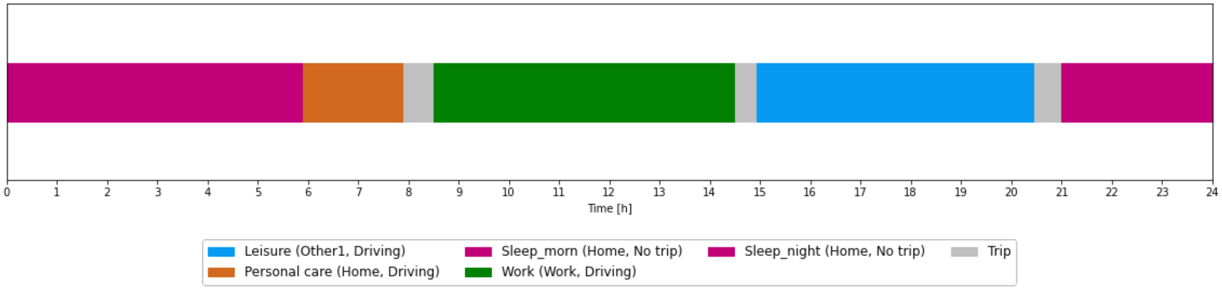
**for** $a : a \in A^{Child}$ *and* $a \in A^{Adults}$ **do**
- **if** *child needs escort for activity a* **then**
  - $\sum_{n \in \text{Adults}} \omega_{a_n} = \omega_{a_{\text{Child}}}$;
  - $\sum_{n \in \text{Adults}} x_{a_n} = x_{a_{\text{Child}}}$;
  - **if** *escort type: "escort and stay"* **then**
    - $\sum_{n \in \text{Adults}} \tau_{a_n} = \tau_{a_{\text{Child}}}$;
    - $\sum_{n \in \text{Adults}} \sum_{b_n \in A^n} (z_{b_n a_n} \ell_{b_n}) = \sum_{b_{\text{Child}} \in A^{\text{Child}}} (z_{b_{\text{Child}} a_{\text{Child}}} \ell_{b_{\text{Child}}})$;
    - $\sum_{n \in \text{Adults}} \sum_{b_n \in A^n} (z_{a_n b_n} \ell_{b_n}) = \sum_{b_{\text{Child}} \in A^{\text{Child}}} (z_{a_{\text{Child}} b_{\text{Child}}} \ell_{b_{\text{Child}}})$;
  - **else if** *escort type: "pick_up from out-of-home location"* **then**
    - $\sum_{n \in \text{Adults}} \tau_{a_n} = \vartheta\, \omega_{a_{\text{Child}}}$;
    - $\sum_{n \in \text{Adults}} \sum_{b_n \in A^n} (z_{a_n b_n} \ell_{b_n}) = \sum_{b_{\text{Child}} \in A^{\text{Child}}} (z_{a_{\text{Child}} b_{\text{Child}}} \ell_{b_{\text{Child}}})$;
  - **else if** *escort type: "drop-off at out-of-home location"* **then**
    - $\sum_{n \in \text{Adults}} \tau_{a_n} = \vartheta\, \omega_{a_{\text{Child}}}$;
    - $\sum_{n \in \text{Adults}} \sum_{b_n \in A^n} (z_{b_n a_n} \ell_{b_n}) = \sum_{b_{\text{Child}} \in A^{\text{Child}}} (z_{b_{\text{Child}} a_{\text{Child}}} \ell_{b_{\text{Child}}})$;
  - **end**
- **else**
  - **pass**
- **end**

**end**

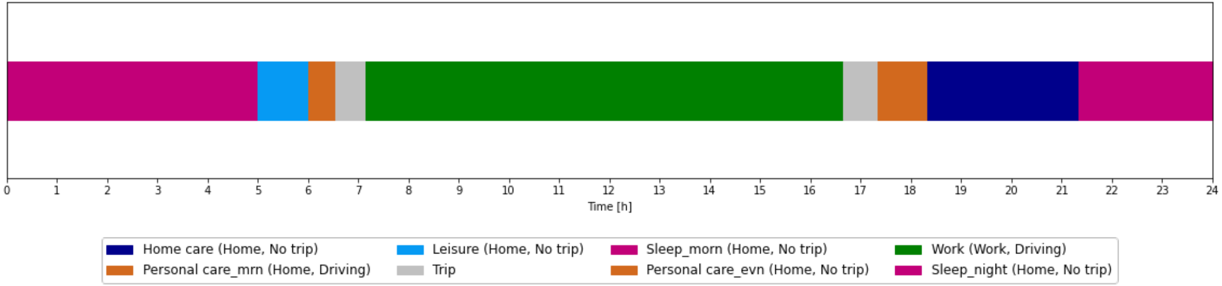
$\upsilon$: *stop time duration needed to pick-up or drop-off*

# Simulation
# From isolated individuals…

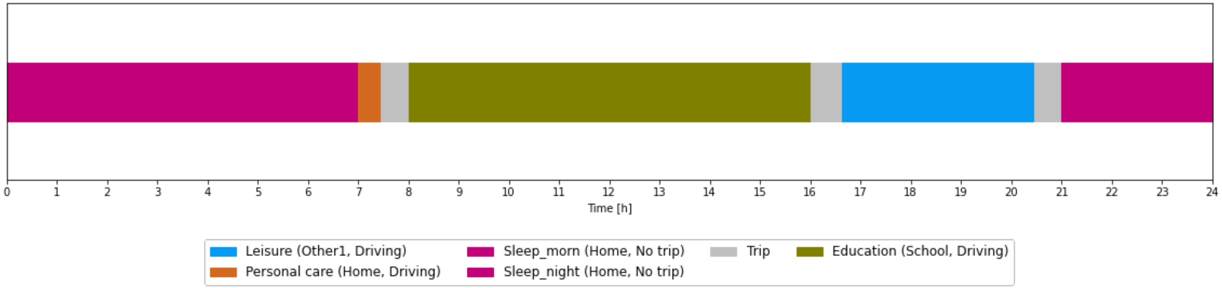
**Sara**




**David**

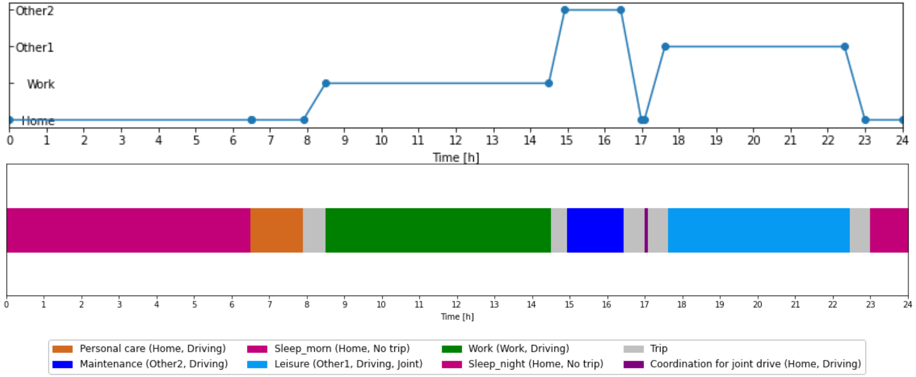



**Alice**

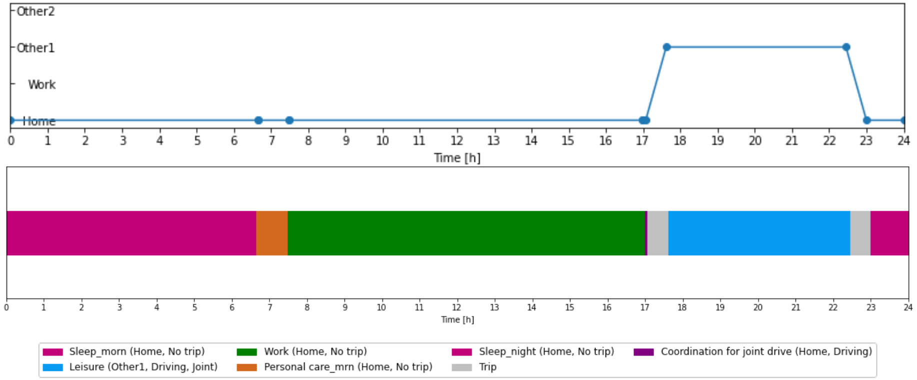


# Simulation
# To family of 2; 2 adults with no children…

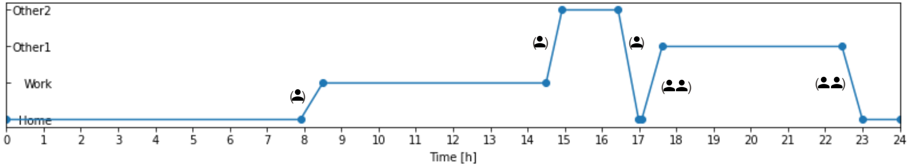
Sara




David




Car



# Simulation
# Family of 2; 2 adults with no children

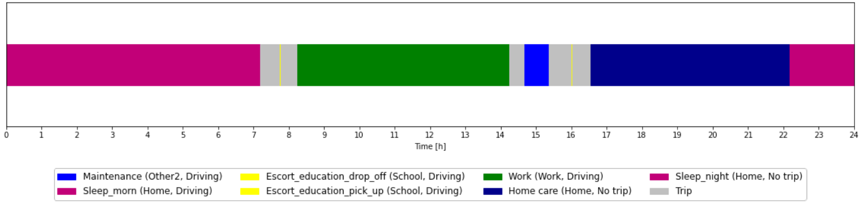


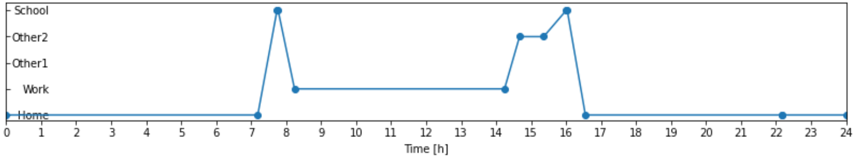
Table 1: Car location sequence and occupancy in the example of family of 2

| Location | Start time (hh:mm) | End time (hh:mm) | Duration (hh:mm) | Person using | Parked_out indicator | Car occupancy |
|---|---|---|---|---|---|---|
| Home | 00:00 | 7:54 | 7:54 | - | 0 | 0 |
| On the road | 7:54 | 8:30 | 0:36 | 1 | 0 | 1 |
| Work | 8:30 | 14:30 | 6:00 | 1 | 1 | 0 |
| On the road | 14:30 | 14:56 | 0:26 | 1 | 0 | 1 |
| Other2 | 14:56 | 16:27 | 1:31 | 1 | 1 | 0 |
| On the road | 16:27 | 17:00 | 0:33 | 1 | 0 | 1 |
| Home | 17:00 | 17:05 | 0:05 | - | 0 | 0 |
| On the road | 17:05 | 17:38 | 0:33 | 1&2 | 0 | 2 |
| Other1 | 17:38 | 22:27 | 4:50 | 1&2 | 1 | 0 |
| On the road | 22:27 | 23:00 | 0:33 | 1&2 | 0 | 2 |
| Home | 23:00 | 24:00 | 1:00 | - | 0 | 0 |

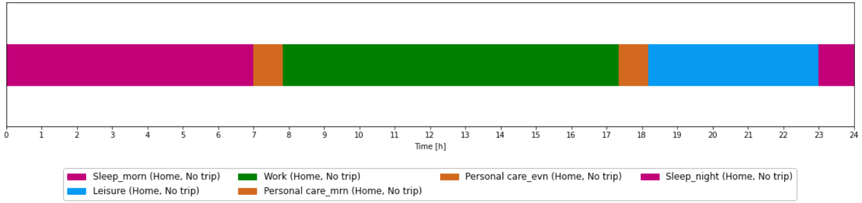
# Simulation
# To family of 3; 2 adults and 1 child…

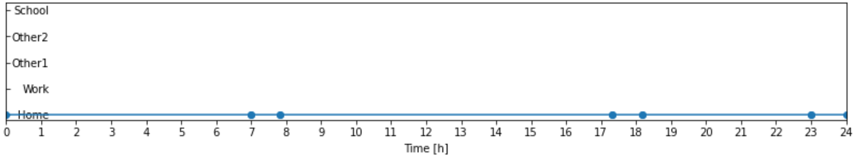
## Sara



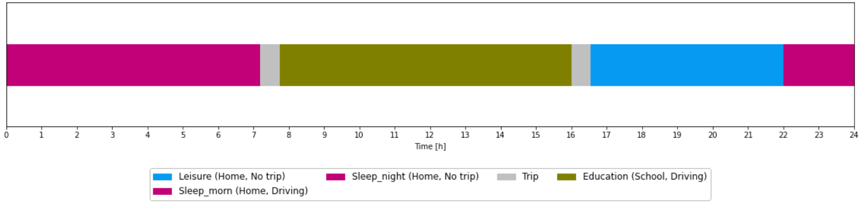



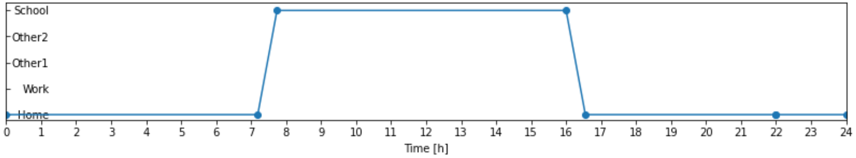

## David



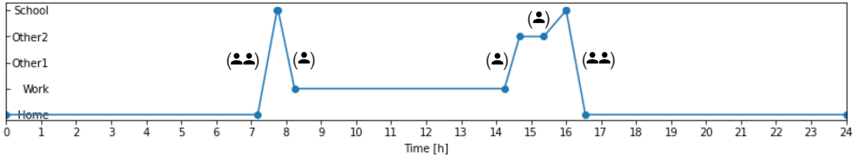




## Alice




## Car



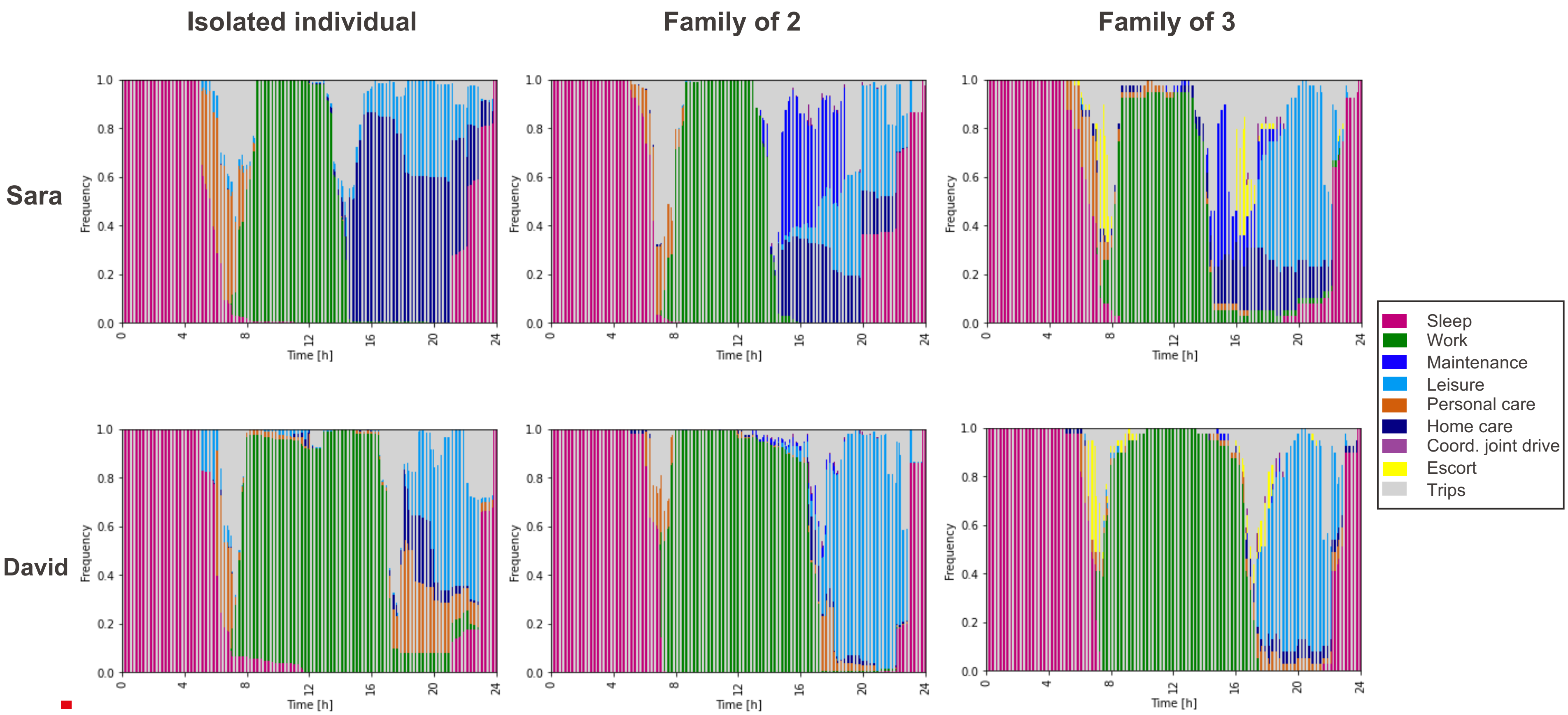
# Simulation
# Family of 3; 2 adults and 1 child

Table 2: Car location sequence and occupancy in the example of family of 3

| Location | Start time (hh:mm) | End time (hh:mm) | Duration (hh:mm) | Person using | Parked_out indicator | Car occupancy |
|---|---|---|---|---|---|---|
| Home | 00:00 | 7:12 | 7:12 | - | 0 | 0 |
| On the road | 7:12 | 7:45 | 0:33 | 1&3 | 0 | 2 |
| School | 7:45 | 7:47 | 0:02 | 1 | 0 | 1 |
| On the road | 7:47 | 8:15 | 0:28 | 1 | 0 | 1 |
| Work | 8:15 | 14:15 | 6:00 | 1 | 1 | 0 |
| On the road | 14:15 | 14:40 | 0:25 | 1 | 0 | 1 |
| Other2 | 14:40 | 15:22 | 0:42 | 1 | 1 | 0 |
| On the road | 15:22 | 16:00 | 0:38 | 1 | 0 | 1 |
| School | 16:00 | 16:02 | 0:02 | 1 | 0 | 1 |
| On the road | 16:02 | 16:33 | 0:31 | 1&3 | 0 | 2 |
| Home | 16:33 | 24:00 | 7:27 | - | 0 | 0 |

# Distributions



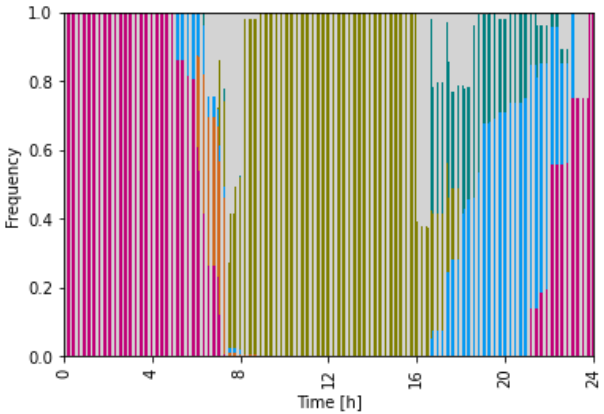


# Distributions

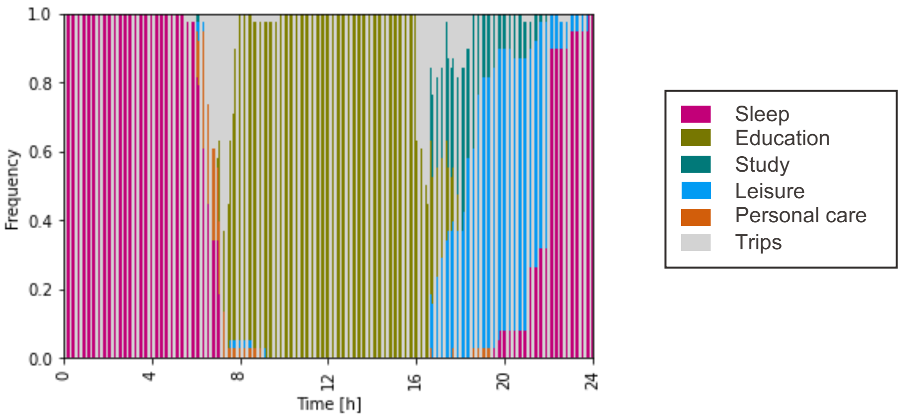


**Alice**

## Isolated individual




## Family of 3



# Conclusion



**Summary:**

- General framework
- Group decision-making mechanism; activity scheduling at the level of the household
- Explicit interactions
- Capture resource constraints
- Flexible framework; interaction dimensions can be arbitrarily added

**Current challenges - future research opportunities:**

- Performance speed, computational expense
- Multi-day interactions
- Validation

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# Thank you!

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