Joint modelling of household activity patterns and domestic energy demand

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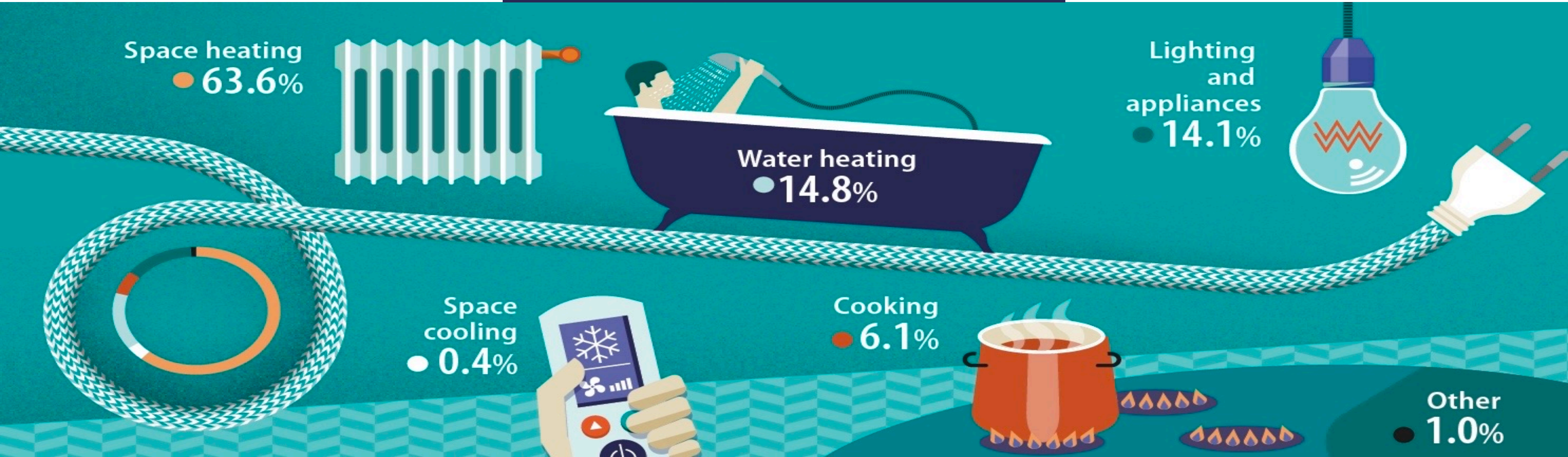

About me

- 3rd year PhD candidate
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- Bachelors and Masters in Civil Engineering, Sharif University of Technology, Tehran, Iran
- Visiting researcher at UCL (March - June 2023)

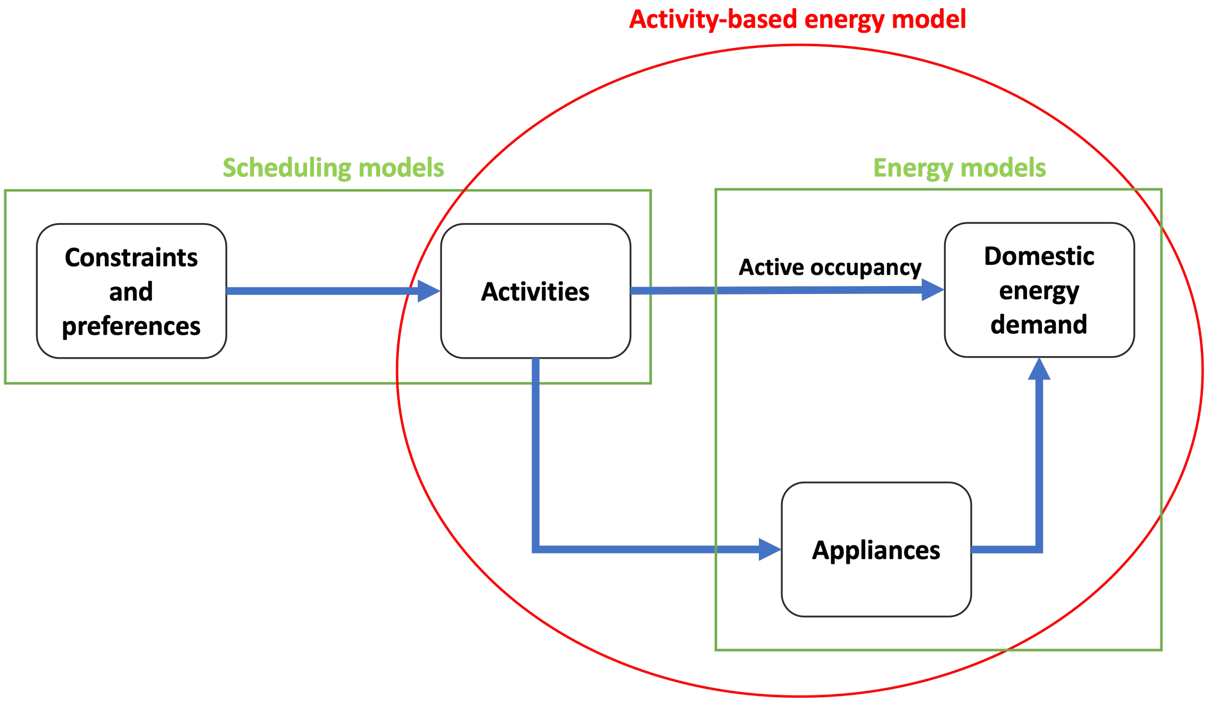
Motivation

- **Domestic energy usage** can be considered as being derived from the **activity patterns** of individuals inside the home (Rezvany et al. 2021).
- Domestic energy usage: energy used in residential buildings including electricity, heating, and hot water.
- As such an **activity-based energy demand model** that can create in-home energy usage profiles from household activity patterns is the key to a better building energy demand analysis.

Activity-based models (ABMs)

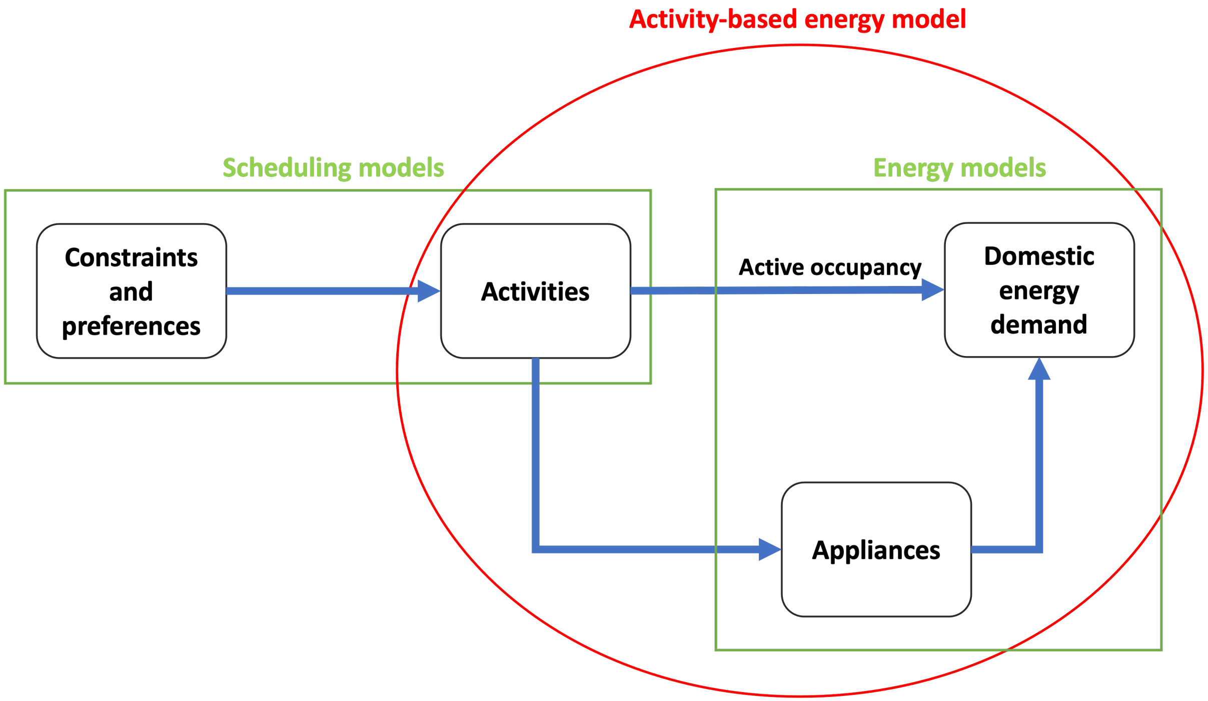
- **Activity-based models** portray how people plan their activities and travels over a period of time such as a day.
- This approach has been of **interest** to **transport modellers** as the demand for travel is assumed to be driven by participation in activities which are distributed in space and time.
- However, using **ABMs** in the domain of **domestic energy demand** research is still very **limited** and the human behaviour element is frequently neglected in the energy demand literature.

Activity-based energy demand scheme



High-level research question

High-level research question: "How can we simulate the domestic energy demand from household activity schedules from first principles?"



Research questions

- In order to answer this high-level question, we should answer the following research questions:

1. How to incorporate **in-home** and **out-of-home activity scheduling** in a **single** scheduling model with **intra-household interactions**?
2. How can we create **in-home energy usage profiles** from **household activity patterns**?

Research question 1

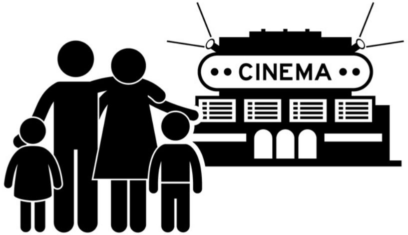
1. How to incorporate **in-home** and **out-of-home activity scheduling** in a **single** scheduling model with **intra-household interactions**? (Rezvany et al. 2023)
   - A framework for joint simulation of in- and out-of-home activities, capturing intra-household interactions

Intra-household interactions: 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.

Example intra-household interactions

- **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

Example intra-household interactions

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

Escorting children

Sharing a ride

Example intra-household interactions

- **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

Importance of capturing intra-household interactions in ABMs

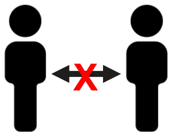
- How can intra-household interactions affect the schedule of individuals?
  - Policies directly affecting the activity and travel patterns of an individual, such as earlier school starting times, can affect the schedule of multiple household members.
  - Joint activities require coordination between 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.

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

- 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**.

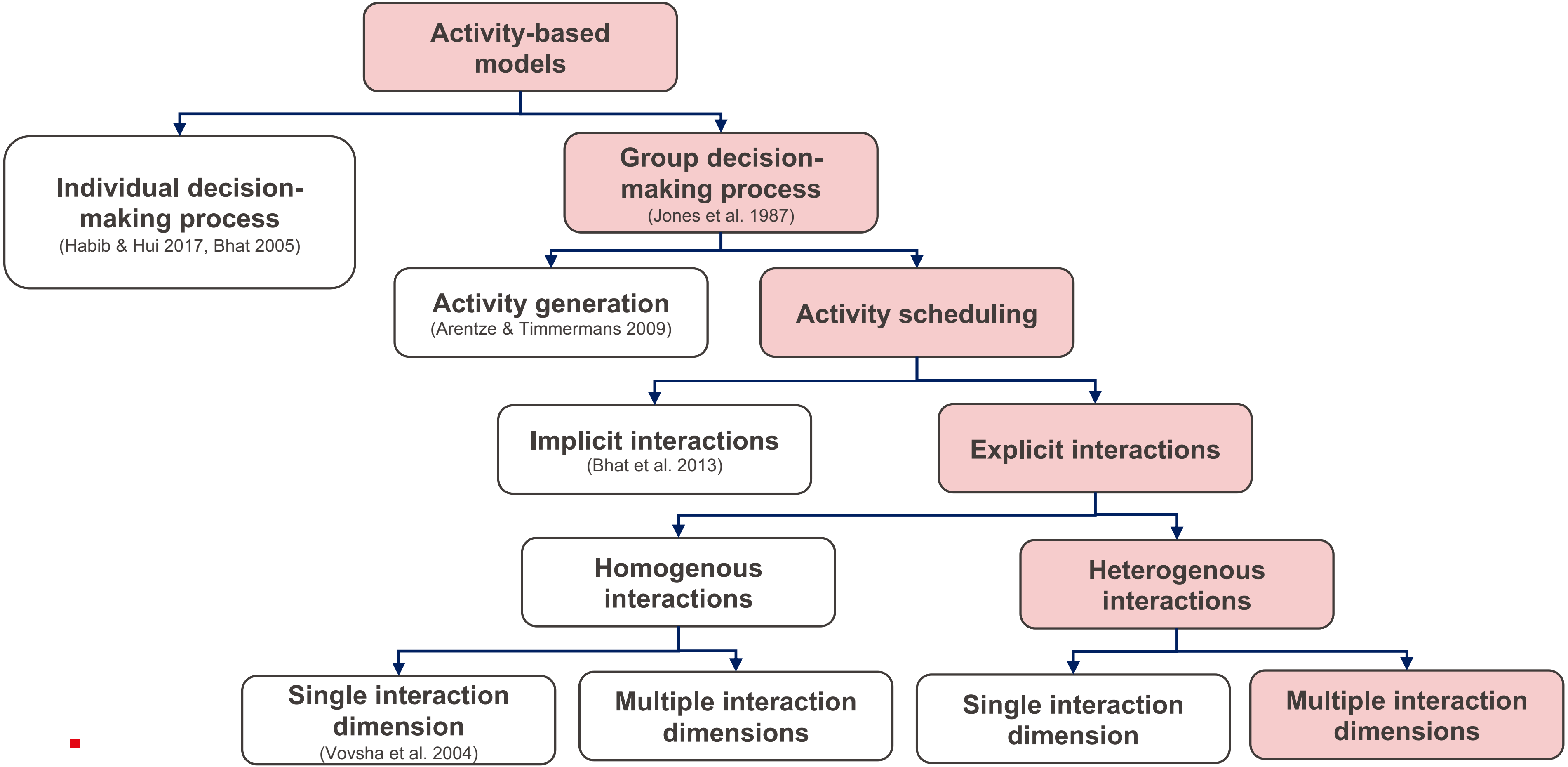
- Most of the **conventional** activity-based models in transportation research are based on **individual decision-making process** where the individuals are treated as **isolated agents** whose choices are **independent** of other decision-makers.



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

- Studies on group choice models are **limited**.

Gap 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
  - **Explicit** interactions
    - Ensures consistency of choices.
  - **Multiple interaction** dimensions
  - High level of **flexibility**
    - Mixed-integer utility optimisation approach
  - **Heterogenous** decision-making
  - Both **in-** and **out-of-home** scheduling are simulated within the same framework
    - Allows modellers to capture the trade-offs between in- and out-of-home activities (e.g. in- and out-of-home activity location choices).
    - Understanding behaviour 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

- Our approach adopts the **Optimisation-based Activity Scheduling Integrating Simultaneous choice dimensions** (**OASIS**) framework *(Pougala et al. 2022)*:
  - A mixed-integer utility optimisation approach
  - 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: Isolated agents

- 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

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

Start time deviations

Travel from activity a_n to b_n

OASIS with interactions: Agents with intra-household interactions

- **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 behaviour 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

- We first ensure that the possible interaction aspects are captured in the utility function.
  - A term capturing the reward of joint activity participation with other member(s) of the household, compared to solo participation in the activity.

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

Joint activity participation

$$\alpha_{a_n}^{jnt}\; p_{a_n}$$

Joint activity engagement parameter

Joint participation indicator (0/1)

Utility

- We first ensure that the possible interaction aspects are captured in the utility function.
  - A term capturing the penalty of escorting other agent(s).

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

Escort

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

Escort penalty parameter

Escort indicator (0/1)

Duration

Utility

- We first ensure that the possible interaction aspects are captured in the utility function.
  - a term capturing the utility of different activity location choices.

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

location

$$\alpha_{l_{a_n}}^{loc} l_{a_n}$$

Location-specific parameter

Location indicator

Objective utility

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

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

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

Constraints

- Specify the model constraints such that they allow the **integration** of **in-home activities** alongside activities **outside** the home in **a single framework**.
- Define **household-level constraints** to **explicitly** capture the interplays as **within-household interactions** lead to **additional and more complex** constraints.
  - Household private vehicle ownership,
  - Allocation of the resources to household members,
  - Sharing household maintenance responsibilities,
  - Joint participation of household members in activities,
  - Joint travels, and
  - Escorting.

An example household-level constraint

- **Allocation of private vehicle to household members:** The availability and allocation of private vehicle is necessary in auto-deficient households.
- The private vehicle is an example of a **moving resource**.
- Resources have **no independent decision-making capabilities** and are purely used by and dependent on the decision-making agents.
- We treat the private vehicle as a **resource**, which has an **event schedule**.
- The moving resources such as private vehicle need a **driver** to move them.
- Thus, the **schedule** of the **moving resources** is **constrained** to that of the **agents**.
- This approach can be used for modelling any household resource.
- This approach for modelling the resource constraints provides valuable information such as the resource location and occupancy.

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

OASIS with interactions:
Agents with intra-household interactions

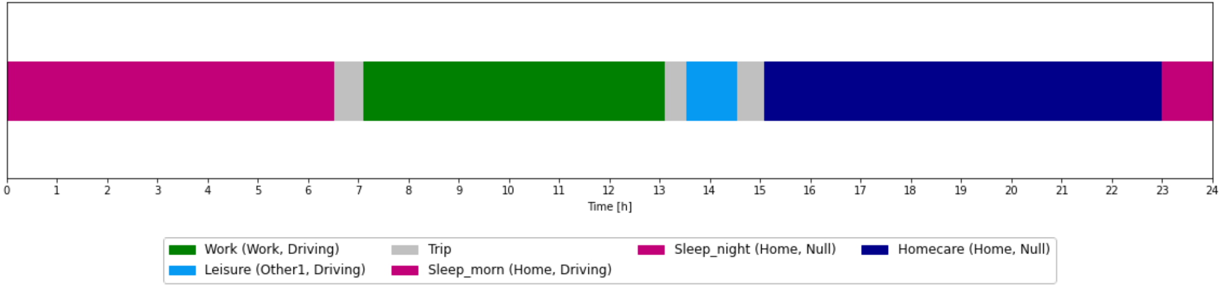
- **Inputs**:
  - Household composition,
  - Scheduling preferences,
  - Activity flexibilities,
  - Activity choice set, and
  - Household resources and their associated events set.

- **Output:**
  - A **realisation** from the **distribution of valid schedules**, under both **individual-** and **household-level constraints** and **preferences**.

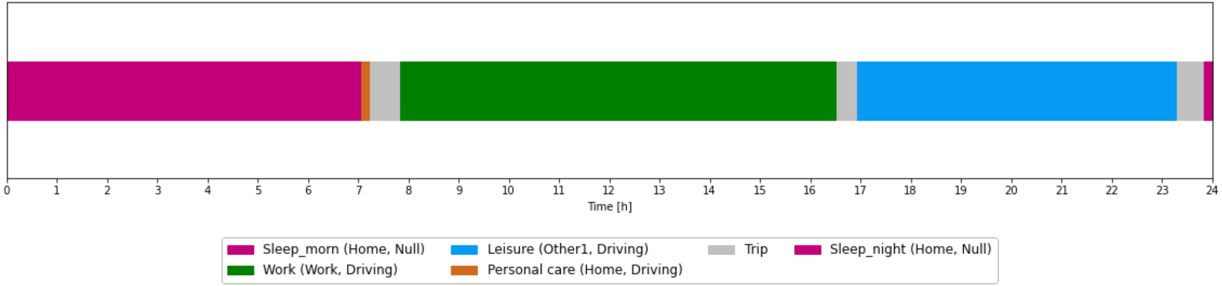
EPFL

Simulation
From isolated individuals…

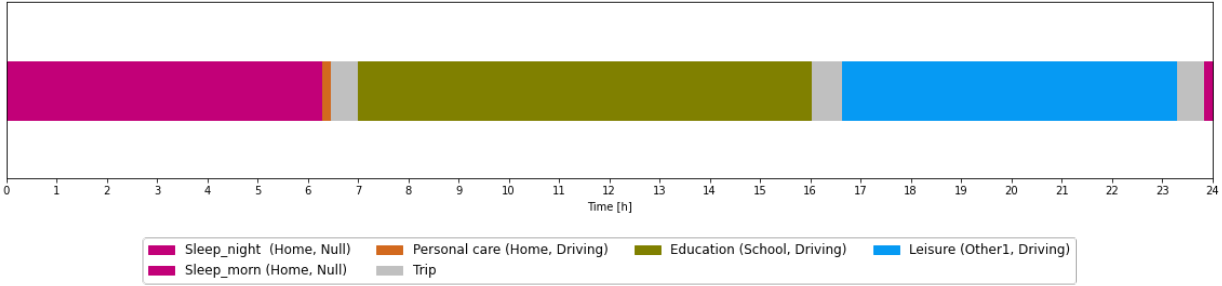
Sara



David

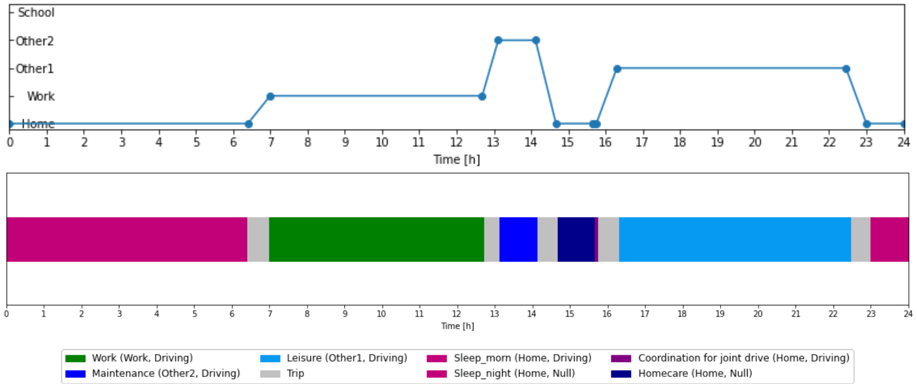


Alice

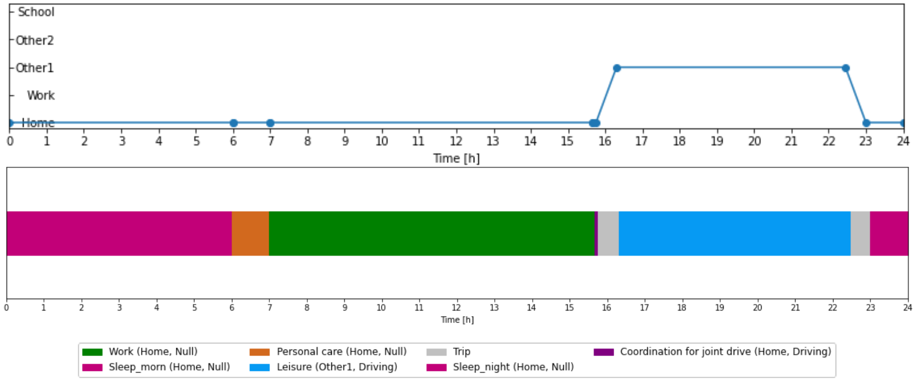


Simulation
To family of 2; 2 adults with no children…

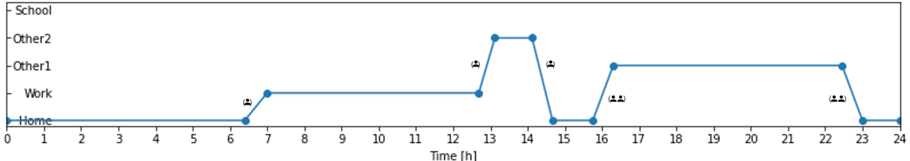
Sara



David



Car



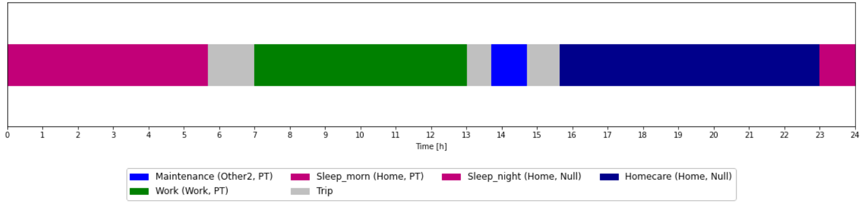
Simulation
Family of 2; 2 adults with no children

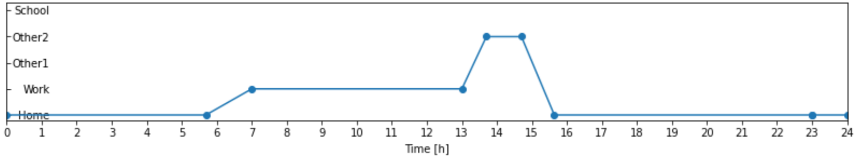
Table 1: Car location sequence and occupancy in the example of family of 2

Location	Start time (hh:mm)	End time (hh:mm)	Duration (hh:mm)	Person using	Parked_out indicator	Car occupancy
Home	00:00	6:24	6:24	-	0	0
On the road	6:24	7:00	0:36	1	0	1
Work	7:00	12:41	5:41	1	1	0
On the road	12:41	13:07	0:26	1	0	1
Other2	13:07	14:07	1:00	1	1	0
On the road	14:07	14:40	0:33	1	0	1
Home	14:40	15:45	1:05	-	0	0
On the road	15:45	16:18	0:33	1&2	0	2
Other1	16:18	22:27	6:08	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

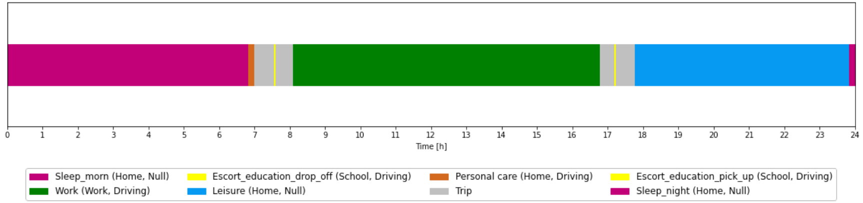
Simulation
To family of 3; 2 adults and 1 child…

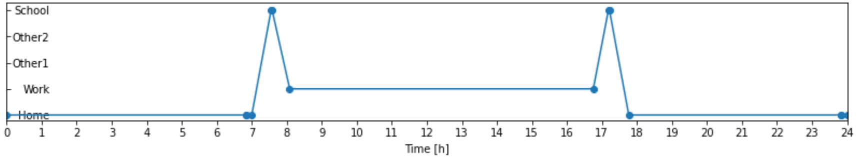
Sara



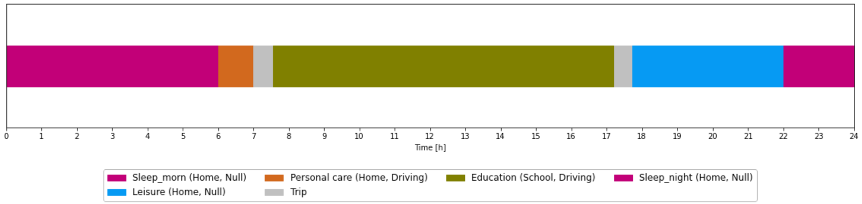


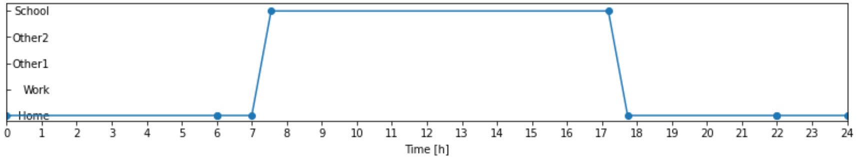
David



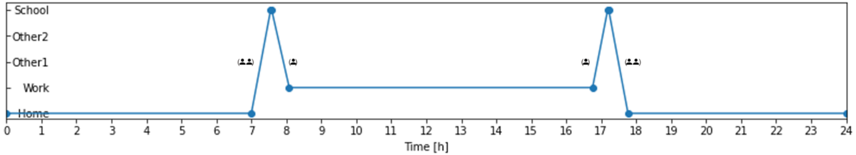


Alice





Car

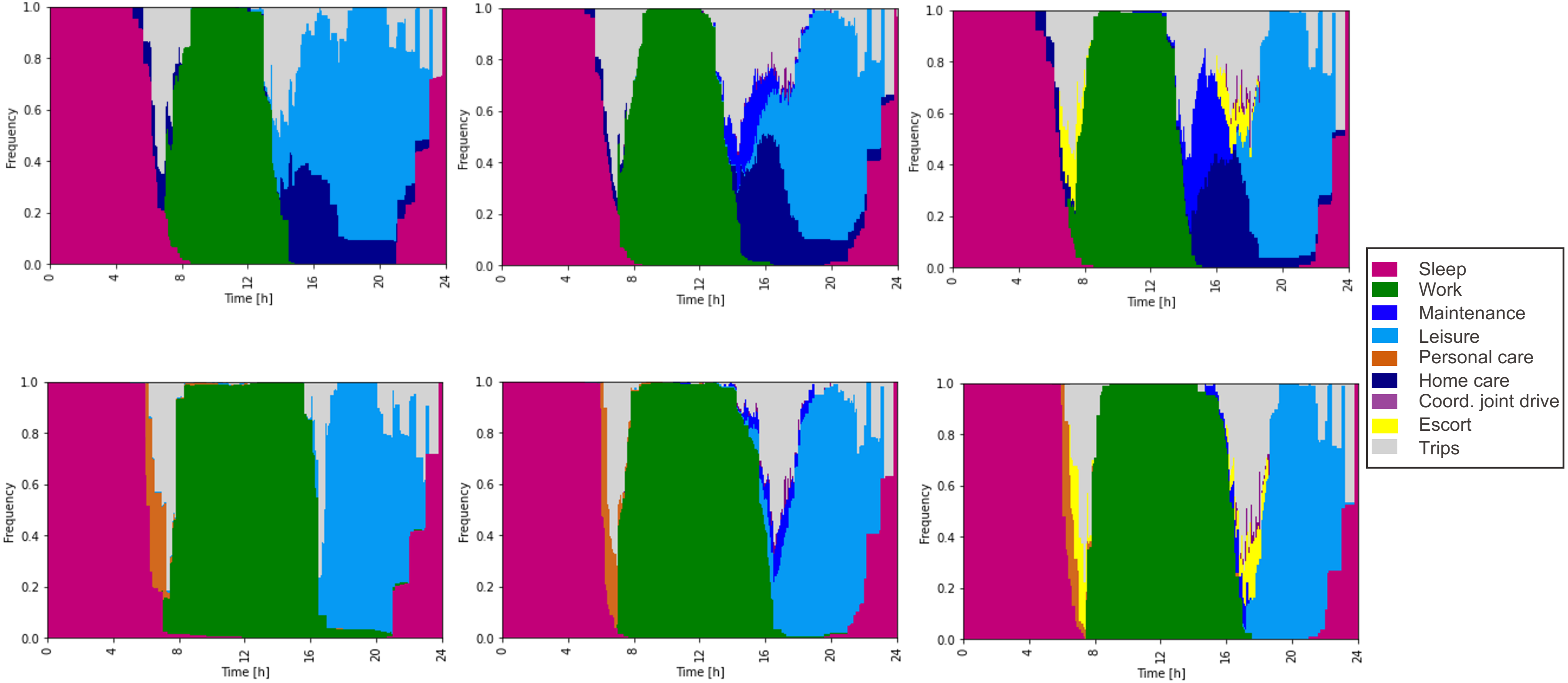


Distributions

Isolated individual | Family of 2 | Family of 3

Sara

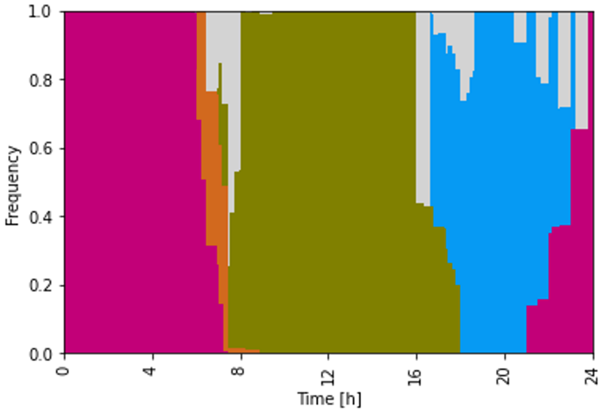
David



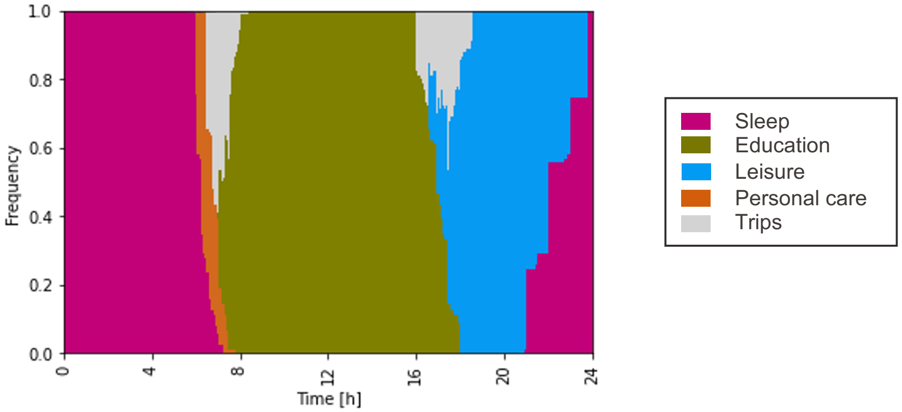
Distributions

Alice

Isolated individual



Family of 3



Summary Research Question 1 :
How to incorporate in-home and out-of-home activity scheduling in a single scheduling model with intra-household interactions?

- 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
- Operationalised model

Research question 2

How can we create in-home energy usage profiles from activity patterns?

- **Goal:** find the **relation between building energy usage and activity profiles**
  - ***Ideal scenario***: **overlapping energy** usage data with **activity** diary survey data
  - ***Pragmatic scenario***: However, there is **no data** containing information on **both household activity schedules** and **energy usage**.

- **BUT** we have **detailed da*ta* on building energy usage**, as well as, **detailed time-use-data**, **separately** (no overlap between data**).**

How can we infer activity patterns from in-home energy usage profiles?

- **New goal:** How do we use energy data to enhance existing activity models?
  - Add functionality to ABM model
  - Generate energy demand profiles
  - Without having overlapping data to train it

- We looked in the literature to see if anyone tried to link energy and activity data to create a joint model.

- Now, however, there are parallels to similar problems in other contexts (e.g. detecting pedestrian activity patterns from WiFi signatures)

From Wifi traces to activity episodes

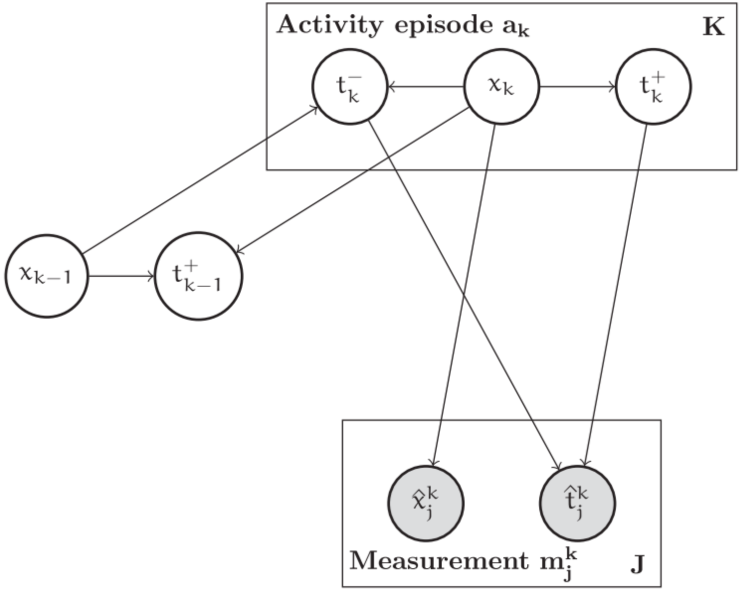
- Wifi traces are **not accurate**; either precise sensors with incomplete coverage or full coverage with imprecise sensors.
- As a result, data are **scarce**, **fuzzy**, or both.

- How this is relevant to our problem?
  - Cooking hob on → We do not know if they are doing another activity on the side/ multiple people are helping in the cooking at the same time → not exact indication of the start and end time of food preparation process → Noisy representation of activity → need a joint probabilistic model

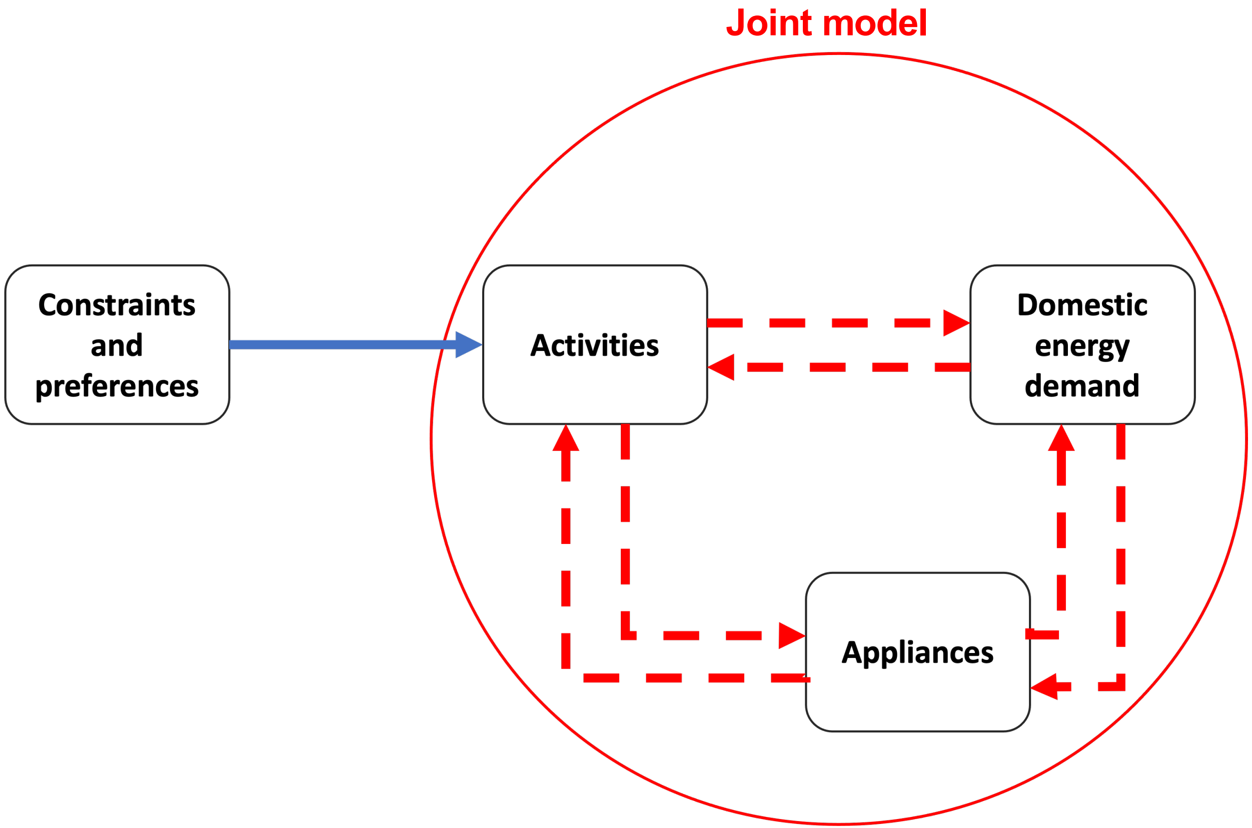
Appliance use ≠ Activity pattern

A Bayesian approach to detect pedestrian destination-sequences from WiFi signatures (Danalet et al. 2014)

- **Goal:** extract the **possible activity-episode sequences** performed by pedestrians from **digital traces** in a communication network.
- **Methodology:** a **Bayesian approach** merges measured **network traces** and **pedestrian semantically-enriched routing graph** to compute the **likelihood** that a **given sequence of activity episodes** has actually generated the observed traces.
- **Output: candidate activity schedules** associated with the **likelihood** to be **the true one**.



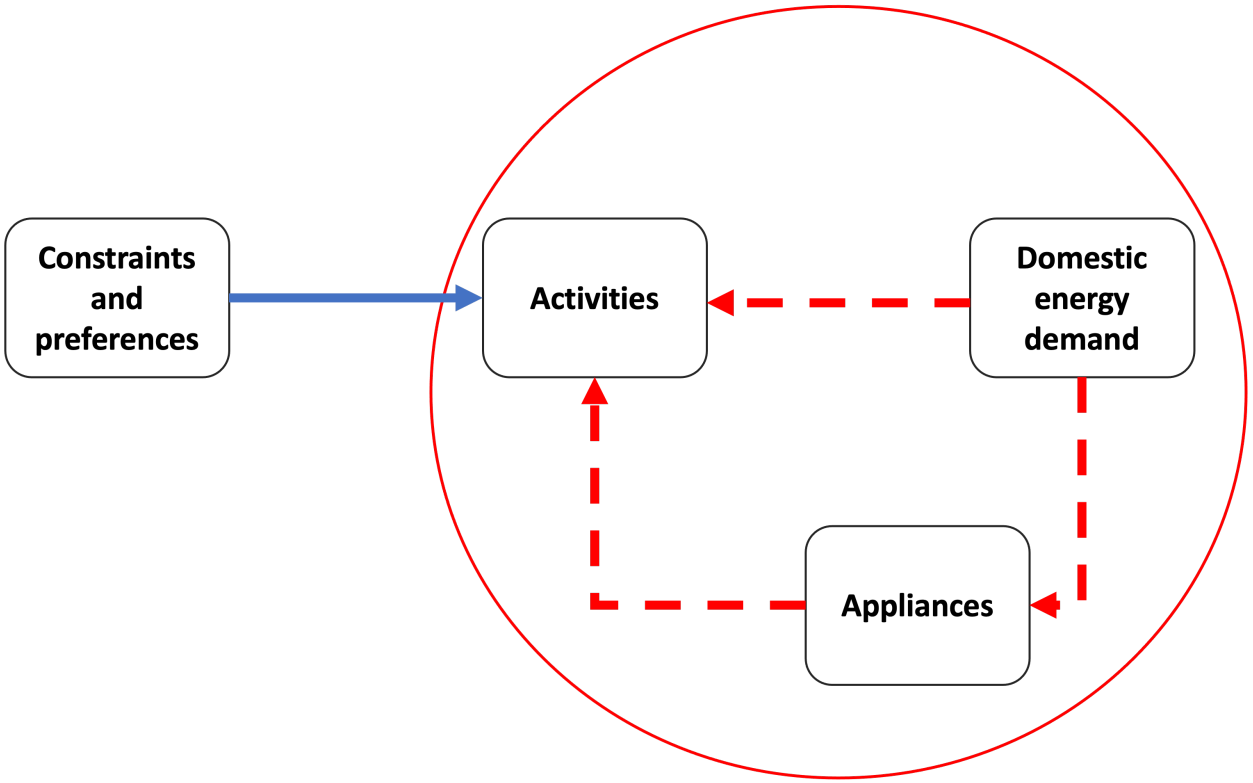
Schematic view of our approach



Methodological approach

- A **Bayesian approach** merging the **measured appliance energy usage profiles** and **semantically-enriched activity-appliance usage profiles** to compute the **likelihood** that a given **sequence of activity episodes** has actually generated the observed appliance energy profiles.

Schematic view of our approach



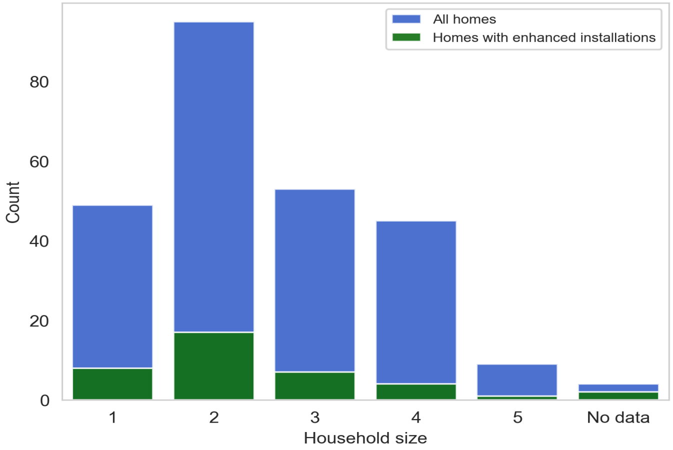
Datasets

Energy dataset

Intelligent Domestic Energy Advice Loop (IDEAL)

(Pullinger et al., 2021; Goddard et al., 2021)

- Comprises data from 255 homes in Edinburgh and the nearby regions, 2016-2018.
- Contains enhanced appliance-level energy monitors in 39 of 255 homes.

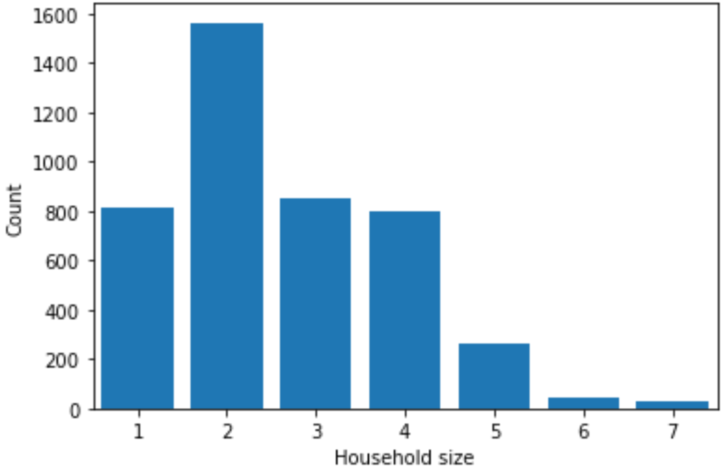


Time use survey

CaDDI* survey - 2016-2020 UK TUS

(Gershuny and Sullivan, 2021)

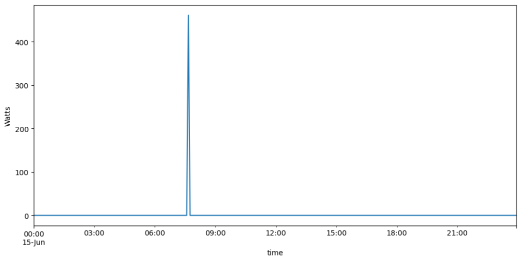
- 4’360 diaries from 2’202 individuals across 4 waves, 2016-2020
- Contains 1 to 3 time-use diaries per respondent (include 1 weekday and 1 weekend day)

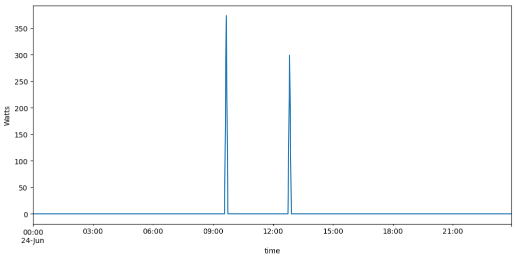


* Click and drag diary

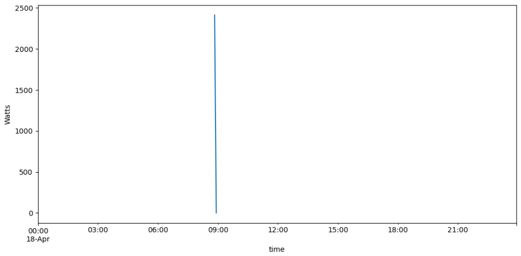
Exploration of data: Appliance energy profiles

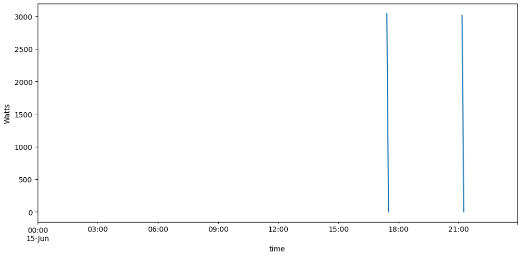
Toaster:



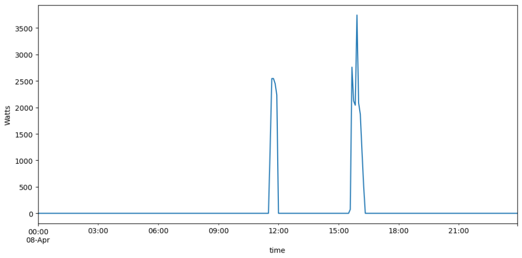


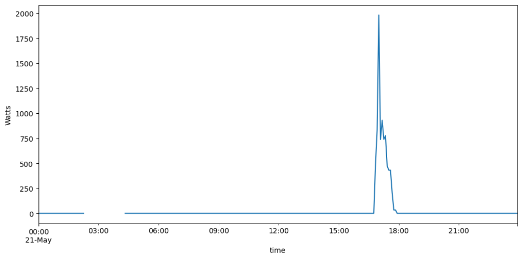
Kettle:





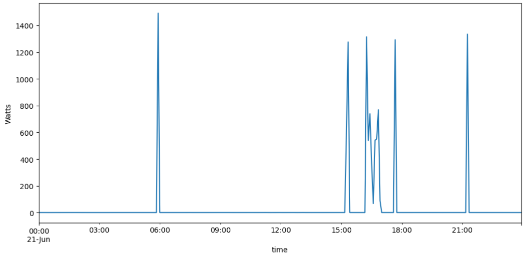
Cooker:

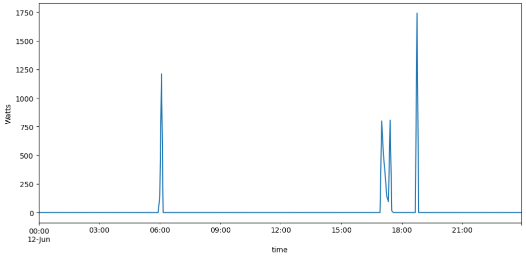




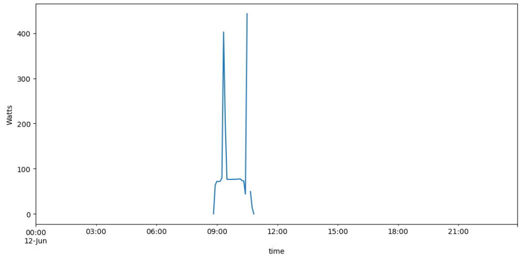
Exploration of data: Appliance energy profiles

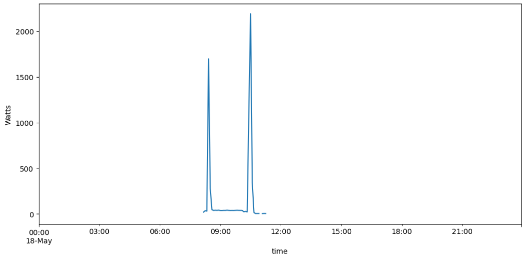
Cooking hob:





Dishwasher:



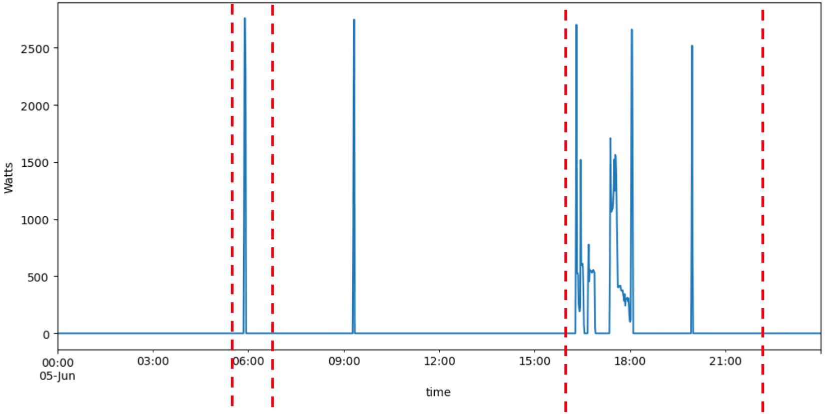


→ **looking for a set of patterns and rules…**

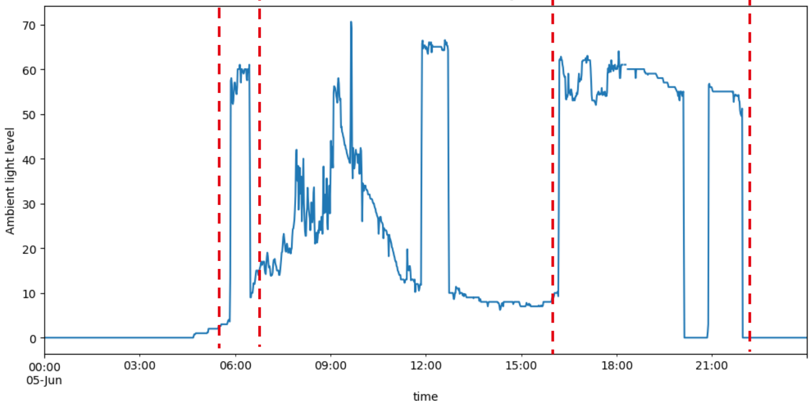
→ **need a probabilistic joint model to relate energy profiles to activity patterns**

Exploration of data: Ambient light-level vs energy profiles

Electricity usage – cooking hub:

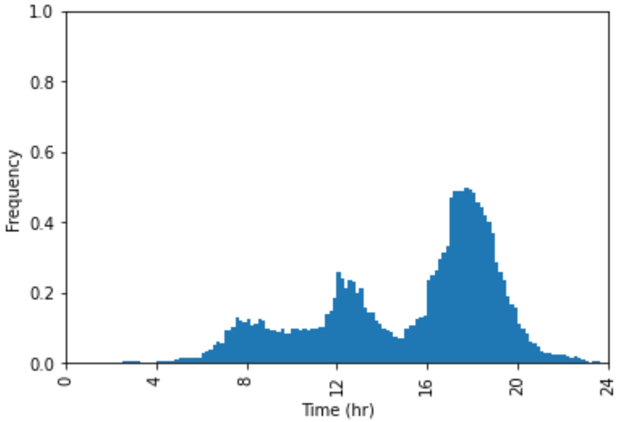


Kitchen ambient light:

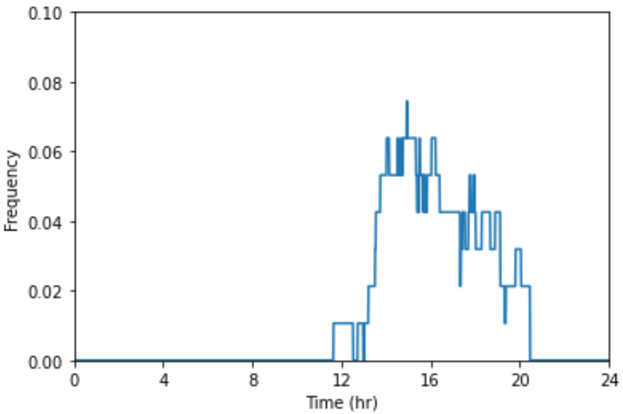


Exploration of data: Parallels at aggregate level

Distribution of "Preparing food/cooking" activity:



Distribution of "electric oven" usage:



To conclude

On-going research:

- Joint model of domestic energy and activity profiles
- Recreate household activity patterns from domestic energy usage profiles
- Non-overlapping data
- Probabilistic model - Bayesian approach

Related publications

- Rezvany, N., M. Bierlaire and T. Hillel (2023) **Simulating intra-household interactions for in- and out-of-home activity scheduling**, Technical Report.
- Rezvany, N., T. Hillel and M. BIerlaire (2021) **Integrated models of transport and energy demand : A literature review and framework**, Proceedings of the 21st Swiss Transport Research Conference (STRC), 12-14 September, Ascona, Switzerland.

Thank you!

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