E-waste Collection and Recycling Behaviours: An Agent-Based Model for Intervention Assessment in Singapore

by

Quoc Khanh Tran, Lan Zhao, Yajuan Sun, Gaoxi Xiao, Zhiquan Yeo, Chuan Fu Tan

Presenting author: Quoc Khanh Tran – Hanoi University of Science and Technology
Email: khanh.tq190085@sis.hust.edu.vn

Procedia CIRP
www.LCE2025.com

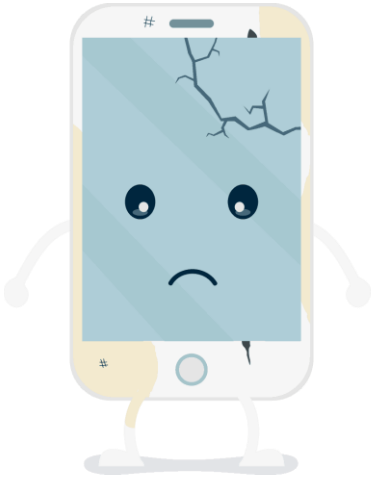
Agenda

- Introduction
- Modeling Methodology
- Experiment Results
- Conclusion and Developments

INTRODUCTION

What would you do, if you had a no-longer-used smartphone?

60% of Singapore residents **do not know** or are **unsure** of how to recycle their electronic waste.



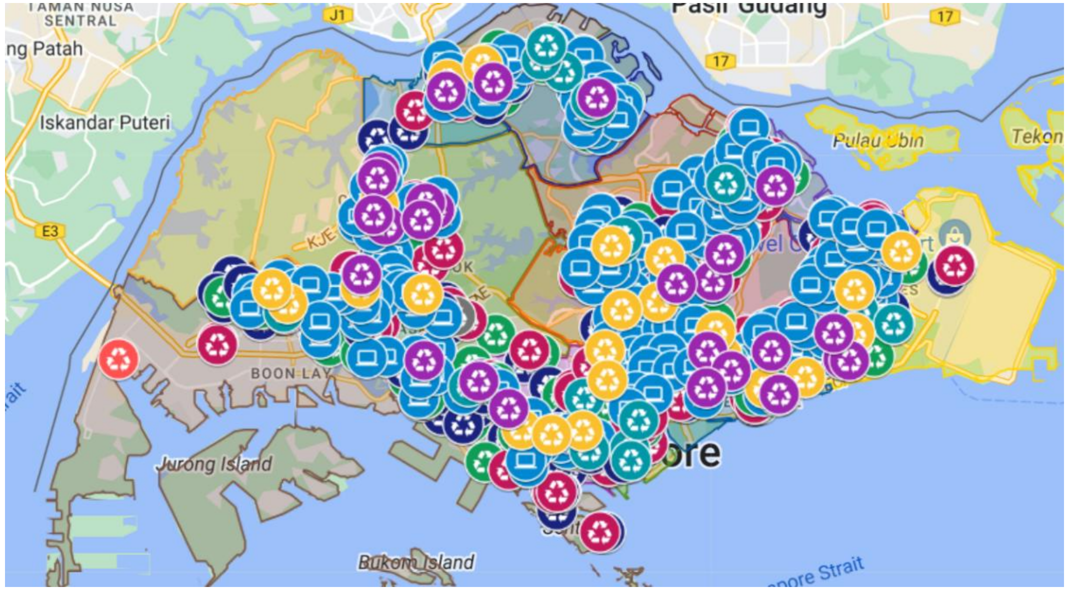
Research Problem

- Significant increase of electronic waste (e-waste) generation.
- **62 millions metric tons,** approximately 155,000 Boeing 747s, of e-waste was generated in 2022 globally.
- E-waste is:
  - **Valuable** raw material, e.g. gold, silver, and copper.
  - Environmentally **hazardous**.
- Only 22.3% were documented as formally recycled worldwide.
- Only 6% of 60,000 tonnes e-waste generated each year in Singapore are recycled.

→ Model e-waste collection for **policymakers** to **assess recycling interventions**.

E-waste Management in Singapore

- **Extended Producer Responsibility** (EPR): producers are responsible for their end-of-life products.
- **E-Bins** in public areas across Singapore to collect e-waste.



Locations of E-Bins in Singapore, information from National Environment Agency.

A 3-in-1 e-bin placed at Harvey Norman Millenia Walk. Photo from National Environment Agency.

MODELING METHODOLOGY

Agent-Based Modeling (ABM)

- **Agent-Based Modeling:** A computational method to study interactions between individuals.
  - **Agent**: autonomous entity with unique characteristics and behaviours.
  - **Emergence**: system-level phenomenon arises from agent interactions, unpredictable from individual components.
- **E-waste collection system**: a Complex Adaptive System (CAS) composes of multiple interacting components that adapt to changes.

→ ABM is suitable to simulate e-waste collection system.

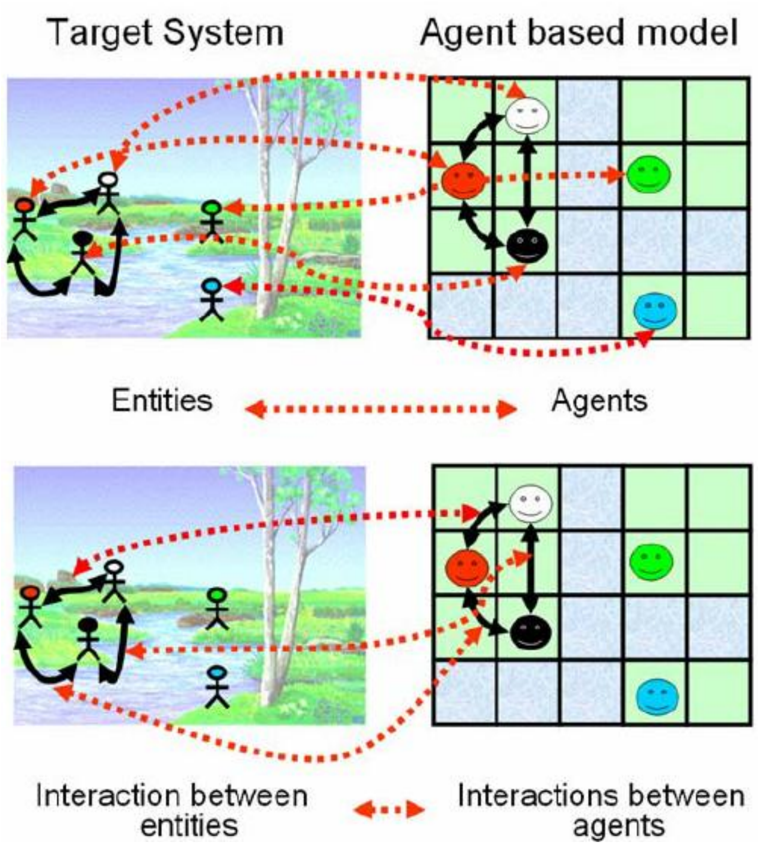
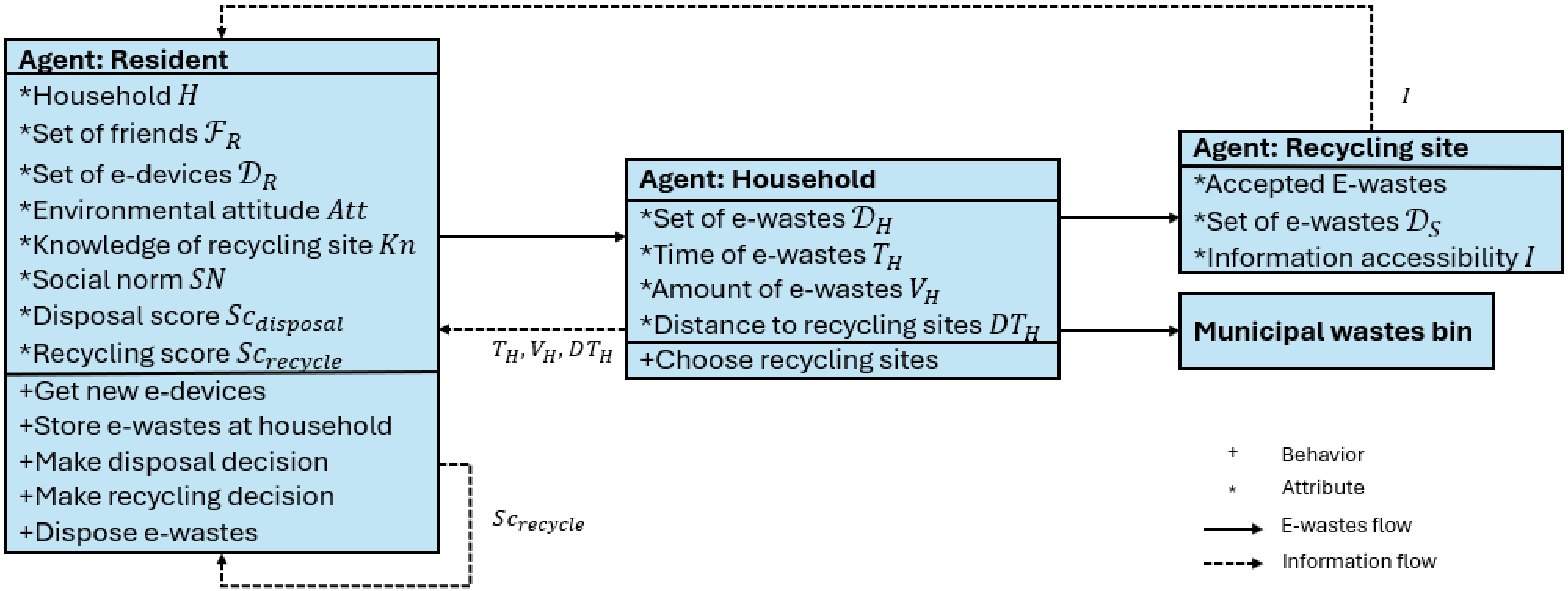


Illustration of Agent-Based Modeling. Figure extracted from Galán et al.

Modeling Framework

- Agent-based model for e-waste collection and recycling behaviours.
- Agents in the model: **Resident**, **Household**, and **Recycle Site**.



Conceptual model of the agent-based model for e-waste collection and recycling behaviours.

Resident

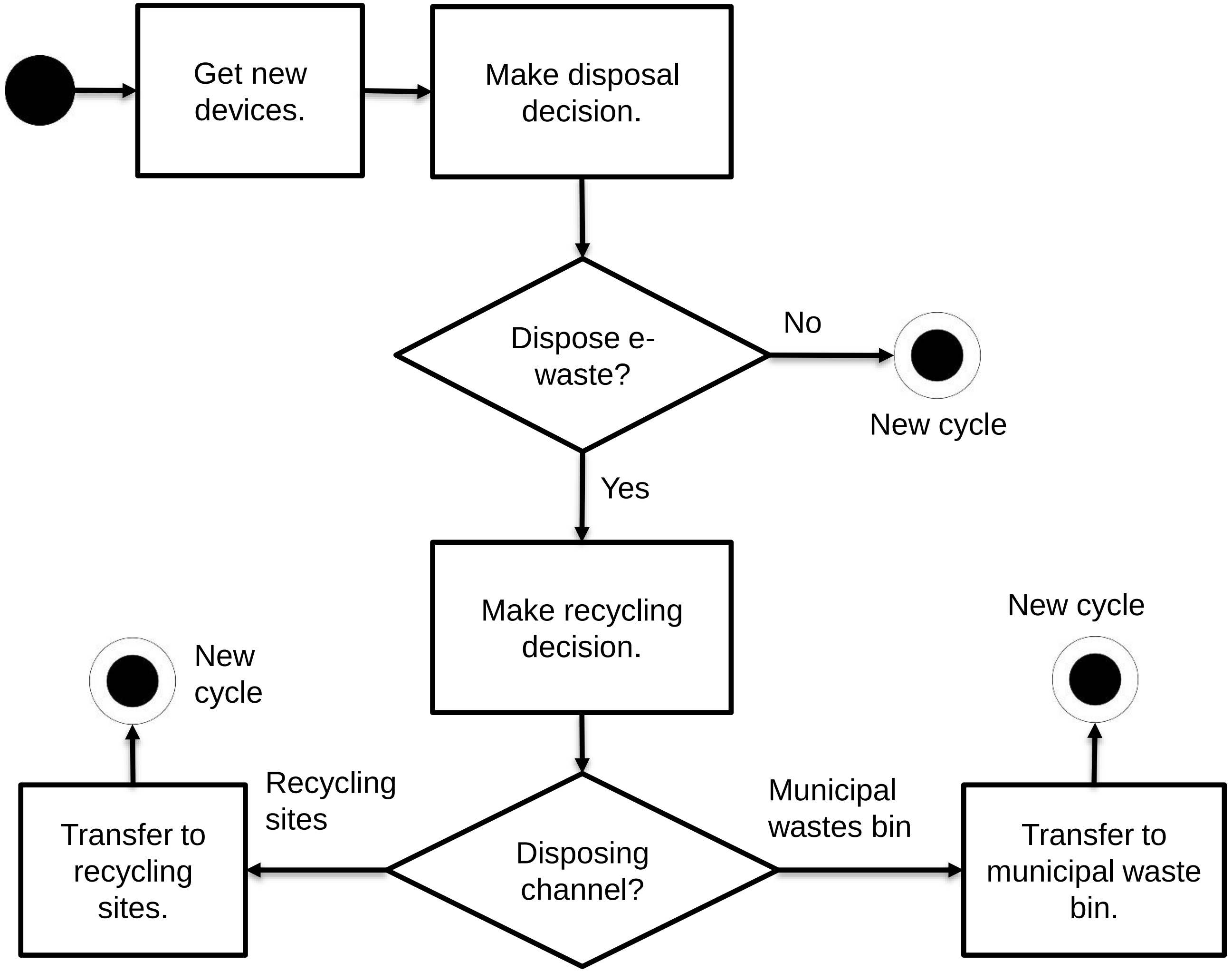
- **Disposal decision** to dispose e-waste at a cycle, probability $P_{disposal}$.

$$S_{disposal} = \alpha_T \cdot T_{H_i} + \alpha_V \cdot V_{H_i} + \alpha_{DT} \cdot DT_{H_i}$$

$$P_{disposal} = \frac{S_{disposal} - S_{disposal_{min}}}{S_{disposal_{max}} - S_{disposal_{min}}}$$

Where:

- T_{H_i} is retention time of e-waste.
- V_{H_i} is amount of e-waste in household.
- DT_{H_i} is travelling distant needed to dispose e-waste at recycling sites.



Activity diagram of resident at a cycle.

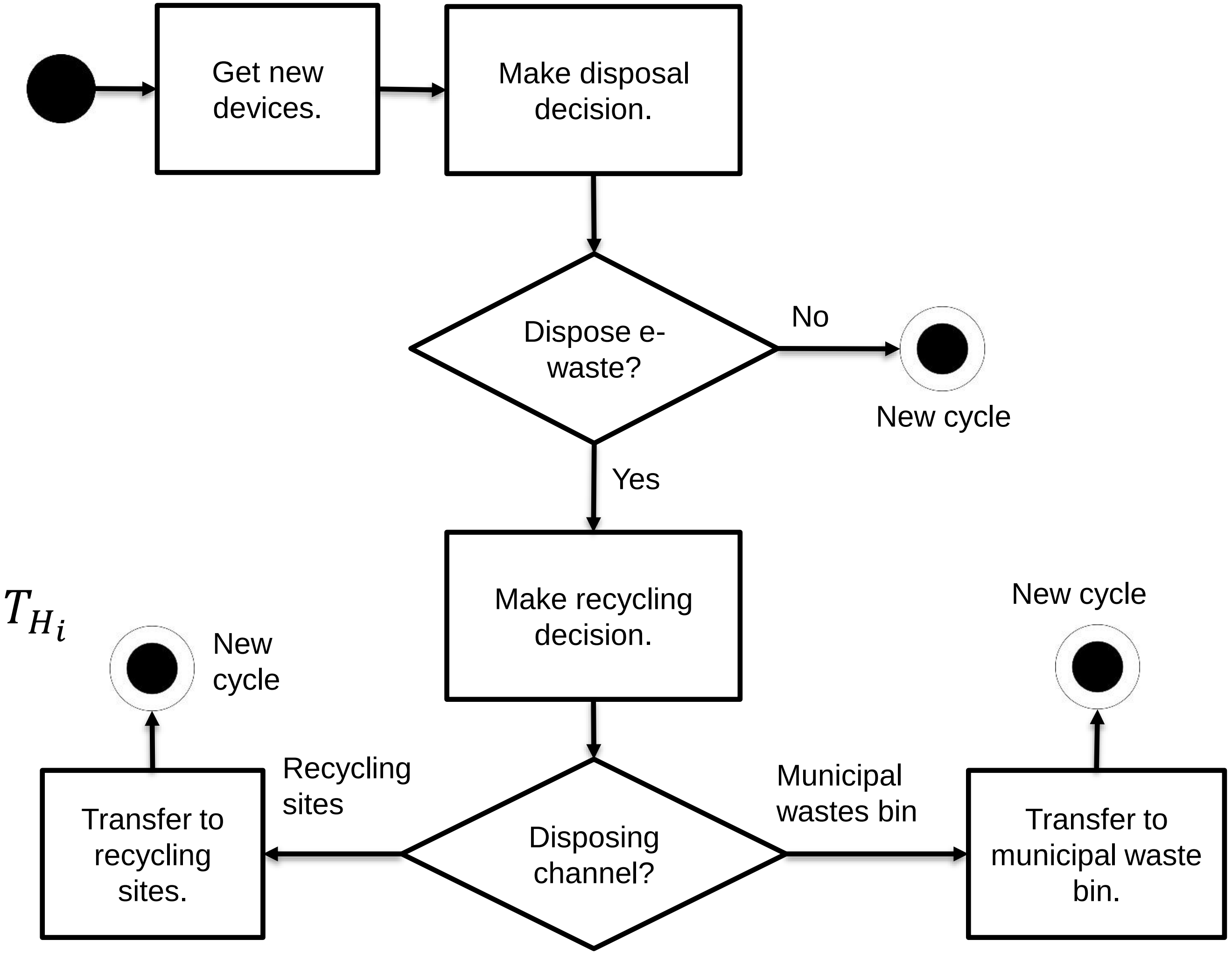
Resident (cont.)

- **Recycling decision**: Recycling sites or municipal bin?
  - Thresholding recycling score $S_{recycle}$ to Very Bad, Bad, Good, Very Good behaviours.
  - Corresponding probability of selecting recycling sites: 0.2, 0.4, 0.6, and 0.8

$$S_{recycle} = \beta_{SN} \cdot SN + \beta_{Att} \cdot Att + \beta_{Kn} \cdot Kn + \beta_{DT} \cdot DT_{H_i}$$

Where:

- SN is social norm, averaged of friends' $S_{recycle}$.
- Att is attitude toward recycling practices.
- Kn is knowledge about how to recycle.
- DT_{H_i} is travelling distant needed to dispose e-waste at recycling sites.



Activity diagram of resident at a cycle.

Recycling Indicators

- **Average retention time** of e-waste:

$$T_{avg} = \frac{\sum_{S\in\mathcal{S}} \sum_{D\in\mathcal{D}_S} t_D}{\sum_{S\in\mathcal{S}} |\mathcal{D}_S|}$$

Where:
- t_D is time at home of device D.
- $\mathcal{D}_S$ is set of all devices at recycling site $\mathcal{S}$.
- $\mathcal{S}$ is set of all recycling sites in the system.

- **Recycling rate**:

$$PCT_{recycled} = \frac{V_{recycled}}{V_{recycled} + V_{misplaced}}$$

Where:
- $V_{recycled}$ is amount of e-waste disposed into recycling sties (properly).
- $V_{misplaced}$ is amount of e-waste disposed into municipal bins (improperly).

Nearest Recycling Sites Assignment Intervention

- Promote e-waste recycling by **increasing convenience** associated with **proximity**.
- Recycling sites with **minimal travelling distance** are assigned.
- Assessed scenarios: Random Assignment and Nearest Recycling Sites Assignment.

$$\mathcal{S}_H^{nearest} = \arg \min_{\mathcal{S}_H \in O_H} \sum_{S \in \mathcal{S}_H} dist(S, H)$$

Where:

- $dist(S, H)$ is Euclidean distant of household H and recycling sites S.
- $\mathcal{S}_H$ is set of recycling sites needed for one option.
- O_H is set of all feasible options (consists of several recycling sites) to dispose e-waste.

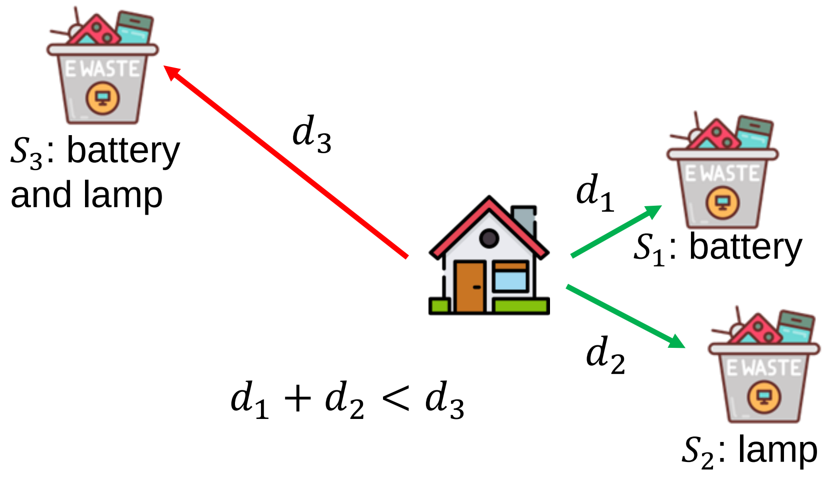


Illustration of Nearest Recycling Sites Assignment intervention. E-wastes at home: batteries and lamps. Assigned sites: $\mathcal{S}_H^{nearest} = (S_1, S_2)$

Recycling Information Campaign Intervention

- Promote e-waste recycling by **disseminating recycling knowledge**.
- Frequently organized events to increase resident's knowledge on proper recycling.
- **Increase information accessibility** I of Recycling Sites.
- Assessed scenarios: annually, bi-annually, quarterly, and no events organization.

Recycle Right campaign run by NEA in January 2022. Photos from Mural Lingo.

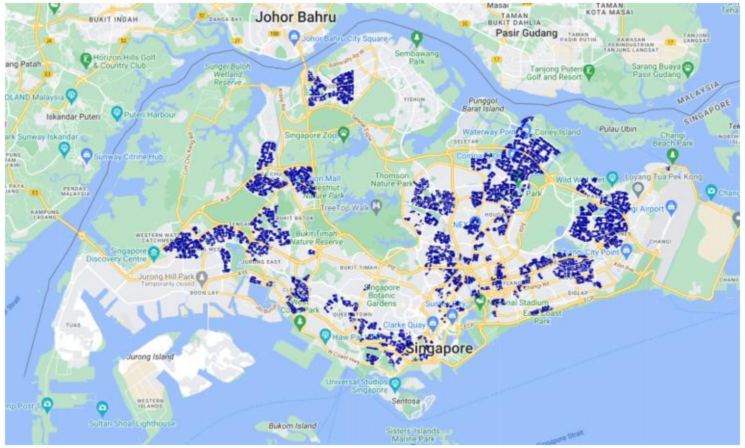
Do you remember that **60%** of Singapore residents **do not know** or are **unsure** of how to recycle their electronic waste?

Experiment Scenarios

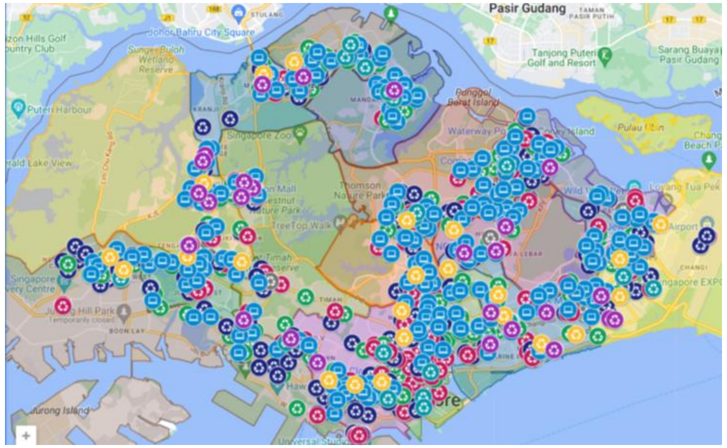
- **Baseline**: random sites assignment and no recycling information campaign.
- **Nearest Recycling Sites Assignment.**
- **Recycling Information Campaign**: annually, bi-annually, quarterly events.
- **Enhanced Scenario**: Nearest Recycling Sites Assignment and Recycling Information Campaign (bi-annual events).

Implementation

- GAMA Platform version 1.9.3.
- Data:
  - NEA recycling sites.
  - Housing & Development Board (HDB) geometric data.
  - HDB property information.
- More than 11,000 residents and 946 recycling sites.
- Simulation: 2080 cycles = 20 years, repeated 4 times.



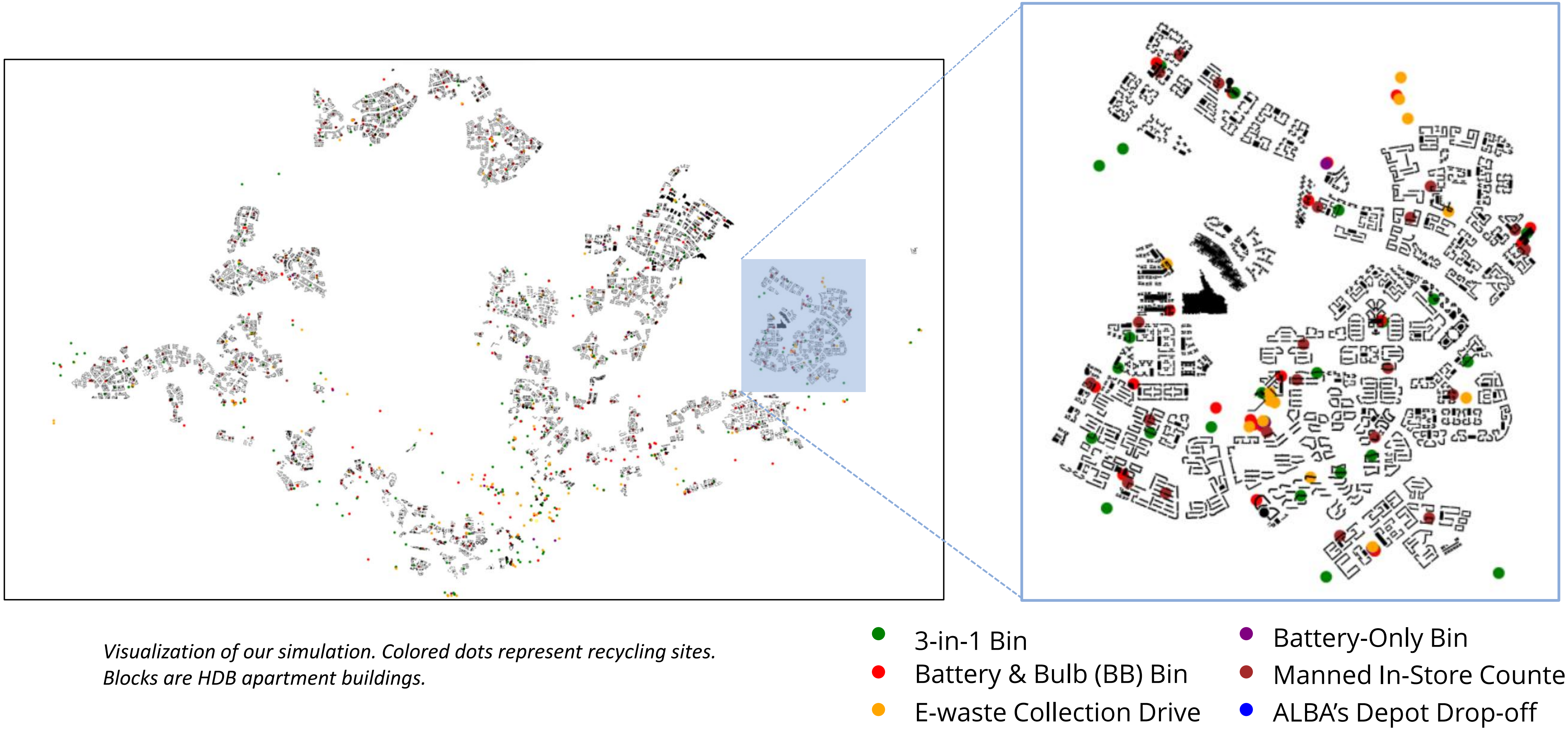
HDB geometric data.



NEA recycling sites.

EXPERIMENT RESULTS

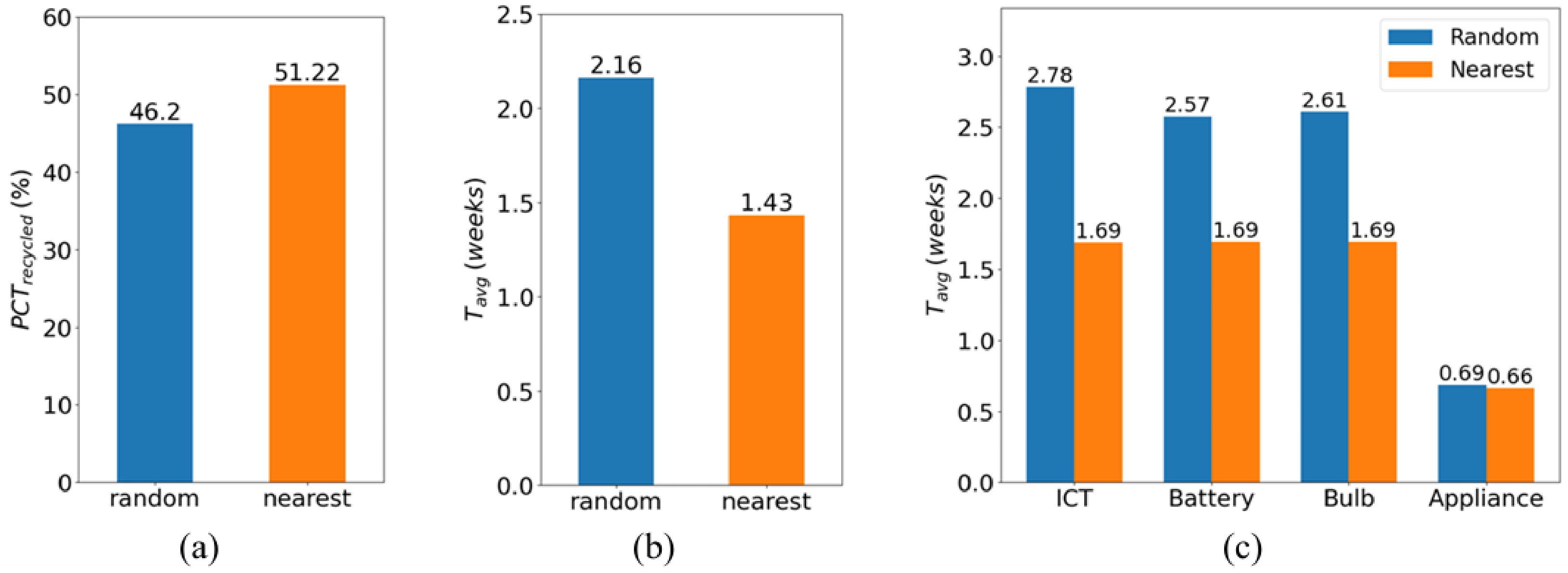
Simulation Visualization



Visualization of our simulation. Colored dots represent recycling sites. Blocks are HDB apartment buildings.

Nearest Recycling Sites Assignment

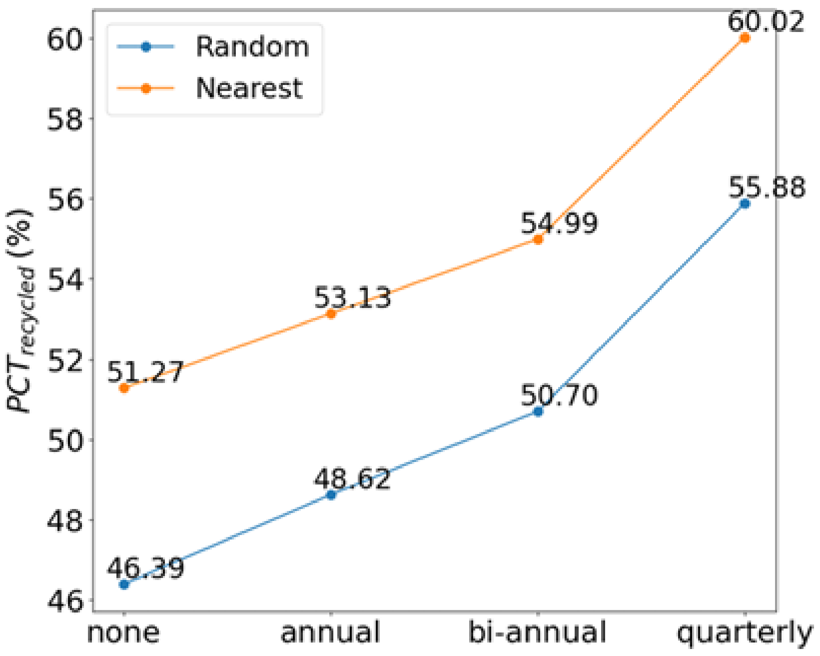
- Increase recycling rate $PCT_{recycled}$ and reduce retention time T_{avg}.
- Decrease of retention time for ICT, Battery, and Bulb.



Results of Nearest Recycling Sites Assignment: (a) recycling rate $PCT_{recycled}$ (higher is better); (b) average retention time T_{avg} (lower is better); (c) average retention time T_{avg} by types of e-wastes (lower is better).

Recycling Information Campaign and Enhanced Scenario

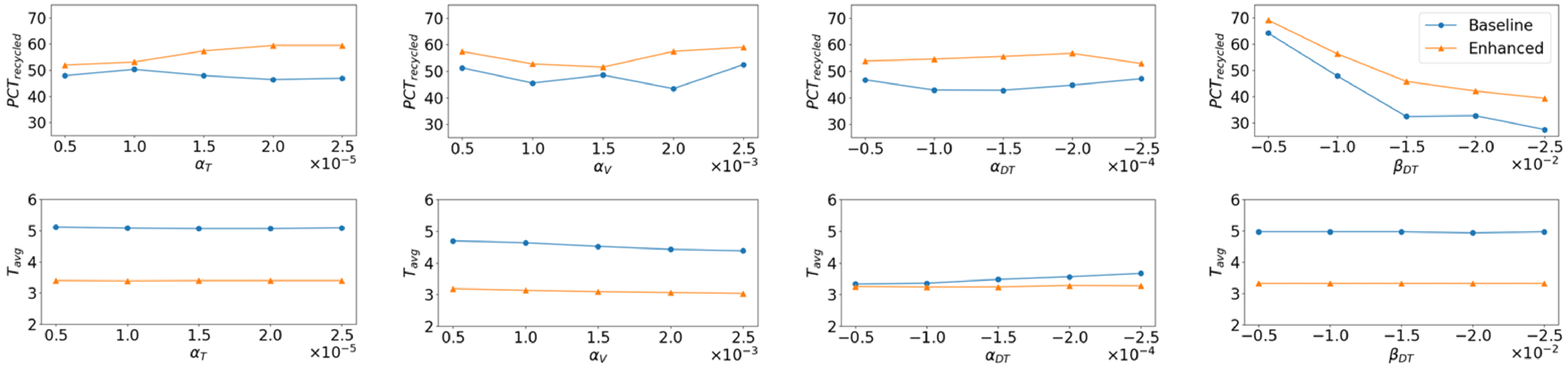
- Recycling Information Campaign: recycling rate $PCT_{recycled}$ increases proportionally to events organization frequency.
- Enhanced Scenario (both interventions) further improves recycling rate.



Recycling Information Campaign result: recycling rate $PCT_{recycled}$ (higher is better) by campaign frequency.

Sensitivity Analysis – Are the Results Trustworthy?

- One-factor-at-a-time (OFAT) sensitivity analysis.
- Scenarios: baseline (no intervention) and enhanced (both interventions).
- Implementing interventions **constantly improves recycling participation**.

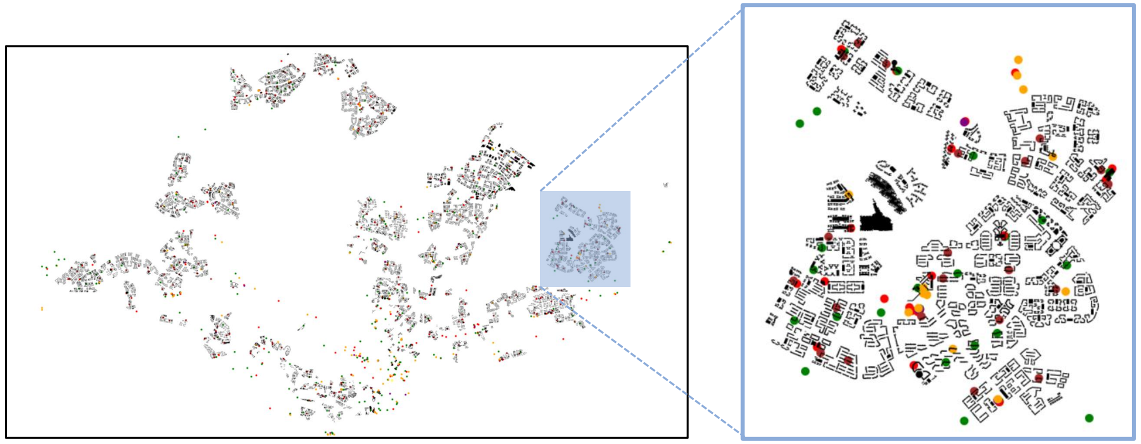


Results for sensitivity analysis on recycling rate $PCT_{recycled}$ (higher is better) and retention time T_{avg} (lower is better). Baseline: no intervention is implemented. Enhanced: implementing both Nearest Recycling Sites Assignment and Recycling Information Campaign (bi-annual frequency).

CONCLUSION AND POTENTIAL DEVELOPMENTS

Conclusion

- Agent-based model to simulate e-waste collection system and recycling behaviours in Singapore.
- Provide **policymakers** with **insights for interventions design**.
- Assessment of Interventions: Nearest Recycling Sites Assignment and Recycling Information Campaigns.



Visualization of our simulation. Colored dots represent recycling sites. Blocks are HDB apartment buildings.

Ideas for Potential Development

- Exploration of other strategies: deposit refund schemes and incentive programs.
- **Collective Intelligence** and **Multi-Agent Reinforcement Learning** to enhance recycling objectives by **collaboration** and **competition** of individuals.

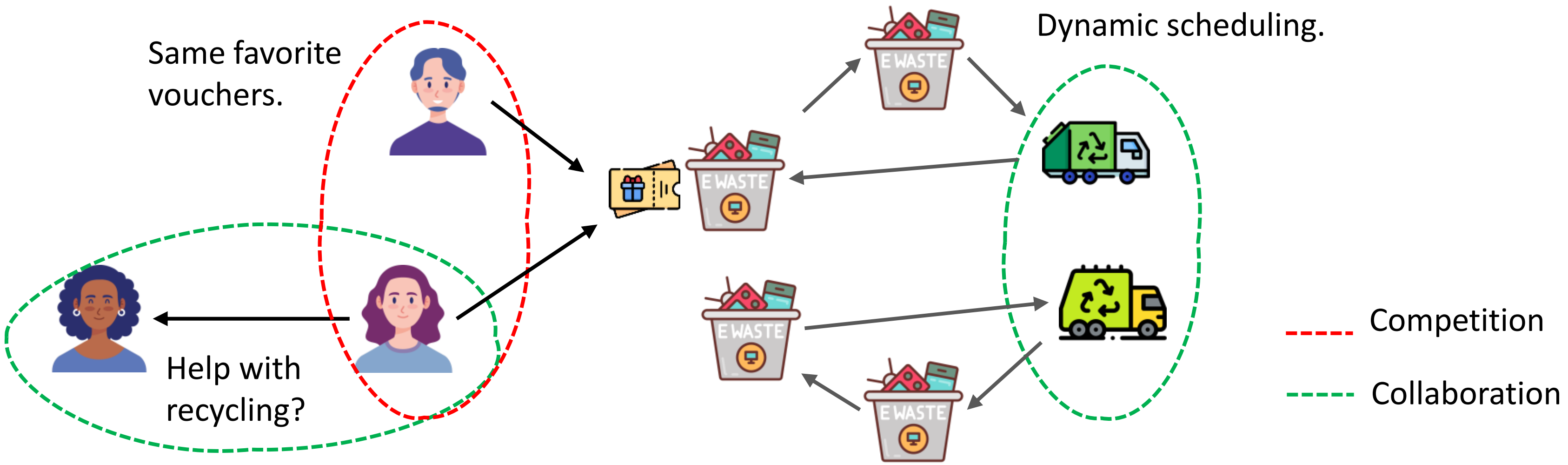


*Illustration of employing **Collective Intelligence** and **Multi-Agent Reinforcement Learning** to improve recycling objectives. Agents are self-interested with individual objectives. Residents may ask their friend to help recycling if they are busy, compete with others to gain favorite vouchers. Collecting trucks need collaboration for optimal dynamic routing.*

Thank you!

I am seeking opportunities for **PhD** in **Artificial Intelligence for Science and Engineering**.

Contact:
- Email: khanh.tq190085@sis.hust.edu.vn
- Profile: khanhtrq.github.io