Modeling Joint Activity-Travel Patterns in Pedestrian Networks with Possibility of Using Wi-Fi Data

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Abstract: This paper proposes a new model for solving the joint activity-travel pattern (JATP) scheduling problem in pedestrian networks. A novel pedestrian-joint-activity-time-space (PJATS) supernetwork is proposed to capture the complex structure of pedestrian networks and pedestrians’ intra-group interactions. The JATP scheduling problem is transformed into an extended User Equilibrium (UE) traffic assignment model with constraints for capturing the intra-group interactions. A heuristic solution method is proposed to solve the extended UE problem. A simplified pedestrian network is used to illustrate the convergence of the proposed heuristic solution method. Furthermore, the possibility of using Wi-Fi tracking data from mobile phones is also investigated and illustrated for estimating the PJATS patterns within the university campus. Results are presented and discussed to preprocess the raw Wi-Fi data and generate the PJATS patterns from matched media access control addresses of detected students in the selected area of the Hong Kong Polytechnic University.

Keywords: activity-travel scheduling, network equilibrium, intra-group interactions, pedestrian network

1. INTRODUCTION

Understanding and predicting pedestrian activity and travel demand play an important role in efficient designs of new infrastructures, such as facilities on university campuses or in shopping centers, as well as daily operations of these infrastructures. Temporal-spatial consistency of pedestrians’ activity/travel choices and intra-group interactions of behaviorally heterogeneous group members require explicitly modeling of activity-travel scheduling decisions. These decisions can be classified into three levels: (1) departure time choice, and activity pattern choice (strategic level); (2) activity scheduling, and route/mode choice (tactical level); (3) walking behavior (operational level) (Hoogendoorn & Bovy (2004)).

While modeling pedestrian walking behavior such as choices of walking orientation and speed plays a central role in pedestrian behavior researches (see Hoogendoorn et al. (2002) and Bierlaire & Robin (2009)), activity-travel choice models for pedestrians at the strategic and tactical levels have received little attention. Hoogendoorn & Bovy (2004) have developed an activity-travel scheduling model in a continuous time-space pedestrian network, but their model mainly focuses on the tactical level. Activity-travel scheduling models in pedestrian

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networks can be distinguished from existing counterpart models in transportation networks (e.g. Miller & Roorda (2003), Bhat et al. (2004), Arentze & Timmermans (2004) and Roorda et al. (2009)) in the following aspects. First, the structure of pedestrian networks is more complex than that of transportation networks. In particular, pedestrian networks would include various types of points at multiple levels (floors), e.g., pathways, stairways, escalators, or elevators while walking. Second, intra-group interactions of behaviorally heterogeneous pedestrians in the same group also play an important role in activity choices behaviors. Finally, crowding effects at activity locations may affect the activity choices of pedestrians.

Lam & Yin (2001) first proposed an activity-based equilibrium model, in which a time-expanded supernetwork was used to capture tempo-spatial constrained scheduling behaviors of individuals. The model has been followed with the use of activity-time-space (ATS) supernetworks, which are extended from the time-expanded supernetwork, for schedule-based transit systems (Li et al. (2010)), congested networks (Ouyang et al. (2011)), stochastic utilities (Fu & Lam (2014)), and weather effects (Fu et al. (2014)). Fu & Lam (2016) recently developed a scheduling model so-called joint-activity-time-space (JATS) supernetwork platform for JATP of two persons in multimodal transit networks. In their proposed supernetwork representation, nodes in the JATS supernetwork then capture interactions among household members. Fu & Lam (2016)'s supernetwork can capture unsynchronized activity participation with flexible joint activity durations. However, the joint activities in their study were simply modeled as each individual's activity-travel patterns (ATPs) were assumed to contain only one joint activity and the joint activity was fixed.

In this paper, we propose a novel activity-based equilibrium model for scheduling ATPs in pedestrian networks, hypothesizing that behaviorally heterogeneous pedestrians in the same group may have joint activities, as well as are affected crowding discomfort while traveling and participating in activities. Then, a pedestrian-joint-activity-time-space (PJATS) supernetwork formulation is proposed to capture the complex structure of pedestrian networks and intra-group interactions, i.e., joint activities, of pedestrians. Based on the proposed PJATS supernetwork, the JATP scheduling problem is transformed into an extended User Equilibrium (UE) static assignment problem with additional constraints for intra-group interactions. A heuristic solution method, based on the Method of Successive Averages (MSA), is proposed to address the extended UE problem. For finding the optimal JATP at each iteration of the solution method and maintaining consistency of ATPs of pedestrians in the same group, Multi-Agent Path Finding (MAPF) problem is then regarded as the subproblem of the UE problem. In this paper, the possibility of using Wi-Fi tracking data from mobile phones is also investigated and illustrated for estimating the JATPs within the study area on a university campus.

The rest of this paper is organized as follows. First, the model assumptions are given in Section 2. The network representation is proposed in Section 3. Then, the problem formulation and solution method are presented in Sections 4 and 5. The numerical example is shown in Section 6, followed by an experimental study in the Hong Kong Polytechnic University (PolyU) with the use of Wi-Fi tracking data to generate JATPs in the selected area of PolyU campus. Finally, a conclusion is given in Section 7 together with recommendations for further studies.

2. MODEL ASSUMPTIONS

In order to facilitate essential ideas without loss of generality, there are several assumptions adopted in this paper:

1. JATPs are considered in a fixed study horizon divided into equally spaced time
intervals (Lam & Yin (2001), Ouyang et al.(2011) and Fu et al.(2014)).
(2) Travel times in the pedestrian network are deterministic and flow-dependent (Lam & Yin (2001), Ouyang et al.(2011) and Fu et al.(2014)), while dynamic and stochastic walking behavior is not considered (Hoogendoorn&Bovy (2004)).
(3) Activity utilities and travel disutilities are deterministic and flow-dependent (Lam & Yin (2001), Ouyang et al.(2011) and Fu et al.(2014)).
(4) Pedestrians have perfect knowledge of traffic conditions throughout the whole network (Fu & Lam (2014)) and activity locations. Note that the proposed model is mainly used for long-term infrastructure planning and facility management purposes.
(5) Joint decision-making process seeks to maximize the utility of JATP of the entire group (Fu & Lam (2016)).

Some commonly-used acronyms in the paper are summarized as follows:
- PJATS: Pedestrian-Joint-Activity-Time-Space supernetwork
- JATP: Joint Activity-Travel Pattern
- ATS: Activity-Time-Space supernetwork
- ATP: Activity-Travel Pattern
- UE: User Equilibrium
- MSA: Method of Successive Averages
- MAPF: Multi-Agent Path Finding
- CBS: Conflict-Based Search
- DBSCAN: Density-Based Spatial Clustering of Applications with Noise
- HMM: Hidden Markov Model
- MAC address: Media Access Control address
- PolyU: The Hong Kong Polytechnic University

3. NETWORK REPRESENTATION

3.1 Pedestrian-Joint-Activity-Time-Space (PJATS) Supernetwork

Given a pedestrian network, aPJATS supernetwork$G^{ig}(N^{ig}, E^{ig})$ is constructed for each member of group$g$, where $N^{ig}, E^{ig}$ are the set of nodes and links, respectively. Each PJATS supernetwork$G^{ig}$ captures both separate and joint activities of member$\mathfrak{i}$ with other group members. Nodes and links of $G^{ig}$ are made up from the exclusive subsets below.

- $N^{ig} = N^{ig}_{\text{act}} \cup N^{ig}_{\text{loc}} \cup N^{ig}_{\text{start}} \cup N^{ig}_{\text{end}},$
- $E^{ig} = E^{ig}_{\text{act}} \cup E^{ig}_{\text{wait}} \cup E^{ig}_{\text{travel}} \cup E^{ig}_{\text{exchange}} \cup E^{ig}_{\text{ingress}} \cup E^{ig}_{\text{egress}} \cup E^{ig}_{\text{start}} \cup E^{ig}_{\text{end}},$

where

- $\text{Node}(a, l, z, m \cup \{i\}, k) \in N^{ig}_{\text{act}}, m \leq g$, is an activity node. It represents a state where a group of members$m$, including $i$, jointly participate in an activity $a$ at time $k$ at location $l$ on floor $z$, or in short location$(l, z)$.
- $\text{Node}(l, z, k) \in N^{ig}_{\text{loc}}$ is a location node. It represents a state where member $i$ stays at location$(l, z)$ at time$k$.
- $\text{NodeStart}(i) \in N^{ig}_{\text{start}}$ is a start node. It is a dummy start node for member$i$.
- $\text{Node End}(i) \in N^{ig}_{\text{end}}$ is an end node. It is a dummy end node for member$i$.
• Link \((a, l, z, m, k) \rightarrow (a, l, z, m, k + 1) \in E^{ia}_{\text{act}}, m \subseteq g, is an activity link. It represents that a group of members \(m\), including \(i\), perform activity \(a\) from time \(k\) to time \(k + 1\) at location \((l, z)\).

\[
\begin{align*}
\text{Pedestrian network} & \\
\text{walking time on} & \\
\text{construction} & \\
\text{location (1)} & \\
\text{walking time} & \\
\text{location (2)} & \\
\text{The group has} & \\
\text{two members} & \\
\text{Number of} & \\
\text{time intervals} & \\
K = 4 & \\
\end{align*}
\]

![Figure 1. PJATS supernetworks for two members \(i_1\) and \(i_2\)]

• Link \((l, z, k) \rightarrow (l, z, k + 1) \in E^{ig}_{\text{wait}}\) is a waiting link. It represents that member \(i\) waits from time \(k\) to time \(k + 1\) at location \((l, z)\).

• Link \((l, z, k) \rightarrow^{r} (l', z', k') \in E^{ig}_{\text{travel}}\) is a travel link. It represents that member \(i\) travels on route \(r\) from location \((l, z)\) to location \((l', z')\) from time \(k\) to time \(k'\), where \(k' - k\) is the travel time on route \(r\).

• Link \((a, l, z, m, k) \rightarrow (a, l, z, m', k + 1) \in E^{ig}_{\text{exchange}}\) is a member-exchange link. It represents that at a given location \((l, z)\), if \(m' \subseteq m\), a group of members \(m' \setminus m\) join \(m\) of min performing activity \(a\) at time \(k\); if \(m \supseteq m'\), a group of members \(m \setminus m'\) leave \(m'\) while performing activity \(a\) at time \(k\); where \(m' \setminus m\) is a group of members in \(m'\) but not \(m\), and both \(m, m'\) include \(i\).

• Link \((l, z, k) \rightarrow (a, l, z, m, k + 1) \in E^{ig}_{\text{ingress}}\) is an activity-ingress link. It means that a group of members \(m\), including \(i\), enter activity \(a\) at location \((l, z)\) at time \(k\).

• Link \((a, l, z, m, k) \rightarrow (l, z, k + 1) \in E^{ig}_{\text{egress}}\) is an activity-egress link. It means that a group of members \(m\), including \(i\), leave activity \(a\) at location \((l, z)\) at time \(k\).
• LinkStart(i) \to (l, z, 1) \in E_{start}^i \text{ is a start link. It is a dummy start link for member } i \text{ begins his/her activity/travel plans at location}(l, z).

• Link (l, z, K + 1) \to End(i) \in E_{end}^i \text{ is an end link. It is a dummy end link for member } i \text{ ends his/her activity/travel plans at location}(l, z).

Figure 1 illustrates the expansion of PJATS supernetworks $G^1\gamma$ and $G^2\gamma$ for two members $i1$ and $i2$ and the number of study time intervals $K = 4$. In this example, the pedestrian network has two locations, i.e. loc1 and loc2. Members $i1$ and $i2$ respectively start and end their activity/travel plans at loc1 and loc2. The two members have lunch on the 9th floor of loc2. With the use of the proposed PJATS supernetwork, a path from node Start(i) to node End(i) in supernetwork $G^i\gamma$, denoted as SE path, represents a feasible activity-travel pattern (ATP) of member $i$ that takes into account joint activities between with other members of group. A feasible joint activity-travel pattern (JATP) of group $g$ is made up from feasible ATPs of group members such that tempo-spatial consistency among the ATPs is maintained.

3.2 Link Utility/Disutility in the PJATS Supernetwork

Let $u_{ai}^{0}(k)$ denote the gained utility when member $i$ separately performs activity $a$ at time $k$. The utility of member $i$ performing activity $a$ with crowding discomfort effect at location $(l, z)$ between times $k$ and $k + 1$, denoted by $u_{ai}^{1}(k)$, can be expressed as

$$u_{ai}^{1}(k) = \int_{k}^{k+1} u_{ai}^{0}(x)dx \left[ 1 - \alpha_{ai}^{i} \left( f_{i}^{z}(k)/C_{i}^{z} \right)^{\theta_{ai}^{a}} \right]$$

where $\alpha_{ai}^{i} \geq 0$ is the crowding discomfort sensitivity of member $i$ to the crowdedness of activity $a$. $f_{i}^{z}(k)$ and $C_{i}^{z}$ are respectively the flow and capacity at location $(l, z)$ between times $k$ and $k + 1$, and $\theta_{ai}^{a}$ is the parameter related to the congestion effect of activity $a$ at location $(l, z)$. The joint utility $u_{ai}^{m}(k)$ gained when a group of members jointly perform activity $a$ between times $k$ and $k + 1$ is given by

$$u_{ai}^{m}(k) = \sum_{i \in m} w_{ai}^{im} u_{ai}^{i}(k) + \frac{\lambda_{a}}{2} \sum_{i, j \in m, i \neq j} w_{ai}^{im} u_{ai}^{i}(k) w_{ai}^{ja} u_{ai}^{j}(k)$$

where $\lambda_{a} \geq 0$ is a parameter representing the intra-group interactions for the joint participation of activity $a$, and $w_{ai}^{im}$ is member $i$’s weight parameter representing the relative influence of member $i$ in group $m$ on joint activity participation of activity $a$. A detailed interpretation of the group utility function and alternative formulations representing different group decision-making strategies can be found in Zhang et al. (2009). Let $v_{r}(k)$ denote the disutility for traveling on route $r$ with departure time $k$. The travel disutility is given by

$$v_{r}(k) = -VOT_{r}(k) \cdot t_{r}(k) \left[ 1 + \beta_{r} \left( f_{r}(k)/C_{r} \right) ^{\theta_{r}} \right]$$

where $VOT_{r} \geq 0$ is the value of time, $\beta_{r} \geq 0$ is the congestion discomfort parameter, $f_{r}(k)$ and $C_{r}$ are respectively the flow and capacity between times $k$ and $t_{r}(k)$, and $\theta_{r}$ is the parameter related to the congestion effect for traveling on route $r$. Note that the value of $VOT_{r}$ is relative to route. For example, the value of time for walking on routes with steps or obstacles might have a higher value of time than that of walking on corridors.

4. THE JATP SCHEDULING MODEL

In the JATPscheduling model, pedestrians in the same group would schedule their activities and
travels in order to maximize the group utility. With the use of the PJATS supernetwork proposed in Section 3, the scheduling decisions are equivalent to the determination of a SE path in the JPATS supernetwork for each group member such that the summation of utilities of SE paths of all members is maximized while maintaining the tempo-spatial consistency among SE paths. Then, the set of SE paths satisfying the above conditions represents the optimal JATP.

4.1 The Optimal JATP

Let \( p_{ig} \) denote the set of SE paths in supernetwork \( G_{ig} \) for member \( i \) of group \( g \). The utility of path \( p \in P_{ig} \), denoted as \( u_{ip}^{ig} \), can be obtained by the summation of utilities of links on path \( p \) as follows.

\[
    u_{ip}^{ig} = \sum_{e \in E_{ig}} \psi_e^{ig} \delta_{ep}^{ig} \quad (4)
\]

where \( \delta_{ep}^{ig} = 1 \) if link \( e \) on path \( p \) and \( \delta_{ep}^{ig} = 0 \) otherwise, and \( \psi_e^{ig} \) is the utility of link \( e \) on path \( p \in P_{ig} \). The utility \( \psi_e^{ig} \) is given by

- if \( e \in E_{ig}^{wait} \cup E_{ig}^{exchange} \cup E_{ig}^{ingress} \cup E_{ig}^{egress} \cup E_{ig}^{start} \cup E_{ig}^{end} \), \( \psi_e^{ig} = 0 \);
- if \( e \in E_{act}^{ig} \), where \( e = (a, l, z, m, k) \rightarrow (a, l, z, m, k + 1) \), \( \psi_e^{ig} = u_a^m(k) \);
- if \( e \in E_{travel}^{ig} \), where \( e = (l, z, k) \rightarrow (l', z', k') \), \( \psi_e^{ig} = \nu_r(k) \),

where \( u_a^m(k) \) and \( v_r(k) \) are the activity utility and travel disutility respectively given by Equations (2) and (3).

Let \( S_g \) denote the set of all feasible JATPs of group \( g \). \( S_g \) can be defined with respect to ATPs of members in group \( g \). \( P_{ig} \), in the following equation:

\[
    S_g = \{ R! \forall (p, p'), \forall p, p' \in R, R \in \times_{i \in g} P_{ig} \} \quad (5)
\]

where \( R \) is a feasible JATP of group \( g \), the term \( \times_{i \in g} P_{ig} \) is the cross product of sets \( P_{ig} \), and condition \( \forall(p, p') \) is true if path \( p \) conflicts with path \( p' \). The condition \( \forall(p, p') \) is given by Definition 2, where \( e^{pk} \) denotes the link on path \( p \in P_{ig} \) elapsed through time \( k \) to time \( k + 1 \), and \( m^{pk} \) denotes the set of members related to link \( e^{pk} \). Then, \( m^{pk} = m \subseteq g \) when link \( e^{pk} \) has one of the following forms:

- \( e^{pk} = (a, l, z, m, k) \rightarrow (a, l, z, m, k + 1) \in E_{act}^{ig} \)
- \( e^{pk} = (l, z, k') \rightarrow (l', z', k'') \in E_{travel}^{ig}, k' \leq k \leq k'' \)
- \( e^{pk} = (a, l, z, m', k) \rightarrow (a, l, z, m'', k + 1) \in E_{exchange}^{ig}, m' = m \) or \( m'' = m \)
- \( e^{pk} = (l, z, k) \rightarrow (a, l, z, m, k + 1) \in E_{ingress}^{ig} \)
- \( e^{pk} = (a, l, z, m, k) \rightarrow (l, z, k + 1) \in E_{egress}^{ig} \)

Otherwise, \( m^{pk} = \emptyset \).

**Definition 1** (Link conflict). Given two links \( e^{pk} \in E_{ig}^{ig} \) and \( e^{pk'} \in E_{ig}^{ig} \) with their corresponding sets of members \( m^{pk} \) and \( m^{pk'} \), link \( e^{pk} \) conflicts with link \( e^{pk'} \), denoted as \( \forall(e^{pk}, e^{pk'}) \), if \( m^{pk} \cap m^{pk'} \neq \emptyset \) and \( e^{pk} \neq e^{pk'} \).

**Definition 2** (Path conflict). Given two paths \( p \) and \( p' \), pathconflicts with path \( p' \), denoted by \( \forall(p, p') \), if \( \exists k: \forall(e^{pk}, e^{pk'}), k = 1 ... K \).

Let \( \Phi_g \subseteq S_g \) denote the feasible JATP of group \( g \) with greatest utility, or the optimal
JATP of group $g$, where the JATP utility is the summation of utilities of ATPs of all group members. The optimal JATP of group $g$ can be expressed as

$$
\phi^g = \arg\max_{R \in R^g} \sum_{i \in g} \sum_{p \in R \cap p^ig} u^g_p.
$$

(6)

Note that $R \cap p^ig$ in Equation (6) represents a unit set for the feasible ATPs of member $i$ in JATPR of group $g$ such that $p$ does not conflict with ATPs of other members of group $g$ in terms of time and space.

### 4.2 The JATP Scheduling Model Formulation

Based on the proposed PJATS supernetwork, the JATP scheduling problem can be transformed into an extended static UE traffic assignment problem. In this paper, behaviorally heterogeneous classes of pedestrians and intra-group interactions of pedestrians in the same group are both considered. The JATP chooses the pedestrian network reach equilibrium if (1) pedestrians cannot improve their utility by unilaterally changing their ATPs to any other feasible ATPs, (2) pedestrians in the same group must ensure the tempo-spatial consistency among their ATPs when they perform joint activities. In other words, the utilities of all used JATPs are the greatest, and all unused JATPs have smaller utilities. The UE condition can be expressed as

$$
f_p^ig(\phi^g - u_p^g) = 0, \forall p \in R \cap p^ig, R \in S^g, g \in \Lambda,
$$

(7)

$$
\phi^g - u_p^g \geq 0, \forall p \in R \cap p^ig, R \in S^g, g \in \Lambda,
$$

(8)

$$
q^g = \sum_{R \in R^g} \sum_{p \in R \cap p^ig} f_p^ig, \forall g \in \Lambda,
$$

(9)

$$
f_p^ig \geq 0, \forall p \in R \cap p^ig, R \in S^g, g \in \Lambda,
$$

(10)

where

$f_p^ig$: the flow on path $p$ related to the ATP of member $i$ of group $g$,

$q^g$: the utility of optimal ATP of member $i$ of group $g$,

$q^g$: the demand for member $i$ of group $g$,

$\Lambda$: the set of groups.

The flow on link $e$ in the PJATS supernetwork can be determined by

$$
x_e = \sum_{g \in \Lambda} \sum_{i \in g} \sum_{R \in R^g} \sum_{p \in R \cap p^ig} f_p^ig \delta^ig_{ep}.
$$

(11)

Then, if $e \in E^act_{\sum}$, $x_e$ represents the crowdedness at the corresponding activity location where member $i$ of group $g$ participate in. If $e \in E^i_{\text{travel}}$, $x_e$ represents the traffic flow of the corresponding route where member $i$ of group $g$ travels on. The UE problem can then be expressed below as the minimization problem of the following gap function

$$
\min \text{GAP} = \sum_{g \in \Lambda} \sum_{i \in g} \sum_{R \in R^g} \sum_{p \in R \cap p^ig} f_p^ig(\phi^g - u_p^g).
$$

(12)

The UE solution convergence can be evaluated by the relative gap RGAP (Fu & Lam (2014))

$$
\text{RGAP} = \text{GAP} / \sum_{g \in \Lambda} \sum_{i \in g} \sum_{R \in R^g} \sum_{p \in R \cap p^ig} f_p^ig u_p^g.
$$

(13)
5. THE HEURISTIC SOLUTION METHOD

In this section, a algorithm for Multi-Agent Path Finding (MAPF) problem to determine the optimal ATP is first presented. Based on this algorithm, a heuristic solution for solving the UE problem is proposed.

5.1 A Solution Algorithm for Finding The Optimal JATP

The proposed PJATS supernetwork does not ensure tempo-spatial consistency among SE paths of members \(i\) of group \(g\) if each \(path \in P_i^g\) for member \(i\) is searched separately in each \(G_i^g\). Therefore, the optimal JATP defined by Equation (6) is not simply the path with the greatest utility in each network \(G_i^g\) separately. The path-finding problem must be treated as a MAPF problem in which each member \(i\) is regarded as an agent, and the conflicts between member \(i\) and other members in the same group are considered simultaneously in the path-finding process for each \(G_i^g\). To solve the MAPF problem, we propose a solution algorithm, based on so-called Conflict-Based Search (CBS) proposed by Sharon et al. (2015). The pseudo code of the proposed solution algorithm is given below.

\[\text{Algorithm Conflict-Based Search}\]

**Inputs:** \(G_i^g(N_i^g, E_i^g), \forall i \in g;\)

**Outputs:** The optimal GATP \(\Phi^g;\)

1. \(C_0 = \emptyset;\)
2. \(R_0 = \{pi | i \in g\}, \) where \(pi\) is the greatest-utility path in \(G_i^g\) based on \(C_0 = \emptyset;\)
3. \(\Gamma = \{(R_0, C_0)\};\)
4. while \(Q \neq \emptyset\) do
5. \((R, C) = \) the best element in \(Q,\) where \(R\) is the JATP with maximum utility;
6. \(Q = Q \setminus \{(R, C)\};\)
7. if JATPR has no conflict then
8. \(\text{return} \Phi^g = R;\)
9. Se determ ine a conflict between \(p \in R \land P_i^g\) and path \(p' \in R \land P_i^g, i \neq i',\) at time interval \(k'\) th by Definition 1;
10. for each member, \(i'\) involved in the conflict do
11. \(RR = R;\)
12. if member \(i\) avoids the conflict then
13. \(CE = \{e_p^{ik}\} \text{ and all links of } G_i^g \text{ that conflict link } e_p^{ik};\)
14. \(CC = C \cup CE;\)
15. Replace \(p \in RR \land P_i^g\) by the greatest-utility path in \(G_i^g\) based on \(CC;\)
16. elseif member \(i'\) avoids the conflict then
17. \(CE = \{e_p^{ik}\} \text{ and all links of } G_i^g \text{ that conflict link } e_p^{ik};\)
18. \(CC = C \cup CE;\)
19. Replace \(p' \in RR \land P_i^g\) by the greatest-utility path in \(G_i^g\) based on \(CC;\)
20. \(Q = Q \cup \{(RR, CC)\};\)

The key idea of the proposed solution algorithm is that the conflict is examined at each time \(k\) between path \(p \in RR \land P_i^g\) and path \(p' \in RR \land P_i^g,\) with \(i \neq i'(\) Line 9). If there is one, either member \(i\) or member \(i'\) avoids the conflict, i.e. either path \(p\) uses link \(e_p^{ik}\) or path \(p'\) uses link \(e_p^{ik}.\) The details for the development, optimality and completeness of the CBS can be found in Sharon et al. (2015). The path-finding problem for the SE path with the greatest utility in each iteration of the CBS for each \(G_i^g\) is a longest path problem. The problem is known NP-hard for a general graph. Fortunately, the PJATS supernetwork \(G_i^g\)
constructed for each member $i$ is directed acyclic graphs (see Figure 1). Thus, paths with the greatest utility can be determined by using dynamic programming.

5.2 A Heuristic Solution for Solving The Extended UE Problem

Based on the solution algorithm for finding the optimal JATP proposed in Section 5.1, the extended UE problem can be solved without requirement of JATP enumeration. The solution algorithm for solving the extended UE problem is outlined as follows.

Step 1 Network expansion. Transform the pedestrian network into PJATS supernetworks $G^i_{ig}(N^i_{ig}, E^i_{ig}), \forall i \in g, g \in \Lambda$.

Step 2 Initialization. Let $n = 0$. Find the optimal JATP $\Phi^g$ using the CBS algorithm in supernetworks $G^i_{ig}, \forall i \in g, g \in \Lambda$. Assign all demand $q^i_{ig}$ on ATP $p$ for member $i$ in JATP $\Phi^g$, i.e. $f^n_p(q^i_{ig}) = q^i_{ig}, \forall p \in \Phi^g, i \in g, g \in \Lambda$. Set $S^g = \{ \Phi^g \}, \forall g \in \Lambda$. Update link flows and link utilities.

Step 3 Column generation. Find the optimal JATP $\Phi^g$ using the CBS algorithm in supernetworks $G^i_{ig}, \forall i \in g, g \in \Lambda$. Update $S^g = S^g \cup \{ \Phi^g \}, \forall g \in \Lambda$.

Step 4 Flow update. Find the optimal JATP $\Phi^g$ among JATPs in $S^g$. Assign all demand $q^i_{ig}$ on ATP $p$ for member $i$ in JATP $\Phi^g$ to obtain the auxiliary flow for ATP $p$, i.e. $f^n_p(aux) = q^i_{ig}, \forall p \in \Phi^g, i \in g, g \in \Lambda$. And set $f^n_p(aux) = 0$ if ATP $p$ for member $i$ is not in JATP $\Phi^g, \forall p \in \Phi^g, i \in g, g \in \Lambda$. Obtain the flow $f^{n+1}_p, \forall p \in R \cap P^i_{ig}, R \in S^g, i \in g, g \in \Lambda$, using MSA (Method of Successive Averages) as below.

$$f^{n+1}_p = f^n_p + \frac{1}{n} \left( f^n_p(aux) - f^n_p(n) \right).$$

Then, update link flows and link utilities.

Step 5 Convergence test. For an acceptable convergence level $\varepsilon$, if $GRAP \leq \varepsilon$, Stop. Otherwise let $n = n + 1$ and go back to Step 3.

6. NUMERICAL EXAMPLE

The numerical example aims to illustrate (1) the results of the proposed model and the convergence of the solution, (2) the sensitivity of the proposed model with respect to intra-group interaction, (3) the application of the proposed model to evaluation of facility management policies, and (4) the possibility of using Wi-Fi tracking data to generate the PJATS patterns from matched media access control (MAC) address of detected pedestrians in the selected network within the campus of the Hong Kong Polytechnic University (PolyU).

6.1 Input Data
In the numerical example, a simplified pedestrian network (as shown in Figure 2) on the campus of PolyU was adapted to illustrate the essential ideas of the proposed supernetwork platform. The study network consists of six locations, i.e. locations (1) (student halls), (2) (canteen), (3) (entrance 1) and (5) (entrance 2) located on the ground floor; and locations (4) and (6) (classroom) on the ninth floor of the Block Z building (Faculty of Construction and Environment, FCE). These six locations are related to three common activities, i.e. home, studying (lecture) and eating activities, of students from FCE of PolyU. Note that the study network only covers a small area of the PolyU campus at which installed MAC addresses scanners are located for this case study. Besides, only students with home at the student hall were considered although some of PolyU students may live outside of the campus.

Pathways for walking are only available between locations on the same floor. There are two lifts, i.e. lifts 1 and 2 respectively at entrances 1 and 2 on the ground floor, to access to the ninth floor. Parameters related to travel disutility of link types, i.e. pathways or lift, are presented in Table 1. Lift capacity is less than pathway capacity and greater crowding discomfort.

### Table 1. Basic link data for the example pedestrian network

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Link type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pathway</td>
</tr>
<tr>
<td>Capacity ( C_r ) (students/minute)</td>
<td>70</td>
</tr>
<tr>
<td>Crowding discomfort parameters ( \beta_r, \theta_r )</td>
<td>30, 2</td>
</tr>
<tr>
<td>Value of time ( VOT_r ) (HK$/minute)</td>
<td>1</td>
</tr>
</tbody>
</table>

The studying horizon is 9 hours from 10:00 to 19:00. Each hour is equally divided into
60 intervals, i.e. 1 minute per interval. We assume that all students start and end their schedules at the student halls. Students can perform four types of activities, i.e. staying home at the student halls, eating and/or café at the canteen, and attending lecture at the classroom. No congestion effect is considered when students stay at the student halls and attend lecture at the classroom. The capacity of the canteen is set to 300 students per minute. It is assumed that students perceive the utility functions of four activities identically. In this paper, the bell-shaped marginal utility function proposed by Ettema & Timmermans (2003) is adopted as shown in Figure 3.

The numerical example aims to illustrate JATPs for modeling intra-group interactions of two behaviorally heterogeneous student classes, i.e. A and B. Table 2 shows all feasible group types for two student classes. In order to facilitate the presentation of essential ideas on the joint activity issue, it was assumed that class A students may only take part in joint activities with class B students. In other words, intra-group interactions between either two class A or two class B students are ignored in this paper. Thus, there are only three group types, X, Y and Z as shown in Table 2. In particular, each group with type X (or Y) consists of only one student with class A (or B) who have no intra-group interactions with class B (or A) students. Each group with type Z comprises two students, i.e. one with class A and one with class B performing activities jointly. However, it should be noted that the proposed model is not restricted to the scenarios with only two student classes and three possible group types. The extension of the proposed model is recommended for further studies with consideration of multi-user classes and different combination of group types.

Table 2. Feasible group types for intra-group interactions of two student classes

<table>
<thead>
<tr>
<th>Student 1</th>
<th>Class A</th>
<th>Class B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With intra-group interactions</td>
<td>Without intra-group interactions</td>
</tr>
<tr>
<td>Class A</td>
<td>√</td>
<td>N.A.</td>
</tr>
<tr>
<td>Without intra-group interactions</td>
<td>N.A.</td>
<td>√</td>
</tr>
<tr>
<td>Class B</td>
<td>√ (group Z)</td>
<td>N.A.</td>
</tr>
<tr>
<td>Without intra-group interactions</td>
<td>N.A.</td>
<td>√ (groups X, Y)</td>
</tr>
</tbody>
</table>

√: feasible group type; N.A.: infeasible group type.

The total number of students is 500. For illustrative purposes, 250 class A students were assumed to have joint activities with 250 class B students. Thus, the demand for the JATPs of class A and B students with intra-group interactions is 250. Note that, in reality, the numbers of class A and B students are not necessarily equal. For example, suppose that 300 class A students may have joint activities with 200 class B students. Therefore, demand for the JATPs of class A and B students with intra-group interactions should be 200 each. The remaining 100 class A students are considered separately without the intra-group interactions.

The parameters related to student and group types for activity utility as shown in Equations (1) and (2) are set as \( w_a^{A Z} = w_a^{B Z} = 0.5 \), \( w_a^{A X} = w_a^{B Y} = 1 \), \( \lambda_a = 0.4 \), \( \alpha_a^A = 0.4, \alpha_a^B = 0.6 \), and \( \theta_{a Z} = 2 \), where activity \( a \) can be either eating or café. It must be noted that
\( \alpha_A = 0.4 \) and \( \alpha_B = 0.6 \) mean that students with class B are more sensitive to crowding discomfort at the location of activity than students with class A are.

6.2 Results

We consider the base case in which the number of groups with type Z is 125 over the population of 500 students. That means the numbers of groups with types X and Y are respectively 125. The results are presented in Figure 4 for the temporal distribution of students at activity locations and on travel links. It is shown that between 12:00 and 12:30, many students (approximately 70% of students) leave the student halls and go for lunch at the canteen by traveling on link 1-2. For the 13:30-15:30 time period, all students are at the classroom because of the significant high utility of the lecture. From 15:20, students start leaving the classroom to have caféd because of the decreasing utility of the lecture. Because of the congestion at the canteen, approximately 50% of students go straight to the student halls without visiting the canteen for caféd. It can be observed from Figure 6 that students do not arrive and leave the classroom at the same time but within periods of time, i.e. 12:45-13:45 and 15:20-16:20, before and after the lecture, respectively. This is because the only way to enter and leave the classroom is through lifts 1 and 2. However, because lifts have a smaller capacity, i.e. 6 students per minute, compared to 70 students per minute of pathways, it takes some time for the lifts to carry all students.

Figure 4. The spatial student distribution at activity location and travel links
Figure 5. The convergence characteristics of the proposed UE heuristic solution method

The proposed solution algorithm requires about 55 minutes for 5,000 iterations on Window 10, Intel Core i5 3.50 GHz, 8 GB RAM, to solve the UE problem. The convergence characteristic of the proposed heuristic solution method is illustrated in Figure 5. It is shown that the convergence pattern fluctuates significantly, and MSA fails to converge. This is probably because the mapping function, i.e. Equation (4), is not strictly monotonic. Further studies should be carried out to investigate this important issue.

6.3 Sensitivity Analysis Of Intra-Group Interactions

Let $N_Z$ denote the number of groups with type Z. In other words, $N_Z$ is the number of pairs of students who may perform joint eating and/or café. The sensitivity analysis results are given in Table 3. The sensitivity analysis of parameter $N_Z$ shows that the travel demand for trip chains and activity allocations of students are not only dependent on the individual activity utility but also significantly dependent on intra-group interactions among students.

As can be observed from Table 3, the increase of $N_Z$ results in the increasing average duration of joint eating and café. In addition, class A always spend more time on eating and café than class B do. These results can be explained by the higher utilities of joint eating and café, and the smaller crowding discomfort sensitivity of class A. However, with the increasing $N_Z$, the duration of eating and café of class B increase, while class A spend less time on eating and café. Because when more students perform eating and café in pairs, a number of students with class A, who perform activities separately, cancel eating and/or café or shorten the activity durations for the crowding discomfort at the canteen.

<table>
<thead>
<tr>
<th>Table 3. Comparison of results by student classes of three scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student class</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Travel demand of trip chains</td>
</tr>
<tr>
<td>Home-Eating-Lecture-Home</td>
</tr>
<tr>
<td>Home-Lecture-Café-Home</td>
</tr>
<tr>
<td>Home-Eating-Lecture-Café-Home</td>
</tr>
<tr>
<td>Home-Lecture-Home</td>
</tr>
<tr>
<td>Average time allocation of activities (hours/student)</td>
</tr>
<tr>
<td>Home (at the student halls)</td>
</tr>
<tr>
<td>Lecture (at the classroom)</td>
</tr>
<tr>
<td>Eating (at the canteen)</td>
</tr>
<tr>
<td>Café (at the canteen)</td>
</tr>
<tr>
<td>Average travel time (hours)</td>
</tr>
<tr>
<td>Total time (hours/student)</td>
</tr>
</tbody>
</table>
6.4 Evaluation of Facility Management Policies Using The Proposed Model

In this section, with the use of the proposed model, facility management policies can be evaluated. We use the base casesetting, i.e. $N_Z = 125$. Suppose that the university propose two policies to evaluate the significance of the lift 1 and the canteen. In particular, Policy I is to close the lift 1, and Policy II is to expand the canteen capacity from 300 students per minute to 500 students per minute. Figures 6 and 7 depict the effects of Policy I and Policy II on population distributions at different activity locations. The detailed results of average activity time allocation with the effects of the two policies are listed in Table 4. Note that numbers regarding the benefit of the policies are bolded in the table.

As seen from Figure 6, the use of Policy I results in earlier departure times and later arrival times of students to and from the student halls. The durations of eating and café also increase. These results are because of the longer time for only lift 2 to carry all students when lift 1 is not operated. Students then tend to depart earlier and leave activity locations later to wait for the lift to be less congested. With Policy II, the result shows that more students went to the canteen for eating and café with longer activity durations compared with the distribution of the based case given in Figure 4. This is explained by the larger number of students going to the canteen for eating and café and longer eating and café durations (see Figure 7).

<table>
<thead>
<tr>
<th></th>
<th>Home</th>
<th>Lecture</th>
<th>Eating</th>
<th>Café</th>
<th>Travel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case (*)</td>
<td>4.57</td>
<td>2.76</td>
<td>0.58</td>
<td>0.64</td>
<td>0.45</td>
</tr>
<tr>
<td>Policy I (1)</td>
<td>4.00</td>
<td>2.48</td>
<td>0.96</td>
<td>1.06</td>
<td>0.50</td>
</tr>
<tr>
<td>Policy II (2)</td>
<td>4.34</td>
<td>2.89</td>
<td>0.66</td>
<td>0.66</td>
<td>0.45</td>
</tr>
<tr>
<td>Difference (1)- (*)</td>
<td>-0.57</td>
<td>-0.28</td>
<td>0.38</td>
<td>0.42</td>
<td>0.05</td>
</tr>
<tr>
<td>Difference (2)- (*)</td>
<td>-0.23</td>
<td>0.13</td>
<td>0.08</td>
<td>0.02</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Home</th>
<th>Lecture</th>
<th>Eating</th>
<th>Café</th>
<th>Travel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. The tempo-spatial student distribution with Policy I

Figure 7. The tempo-spatial student distribution with Policy II

6.5 Using Wi-Fi tracking data to generate JATPs in pedestrian networks

In this case study, experiments are setup up within the campus of The Hong Kong Polytechnic University (PolyU). MAC addresses are collected from the 6 Wi-Fi scanners located at
different activity locations (see Figure 2 above) on campus. The chosen locations of the installed Wi-Fi scanners are the main entrance of the campus for capturing students from the student halls, the student canteen, entrances and classrooms at Block Z building for Faculty of Construction and Environment (FCE). These selected places are major activity locations of FCE students of PolyU. Since this experimental study is in the context of a university campus, it is expected that major activities (e.g. studying and eating) are conducted inside of these selected locations. With that being said, the installed Wi-Fi scanners can detect the majority of students entering and leaving the buildings concerned. Activity episodes can therefore be extracted by matching the same MAC address’s entering and leaving records from the scanners within a feasible time window. Incomplete episodes with a single detection are then discarded. Although the Wi-Fi scanner cannot capture all the activities in the study area, the detected ones can still serve as samples to study the representative JATPs of university students.

The flowchart shown in Fig. 8 summaries the proposed method and process to generate the JATPs from Wi-Fi tracking data. There are mainly three steps as illustrated. Firstly, raw Wi-Fi data is being preprocessed through a set of filters aiming to eliminate outliers and leave pedestrians’ signatures only. Wi-Fi scanners are mainly installed at different entrance gates, these signatures are captured when pedestrians are traveling between activities. Therefore, in the second step, Density-based spatial clustering of applications with noise (DBSCAN) is applied to each MAC address’s records from different scanners for separating activities. This algorithm is adopted to aggregate Wi-Fi signatures belonging to the same walking trip together in a fast and unsupervised approach. Once different walking trips are separated from one another, activity episodes can be extracted from two consecutive walking trips. Lastly, a Hidden Markov Model (HMM) is applied to all the extracted activity episodes aiming to identify similar activities in terms of spatial and temporal characteristics of the samples. By labeling generated activity types from HMM back to individual temporally-ordered activity episodes of all detected pedestrians, the distribution of different activity patterns can then be determined.

![Flowchart of generating JATPs from Wi-Fi tracking data](image)

Wi-Fi tracking data collected on September 4th, 2018 (Tuesday) is used in this example for illustration. There are 1433 pedestrians (unique MAC address) being detected by the 6 Wi-Fi scanners on the survey day. The following sections show detailed procedures and generated results of each step.

**Step 1: Initial data processing**

The initial processing aims to filter out vehicular devices (e.g. car dashcam, etc.) and fixed
devices (e.g. printers, etc.) captured by Wi-Fi scanners. Their existences will disturb the analysis of pedestrian’s movement. Vehicular devices can be identified by their vendors while fixed devices by their frequencies of detection. Devices captured all the time are most likely to be fixed devices located near the detection region. After the elimination of these noises, the remained pedestrian signatures are ready for activity analysis.

**Step 2: Activity episodes generating**

DBSCAN is a density-based unsupervised clustering algorithm that is often used to deal with large-scale spatial data. Details about this algorithm can be found in Ester et al. (1996). In this example, it is used to separate Wi-Fi signatures from different trips for each pedestrian. Because the study area is a university campus with most of the transfers can be finished within 15 minutes, the maximum distance between two signatures in one cluster is set to be finished in 15 minutes. The minimum number of signatures required to form a cluster is set to be 1 for each trip need to be captured by at least 1 scanner. In this way, each resulted cluster represents one walking trip between two activities. Activity episode information can be extracted from two consecutive walking trips. To be specific, the earliest timestamp in one walking trip’s signatures is the end time of the first activity and the latest timestamp is the start time of the second activity. When a group of pedestrians conducts one joint activity, activity episodes that have a start time and end time with small differences at the same Wi-Fi scanner (activity location) will be generated by different group members. By identifying these activity episodes at each Wi-Fi scanner, JATPs can be generated.

Results of this step are summarized in the Fig. 9 shown below. The left figure shows the distribution of activity episodes from all detected pedestrians. It can be observed that most pedestrians have 1 to 3 activities captured by Wi-Fi scanners on this day, with 2 activity episodes happening the most. Moreover, 5 is the maximum number of episodes that have been captured. The figure on the right hand side of Fig. 9 illustrates the distribution of group members for all the captured pedestrian joint activities. As can be seen, most group activities consist of two group members. With the increase of group members, the number of such group decreases. In the detected dataset, the biggest group captured has 6 behaviorally heterogeneous pedestrians.

![Figure 9. Distribution of generated activity episodes and group activities](distribution of activity episodes on the left and distribution of group numbers on the right)
To illustrate a detailed process of joint activities, an example of the captured JATPs of two persons using this approach is shown in Fig. 10. For each captured pedestrian, Wi-Fi signatures generated by him/her from the same walking trip are clustered together. The seemingly parallel lines represent walking trips, and the vertical lines demonstrate the stop of the pedestrian for some activities. As can be seen, these two persons have three joint activities on the survey day, including activities of lunch, studying in classroom and having dinner together. Detailed tempo-spatial information can also be extracted as shown in the table on the upper right of Fig. 10.

**Step 3: Activity pattern generating**

With all the activity episodes being extracted, it is possible to identify similar activities types so that to analyze JATPs at an aggregate level. HMM is adopted here to label detected activities into groups with similar tempo-spatial characteristics. HMM is a time-state model that can discover the hidden states from observed data in an unsupervised approach. Details about the formulations and solution algorithms about this method can be found in Rabiner (1989). In this example, the start time, duration and location of all detected activity episodes from 1433 MAC addresses are observed inputs in the HMM. The generated hidden states are referred to as various types of activities.

In reality, detailed in-campus activity types can be tedious. To simplify the illustration and be consistent with the proposed model results, all the activity episodes detected by scanners are aggregated into two general categories: studying and eating. To further demonstrate the captured characteristics of these two activity types, Fig. 11 displays the joint distribution of start time and duration for studying activity and eating activity. As can be seen, studying activity happens on campus throughout the whole day with three major clusters. They are denoted as S1, S2, S3 for later analysis. As for eating activity, there are two distinct clusters, denoted as E1 and E2.
By labeling each individual’s temporally-ordered activity episodes with the above-generated activity types, the distribution of different activity patterns is shown in Table 5. It can be observed that 38 ATPs can be extracted from 1433 pedestrians’ Wi-Fi signatures used in this case study. On average, each pedestrian has 2.2 activities captured by Wi-Fi scanners on this day. Frequently observed patterns including two daytime studying activities(S1-S2), two daytime studying activities separated by one eating activity(S1-E1-S2), one morning studying activity(S1), and one afternoon studying activity(S2). There are 15.91%, 15.84%, 12.42%, and 11.24% of captured pedestrians have the above activity patterns respectively. This indicates that many pedestrians did not eat at university canteen when they were at school. In contrast, there are some unique activity patterns that come from less than 10 pedestrians. The uniqueness may be caused by abnormal activity time choice, a long list of activity episodes or unusual combinations of activity episodes.

Table 5. Distribution of activity patterns from detected pedestrians

<table>
<thead>
<tr>
<th>No.</th>
<th>ATP*</th>
<th>Counts</th>
<th>Percentage</th>
<th>No.</th>
<th>ATP*</th>
<th>Counts</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1-S2</td>
<td>228</td>
<td>15.91%</td>
<td>20</td>
<td>E1-S2-E2-S3</td>
<td>11</td>
<td>0.77%</td>
</tr>
<tr>
<td>2</td>
<td>S1-E1-S2</td>
<td>227</td>
<td>15.84%</td>
<td>21</td>
<td>S1-E2</td>
<td>10</td>
<td>0.70%</td>
</tr>
<tr>
<td>3</td>
<td>S1</td>
<td>178</td>
<td>12.42%</td>
<td>22</td>
<td>S1-E1-S1</td>
<td>10</td>
<td>0.70%</td>
</tr>
<tr>
<td>4</td>
<td>S2</td>
<td>161</td>
<td>11.24%</td>
<td>23</td>
<td>E1</td>
<td>9</td>
<td>0.63%</td>
</tr>
<tr>
<td>5</td>
<td>E1-S2</td>
<td>96</td>
<td>6.70%</td>
<td>24</td>
<td>S1-E2-S3</td>
<td>9</td>
<td>0.63%</td>
</tr>
<tr>
<td>6</td>
<td>S1-E1</td>
<td>80</td>
<td>5.58%</td>
<td>25</td>
<td>S2-E2-S2</td>
<td>4</td>
<td>0.28%</td>
</tr>
<tr>
<td>7</td>
<td>S1-E1-S2-E2</td>
<td>74</td>
<td>5.16%</td>
<td>26</td>
<td>S1-E1-S1-S2</td>
<td>4</td>
<td>0.28%</td>
</tr>
<tr>
<td>8</td>
<td>S2-E2</td>
<td>63</td>
<td>4.40%</td>
<td>27</td>
<td>S1-E1-S2-E2-S2</td>
<td>4</td>
<td>0.28%</td>
</tr>
<tr>
<td>9</td>
<td>S1-S2-E2</td>
<td>46</td>
<td>3.21%</td>
<td>28</td>
<td>E1-S1-S2</td>
<td>3</td>
<td>0.21%</td>
</tr>
<tr>
<td>10</td>
<td>S1-E1-S2-E2-S3</td>
<td>32</td>
<td>2.23%</td>
<td>29</td>
<td>E1-S2-S3</td>
<td>3</td>
<td>0.21%</td>
</tr>
<tr>
<td>11</td>
<td>S3</td>
<td>29</td>
<td>2.02%</td>
<td>30</td>
<td>S1-S2-E2-S2</td>
<td>3</td>
<td>0.21%</td>
</tr>
<tr>
<td>12</td>
<td>E2-S3</td>
<td>26</td>
<td>1.81%</td>
<td>31</td>
<td>E2-S2</td>
<td>2</td>
<td>0.14%</td>
</tr>
<tr>
<td>13</td>
<td>S2-S3</td>
<td>18</td>
<td>1.26%</td>
<td>32</td>
<td>S1-S3</td>
<td>2</td>
<td>0.14%</td>
</tr>
<tr>
<td>14</td>
<td>E1-S2-E2</td>
<td>17</td>
<td>1.19%</td>
<td>33</td>
<td>S2-E1-S2</td>
<td>2</td>
<td>0.14%</td>
</tr>
<tr>
<td>15</td>
<td>E2</td>
<td>16</td>
<td>1.12%</td>
<td>34</td>
<td>S1-E2-S2</td>
<td>2</td>
<td>0.14%</td>
</tr>
<tr>
<td>16</td>
<td>S2-E2-S3</td>
<td>16</td>
<td>1.12%</td>
<td>35</td>
<td>S1-E1-S1-E2</td>
<td>2</td>
<td>0.14%</td>
</tr>
<tr>
<td>17</td>
<td>S1-E1-S2-S3</td>
<td>16</td>
<td>1.12%</td>
<td>36</td>
<td>E1-S1</td>
<td>1</td>
<td>0.07%</td>
</tr>
<tr>
<td>18</td>
<td>S1-S2-S3</td>
<td>14</td>
<td>0.98%</td>
<td>37</td>
<td>E1-S2-E2-S2</td>
<td>1</td>
<td>0.07%</td>
</tr>
</tbody>
</table>

Figure 11. Joint distribution plot of duration and start time per activity type (studying activity on the left and eating activity on the right)
**7. CONCLUSIONS**

This paper has proposed an extended user equilibrium model for scheduling the JATP (Joint activity travel patterns) of pedestrians for facility planning and management purposes. The multilayer structure of pedestrian networks and joint activities of pedestrians were captured with the proposed PJATS supernetwork temporally and spatially, in which the intra-group interactions, i.e. joint activities between behaviorally heterogeneous pedestrians in the same group, are considered. A heuristic solution based on CBS (Conflict-Based Search) and MSA (Method of Successive Averages) has been proposed to solve the JATP scheduling problem.

A simplified pedestrian network in the study area within the university campus of PolyU was used to show the application of the proposed model. Results from the numerical example showed that the proposed model could reasonably reproduce the JATPs of students under different scenarios. It was also demonstrated that the Wi-Fi data collected in the study area of the PolyU campus could be used to generate the JATPs from matching the MAC address of detected pedestrians. It is worth mentioning that the given experimental study by Wi-Fi tracking did benefit from the reliable campus wireless network and the high penetration of Wi-Fi enabled devices among university students. When employing this approach in another context under different environment, the performance of the proposed approach may be affected by the valid samples based on the matched Wi-Fi data only. As we are stepping into the 5G era, it can be seen that multiple types of sensors and fully connected infrastructures are available in the near future. Therefore, future studies are worthwhile to extend the proposed model with use of multiple sources of urban big data for smart city development.

**ACKNOWLEDGMENTS**

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