The 21st Behavior Modeling in Transportation Networks
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A structured programming method for matching heterogeneous demand in mixed freight and passenger network

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Introduction

Mixed Passenger-and-Freight Delivery

- Matching heterogeneous demands of passengers and freight can be efficient by sharing temporally vacant slots

Michinoeki (Roadside Station) @Tsukechi town in Nakatsugawa city

Requirements for Demand Transportation

① Trade-off relationship between fairness and efficiency
② Heterogeneity in trip-patterns and usage time
③ Sudden cancels/requests in the middle of the routes

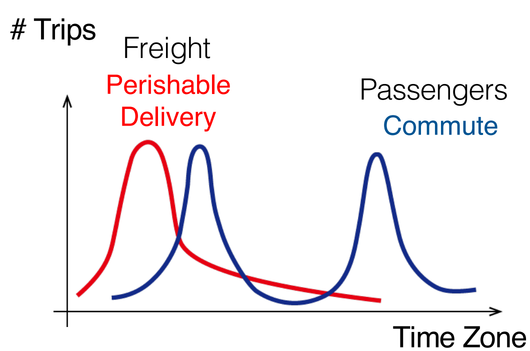
① Policy trade-off

Maximizing #users

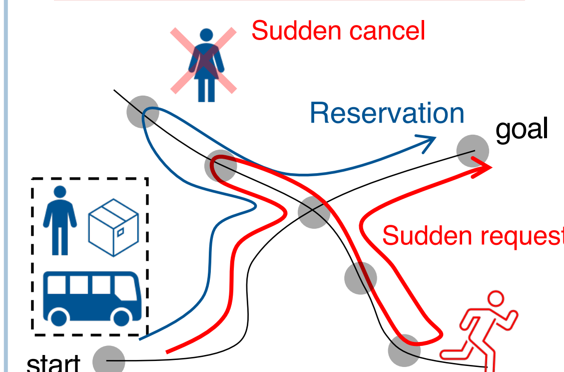
Trade-off

Minimizing travel cost

② Heterogeneity



③ Robustness

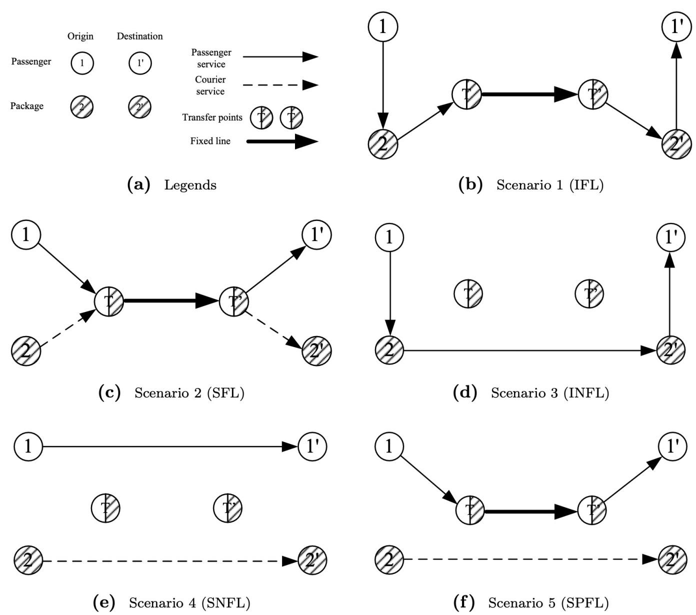


Previous Research

Research on Mixed Passenger-and-Freight Delivery

SARP
Li et al.(2014)
Share-a-Ride Problem

- First assigns passengers to vehicles, and then utilizes the vacant slots for freight



PDP-FSL
Ghilas et al.(2013)
Pick-up and Delivery Problem with Fixed Scheduled Lines

- Represents mixed passenger-and-freight situation by NW setting

▶ Heterogeneity in space-time prism constraints was not fully considered

▶ Interaction between different demands was not analyzed

Previous Research

Dynamic Dial-a-ride problem (DARP)

Jaw et al.(1986) … Sequential insertion method: benchmark

- Online-algorithm for assignment of riders to drivers
- Minimize the difference from pre-determined matching

▶ Algorithm is not supposed to be real-time

Tsubouchi et al.(2009)

- Improve Jaw et al.(1986) to make the algorithm real-time
- Completely separating riders' assignment and scheduling for computation ease

▶ Assignment and scheduling are myopic

▶ Changing the pre-determined routes is not allowed: not flexible

Requirements for algorithm

Based on the previous studies, our motivation for developing scheduling algorithm for mixed passenger-and-freight vehicle is:

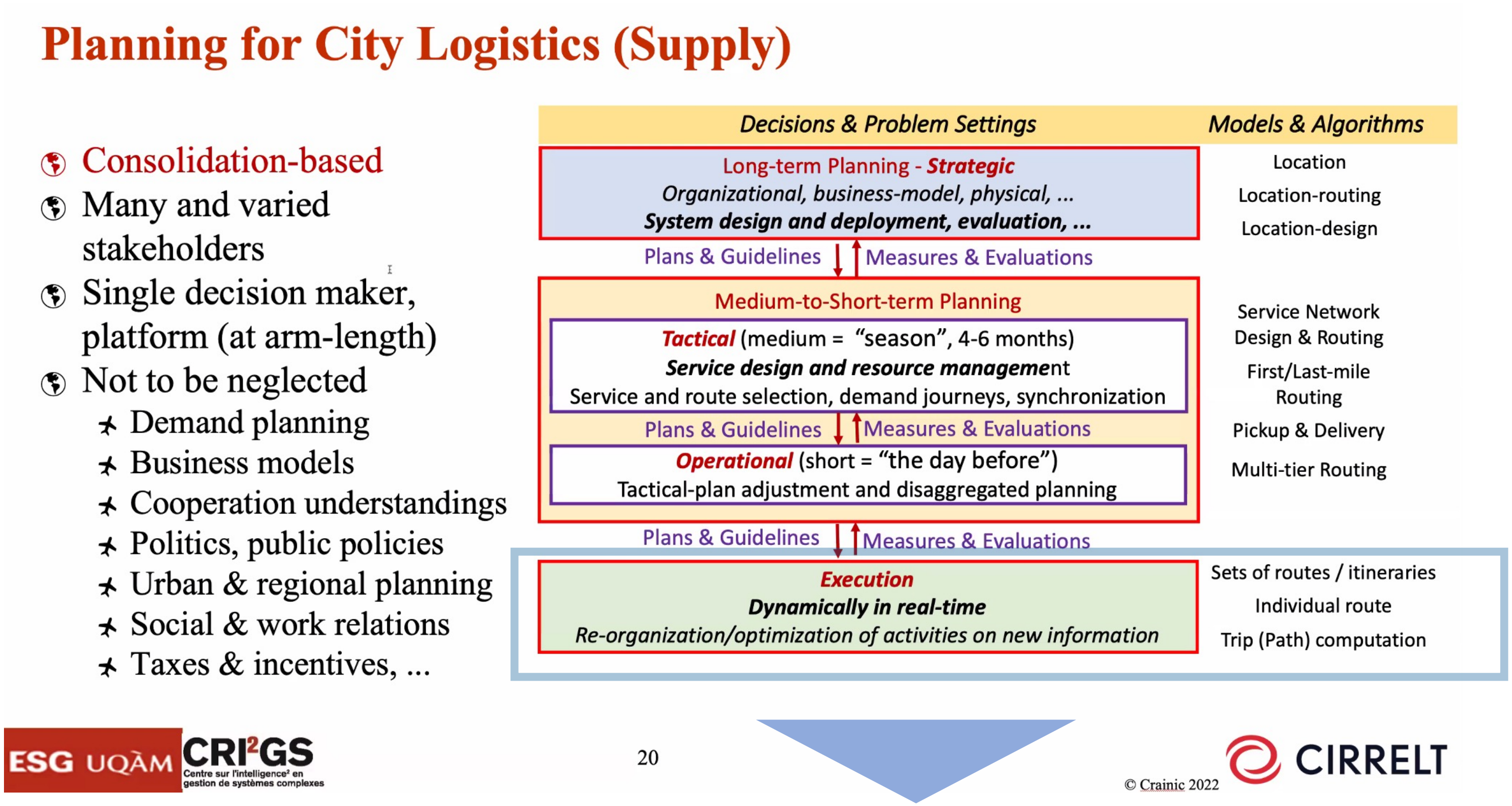
1. Achieving real-time performance for recalculation of scheduling vehicles
2. Incorporating the method to handle and analyze the heterogeneity in individual requests and interaction among them

Our approach

1. Indexing method for flexibly recalculating feasible routes
2. Enumeration method explicitly handle individual demand

Mapping of the research

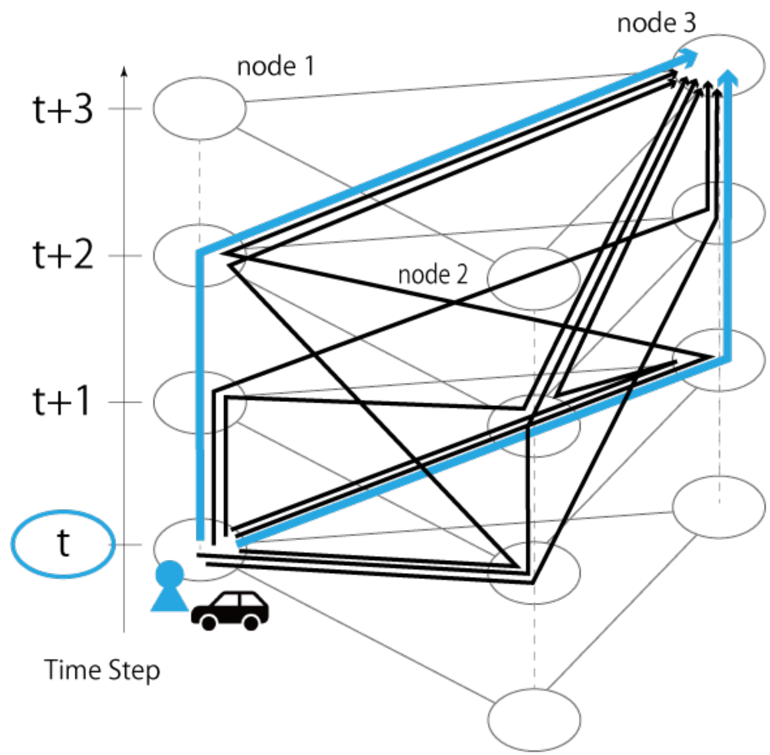
Recall back the lecture from Prof. Teodor yesterday…



today's presentation corresponds to *Execution* part of city logistics

Framework

Motivating example



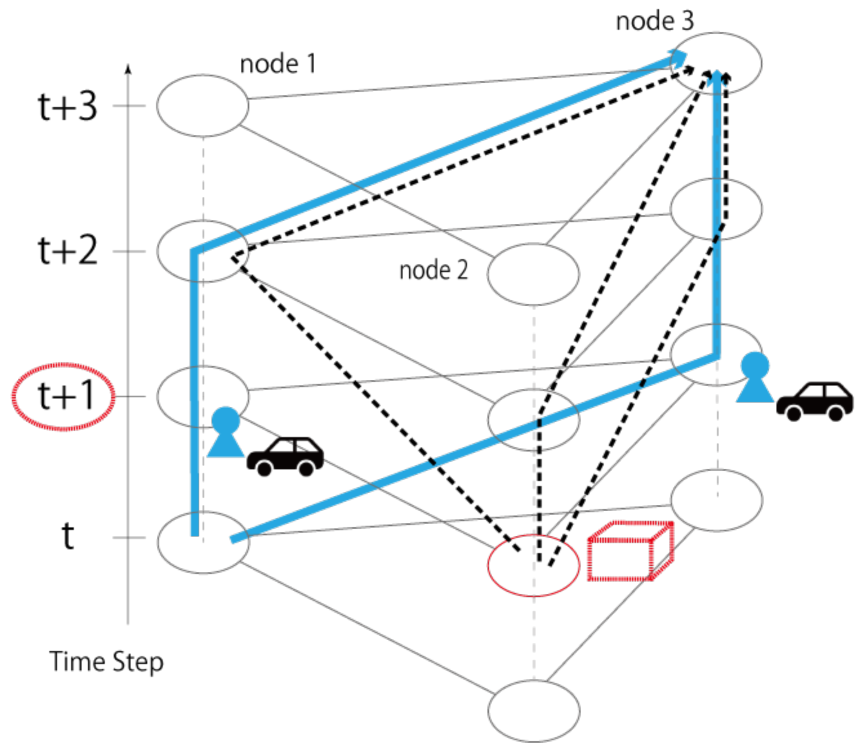
→ Feasible routes of passenger

At period t, requests the driver to arrive at Node 3 within 3 steps from Node 1

- Blue lines are the routes with minimum total travel distance
- is to be at Node 1 or Node 3 at next time step

Framework

Motivating example



- - - - - - -▶ Feasible routes of freight

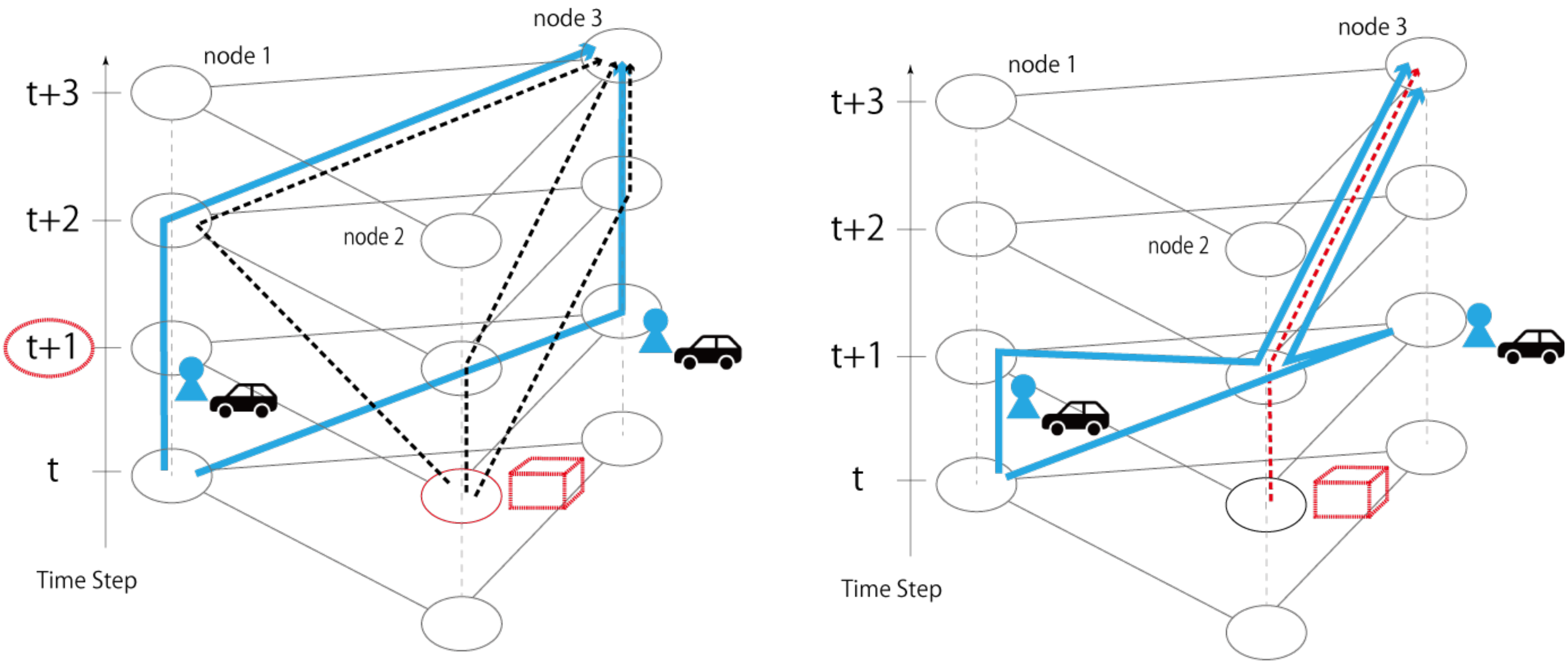
Suppose that

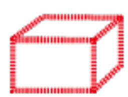
At period $t+1$,  requests to arrive at Node 3 within 2 steps from Node 2

▶ The operator must recalculate the routes to pick-up the freight request

Framework

Motivating example



To satisfy the request of , the operator must recalculate within one time step

▶ Real-time processing of en-route requests is needed for efficient operation

Framework

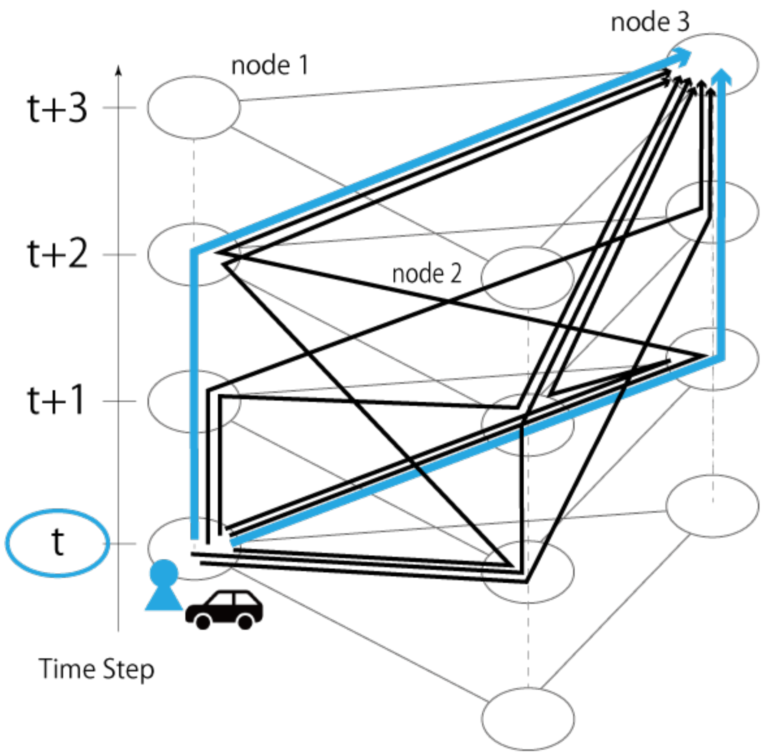
Sequential Enumeration and Indexing Method

Our idea

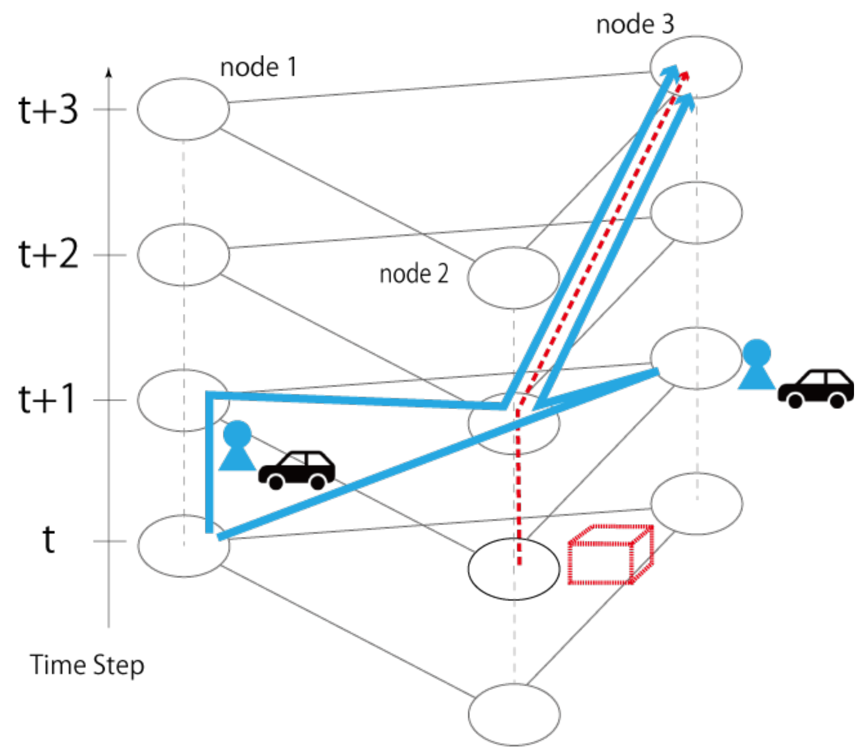
- Preserving the pre-determined feasible paths as indexes which was not selected
- **Utilizing the indexes to select alternative routes** to satisfy new requests

>>> faster than newly calculating the feasible routes from nothing

Enumeration and indexing



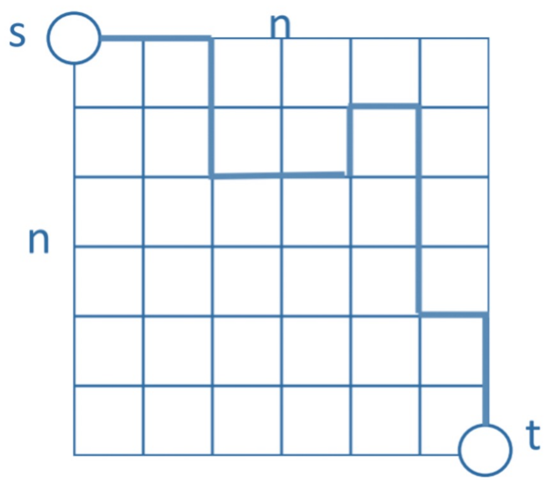
Extraction



Intractability of routes enumeration

The number of feasible routes increases rapidly as the number of selective choices increases : **combinatorial explosion**

Example in the grid network



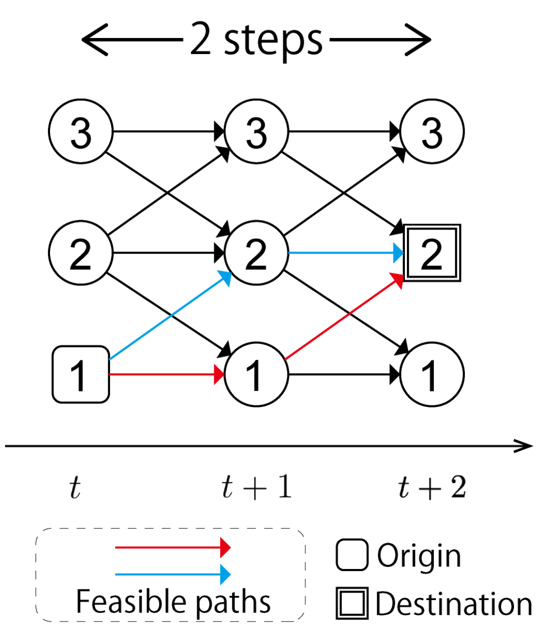
n	# feasible routes
1	2
2	12
3	184
4	8,512
5	1,262,816
6	575,780,564
7	789,360,053,252
8	3,266,598,486,981,642
9	41,044,208,702,632,496,804
10	1,568,758,030,464,750,013,214,100
11	182,413,291,514,248,049,241,470,885,236

Sequential Enumeration and Indexing

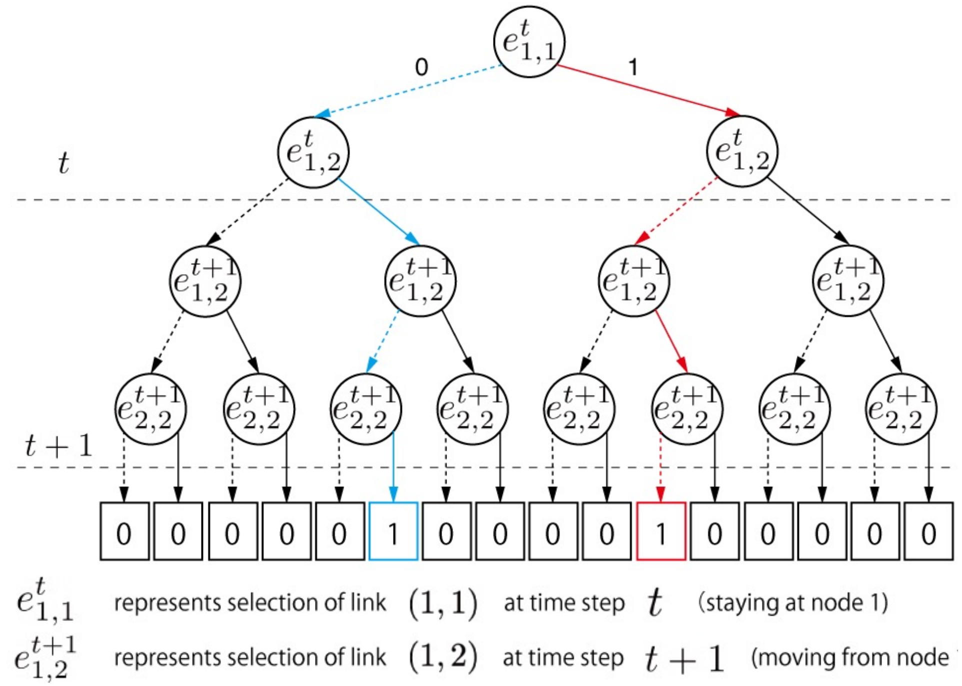
ZDD: a fast enumeration and indexing method

- Zero-suppressed binary Decision Diagrams
- Exact solution to the shortest path problem
- Explicitly representing the space-time prism constraints of individual demand

[Example] Some agent at Node 1 needs to arrive at Node 2 within two time-steps



(a) Feasible Routes



(b) The binary decision tree representation

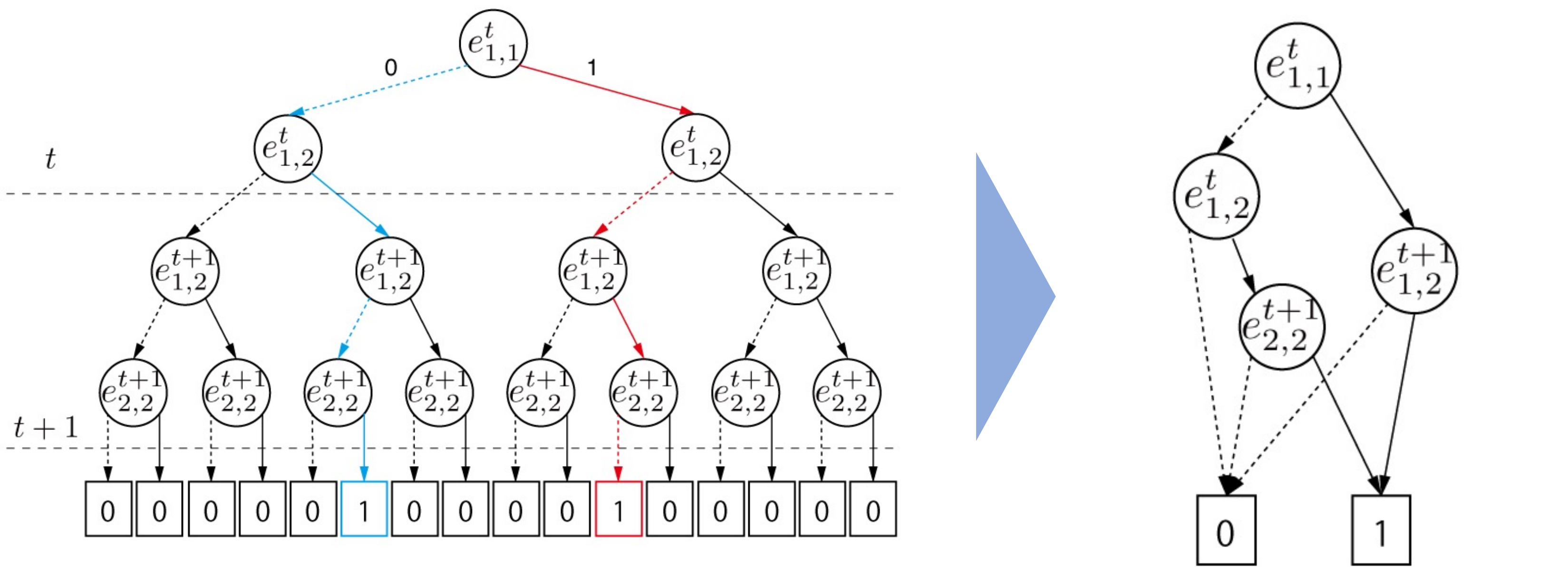
Concise route representation by ZDD

With two contraction rules for nodes irrelevant to the combination set :

① Elimination of redundant nodes

② Sharing equivalent nodes

ZDD enumerates and indexes the feasible routes concisely



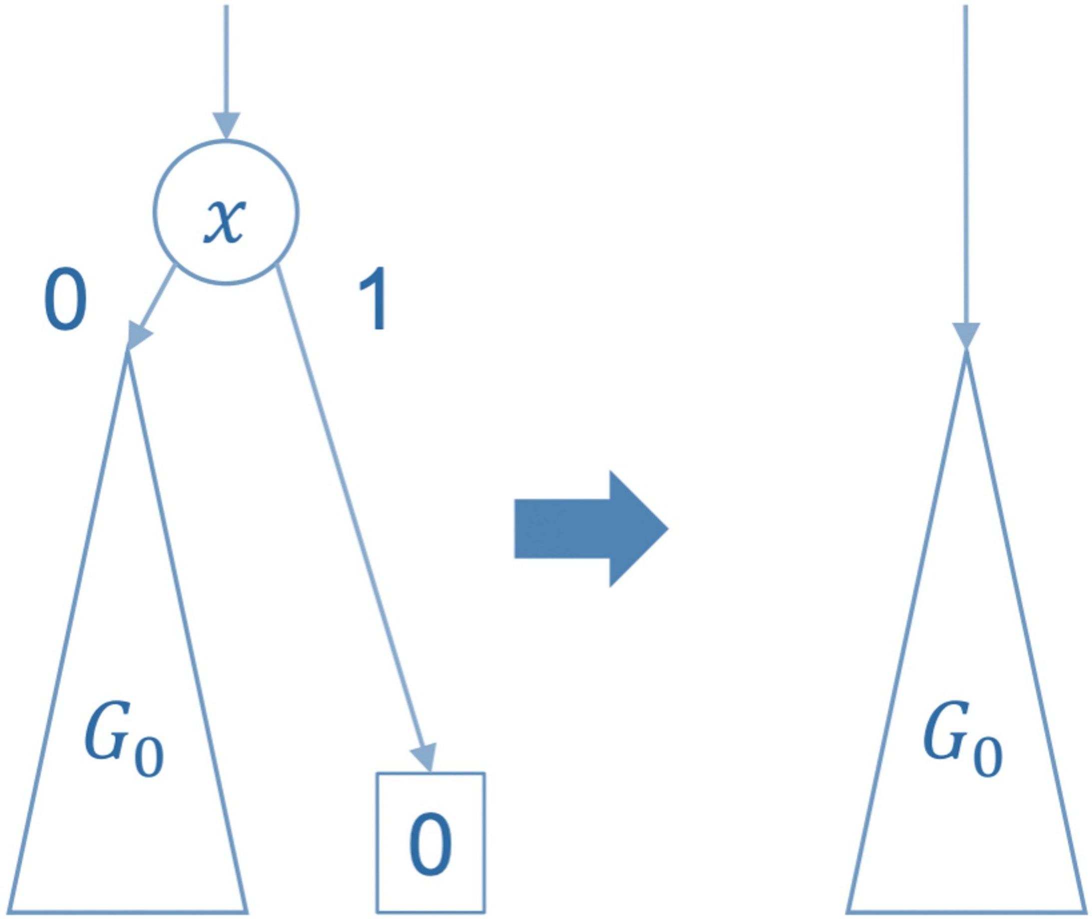
(b) The binary decision tree representation (c) ZDD representation

Outstanding effect on sparse combination sets

Contraction Rule: Elimination

① Elimination of redundant nodes

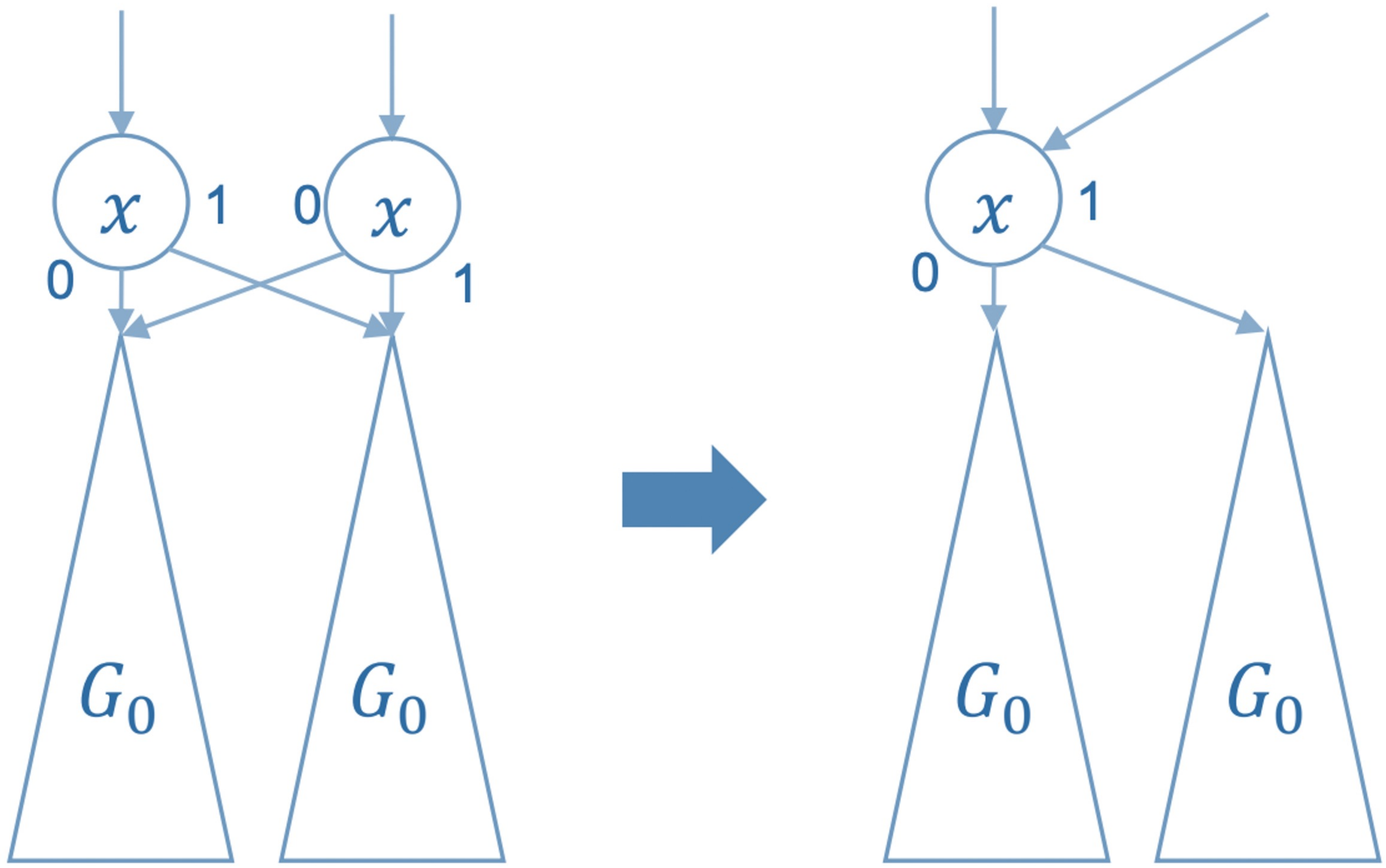
: deleting and skipping the node
when the destination of the 1-branch is 0-leaf



Contraction Rule: Sharing

② Sharing equivalent nodes

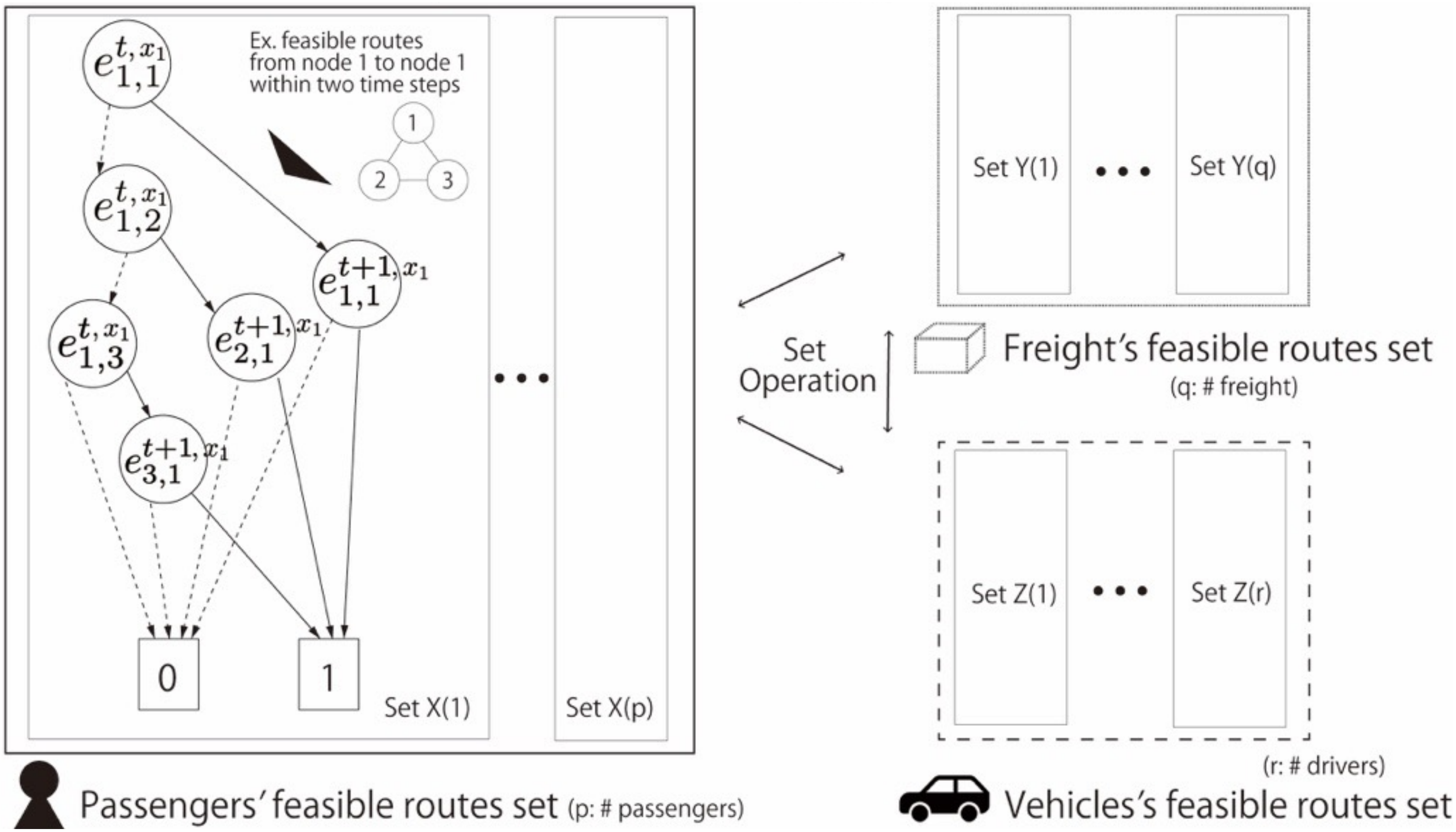
: share the nodes whose names are the same and
the destination of 1-branch and 0-branch is the same



Set operation among ZDDs

Matching multiple requests with set operation

- **ZDDs are capable of set operation among them**
- Enumerate individual feasible routes, and then join them sequentially



Matching criteria matter for improving
success rate of matching or mitigating calculation cost

Set operation among ZDDs

Matching multiple requests with set operation

- **ZDDs are capable of set operation among them**

- We can get the combination of decision variables whether the link in time-extended network is selected concisely by ZDD

$$\{e_{i,j,t}\} \in \{0,1\}^T$$

i, j: Nodes t: time-step T: Whole period

- If we think of matching multiple requests, combination of decision variables has an additional index representing the agent

$$\{e^{n}_{i,j,t}\}$$

n: agent index

▶ Product set of $\{e^{a}_{i,j,t}\} \sqcup \{e^{b}_{i,j,t}\}$ gives feasible routes satisfying multiple requests

- Calculation cost of joining operation among multiple ZDDs are based on the number of nodes in each ZDD, not on the # feasible routes

▶ **ZDDs are thought to be effective for matching problem**

Matching based on marginal contribution

Marginal Contribution

- Marginal contribution in cooperative games quantify the influence of a participator to the coalition (set of agents)
- The assignment maximizing the marginal contributions of all agents is called Shapley assignment, and the problem finding such assignment is called coalition structure generation (CSG) problem.

Coalition S: Combination of passengers and freight
Coalition Value $v(S)$: Score of coalition (characteristic function)
TTD_S : Total travel distance achieved by Coalition S

▶ $$v(S) = \frac{|S|}{TTD_S}$$

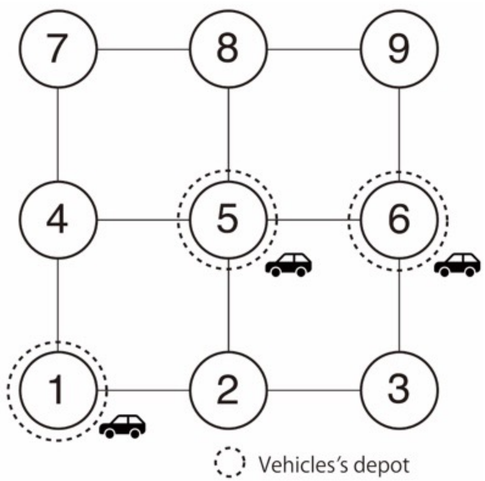
Marginal contribution … Difference between the score with/without i

$$v(S \cup \{i\}) - v(S) = \frac{|S \cup \{i\}|}{TTD_{S\cup\{i\}}} - \frac{|S|}{TTD_S}$$

$\{i\}$ denotes a new participator to the coalition S

Setting for matching simulation

Target Network and Policy of Mixed Passenger-and-Freight



* each link takes 1 time-step

- Passenger or freight requests at each node on NW
- at an arbitrary discretized time-step from $t = 0$ to $t = 9$
- toward three vehicles with initial position at Node 1,5,6

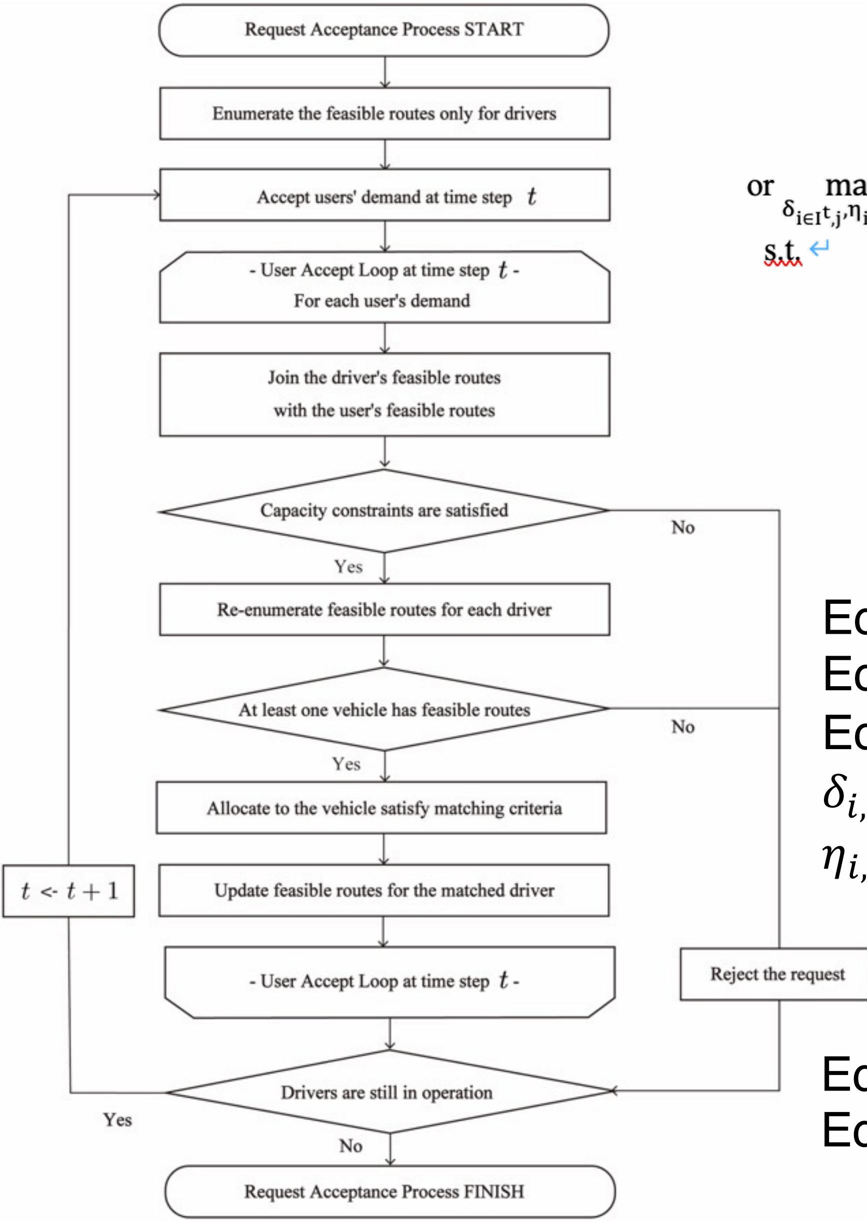
- Operator matches the requests sequentially and calculate the optimum routes of all agents in two policies
  ① TD-model
  Matching with minimizing total travel distance
  ② MC-model
  Matching with maximizing marginal contribution

Heterogeneity in passenger and freight

- Passengers and freight are distinguished by their tolerance to the additional travel time due to accepting the succeeding requests.
  <= We define the tolerance to detouring as a **detour ratio**
- Detour ratio is set to be zero for passenger, and positive for freight

※ The system would like the preceding users to change their routes with equal travel distance or detour to some extent for succeeding requests

Flowchart of matching algorithm



$$\min_{\delta_{i\in I^t,j},\,\eta_{i\in I^t,e,t}} TD^t = \sum_{i\in I^t,j\in J} \delta_{i,j}\left(\sum_{e\in E} \eta_{i,e,t}\tau_e\right), \quad (2)$$

$$\text{or} \max_{\delta_{i\in I^t,j},\,\eta_{i\in I^t,e,t}} MC^t = \frac{\left\{\sum_{i\in I^t,j\in J}\delta_{i,j}\left(\sum_{e\in E}\eta_{i\in I^t,e,t}\tau_e\right)\right\}}{|I^t|+|I^{<t}|} - \frac{\left\{\sum_{i\in I^{<t},j\in J}\delta_{i,j}\left(\sum_{e\in E}\eta_{i\in I^{<t},e,t}\tau_e\right)\right\}}{|I^{<t}|}, \quad (3)$$

s.t.

$$\delta_{i\in I^t,j} \in (0,1),\ \eta_{i\in I^t,e,t} \in (0,1), \quad (4)$$

$$\sum_{i\in I^t,j\in J} \delta_{i,j}\,\eta_{i,e,t} \le L_j, \quad (5)$$

$$\sum_{e\in O(n)} \eta_{i,e,t} - \sum_{e\in I(n)} \eta_{i,e,t-\tau_e} = \begin{cases} \delta_{i\in I^t,j} \\ -\delta_{i\in I^t,j} \\ 0\ otherwise \end{cases}, \quad (6)$$

Eq.(2) … Objective function of TD-model
Eq.(3) … Objective function of MC-model
Eq.(4) … Decision variables
$\delta_{i,j}$: whether vehicle j accepts user i's request
$\eta_{i,e,t}$: whether user i flows into link e at time t

Eq.(5) … Capacity constraint of each vehicle
Eq.(6) … Flow conservation rule

Simulation Results

Comparison of matching success rate in MC-model/TD-model

- The result below is the average of 30 random OD sets in the cases where the detour ratio is 0.1 and 0.2 for five proportion patterns of passenger to freight

Table 1. The difference in the number of matched users for MC-model and TD-model for each proportion pattern of passenger and freight demand out of seven demands ($t = 0,1,2,3,4,5,6$)

	Passenger Dep Time	Proportion (Passenger : Freight)	Ave. Offset
		0:7	0.125
mixed	$t = 1$	1:6	0.075
mixed	$t = 0,1,6$	3:4	0.163
mixed	$t = 0,1,3,5,6$	5:2	0.013
	$t = 0,1,2,3,4,5,6$	7:0	-0.063

(“MC-model” – “TD-model”)

▶ More users were accepted in the MC-model in all patterns where passengers and freight is mixed

△ This is because overlapping of users’ routes are favored in matching with MC-model based on the coalition value

Simulation Results

Comparison of matching success rate in MC-model/TD-model

- The result below is the average of 30 random OD sets in the cases where proportion pattern is 3 passengers and 4 freight

Table 2. Average of matching calculation time, the number of matched users' requests and offset from TD-model of MC-model and coalition value at the final state

Detour ratio	Category	Ave. Cal Time [sec]	# Ave. Matched Users	Ave. Offset	Ave. Coalition Value
0 %	P	3.164	2.233	0.300	0.1898
	F	6.286	2.867		
10 %	P	3.075	2.200	0.267	0.1922
	F	6.007	2.933		
20 %	P	2.969	2.200	0.133	0.1898
	F	1.875	2.233		
30 %	P	3.132	2.167	0.133	0.1902
	F	5.930	2.367		

("MC-model" – "TD-model")

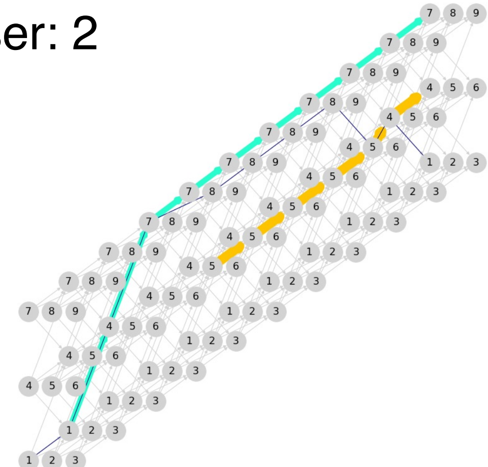
Contrary to expectations, however, Ave. Offset did not get bigger as the detour ratio increased.

This result did not conclude that the detour ratio was not so useful, for the average coalition value did not decrease according to the detour ratio.

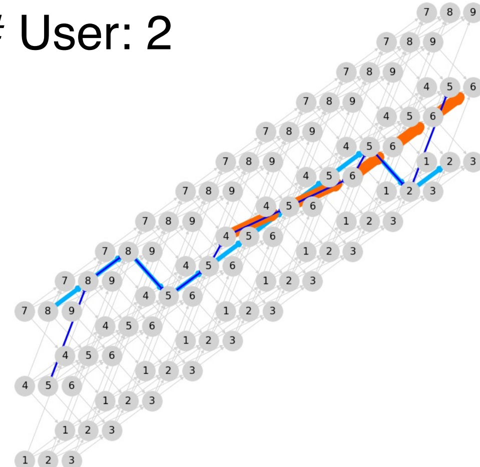
Example of matching result

Matching with TD-model … Total travel distance: 30

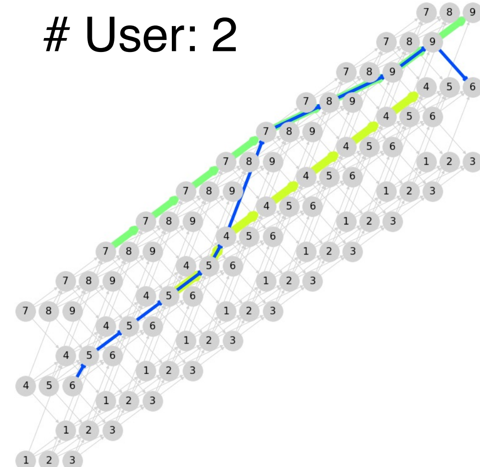
User: 2



User: 2

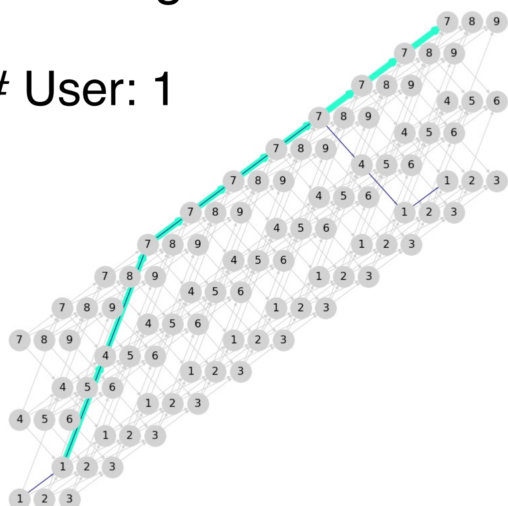


User: 2

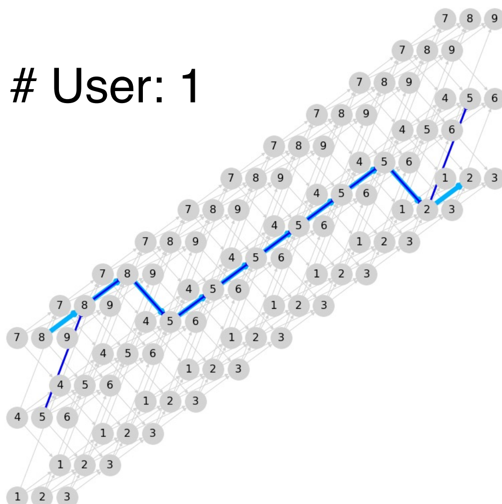


Matching with MC-model … Total travel distance: 26

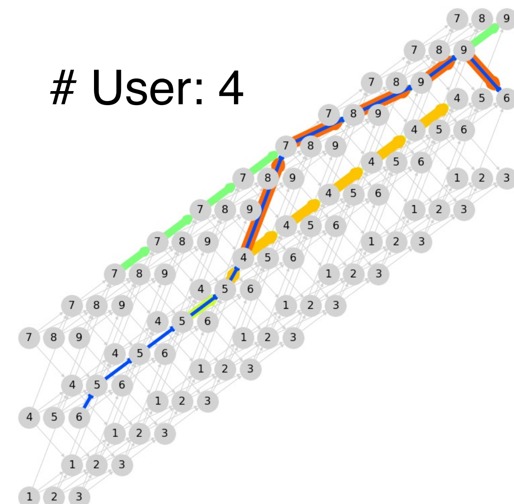
User: 1



User: 1



User: 4



Summary

1. A sequential enumeration and indexing algorithm was constructed using ZDD, satisfying individual heterogeneous space-time prism constraints of passengers and freight.

2. ZDD recalculation of alternative routes was executed within seconds in the case of 3*3 grid network with ten time-steps.

3. Marginal contribution was employed as an assignment (matching) criterion, mitigating the system load and thus achieving robustness to the uncertain future requests.

Future works

a) Construct surrogate model or multi-scale model for large-scale computation in actual network.
b) (Demand side) Suppose some behavioral assumptions for requests to be generated using behavior data.
c) (Supply side) Suppose that the availability of the logistics facility or goods changes based on the behavior history
d) Incentive design for detouring

Thank you for listening ☺

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