Hybrid Heterogeneous Electric Vehicle Routing Problem with Time Windows and recharging stations

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Outline

- Motivation
- Hybrid Heterogeneous E-VRP with Time Windows
- Methodology
- Heuristic solver
- Experiments on preliminary benchmark instances

Motivation – Battery Electric Vehicles (BEV)

- Eco-friendly(ier) way to travel
- Technological advances
  - extended range
  - more cost-efficient
- However
  - initial cost are still high
  - limited battery lifetime/cycle
  - range limited
  - time-consuming recharging operation
  - => efficient routing required (E-VRPTW, see Schneider et al., 2014)

http://cleantechnica.com/2014/06/10/sales-nissan-e-nv200-electric-van-begin-october/

http://en.wikipedia.org/wiki/Tesla_Roadster

http://www.citi.io/2015/04/22/cooler-cities-with-electric-vehicles/

- Alternative: Hybrid Electric Vehicles
  - combination of an internal combustion and a pure-electric engine

Introduction – (Hybrid) Electric Vehicles

- (Full) Hybrid Electric Vehicle
  - energy generated by breaking maneuvers (recuperation)
  - used for stop&go (e.g. at traffic lights/signs) / small distances

- Plug-in Hybrid Electric Vehicles (PHEV)
  - two engines: internal combustion engine (ICE) and pure electric engine
  - separately rechargeable battery (recharging station)
  - on-the-fly switch between engines

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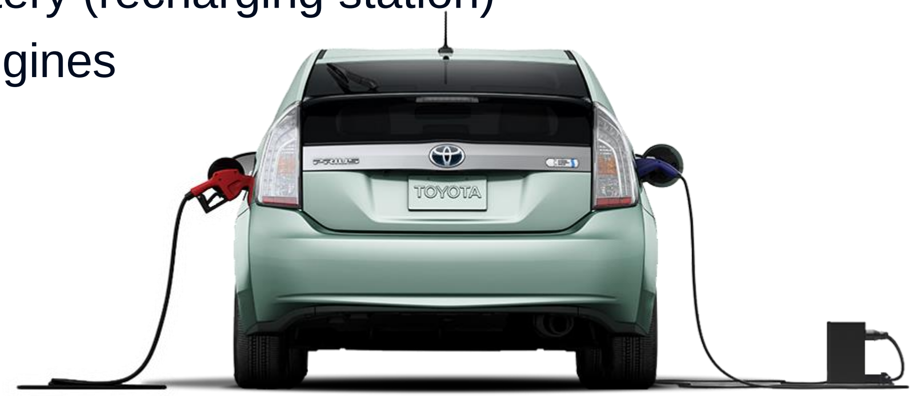


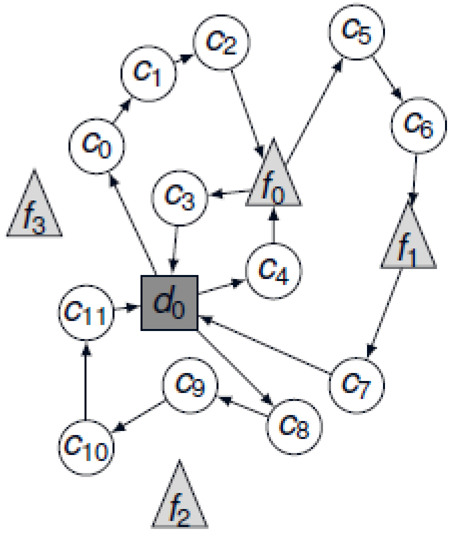
http://www.toyota.com/prius-plug-in-hybrid/

Hybrid Heterogeneous Electric Vehicle Routing Problem with Time Windows and recharging stations

- 3 vehicle classes
  - Internal Combustion Engine Vehicles (ICEV)
  - Battery Electric Vehicles (BEV)
  - Plug-in Hybrid Electric Vehicles (PHEV)

- 2 engine types
  - internal combustion engine
  - pure-electric engine

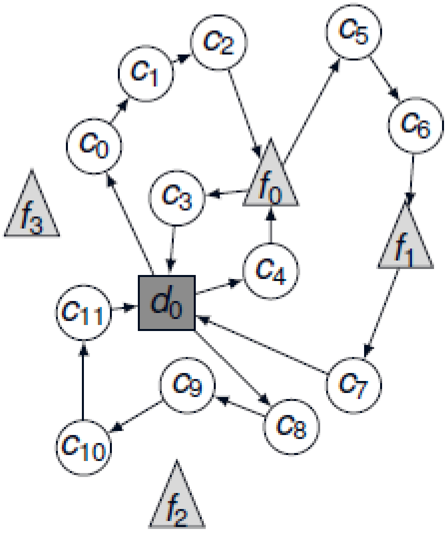
- Sub-types differing in
  - transport capacity
  - acquisition/utility cost
  - battery capacity
  - energy/fuel consumption rate



Fossil Fuel		Energy
ICEV	PHEV	BEV

Hybrid Heterogeneous Electric Vehicle Routing Problem with Time Windows and recharging stations

- E-VRP with
  - single depot (d)
  - customers (C)
    - demand
    - service time windows
  - recharging stations (F)
    - with partial recharging
  - different cost for using energy or fossil fuel

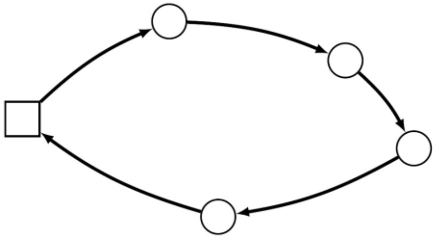


- Assumptions:
  - linear recharging and consumption rate
  - unlimited number of vehicles per type available (fleet size and mix-variant)

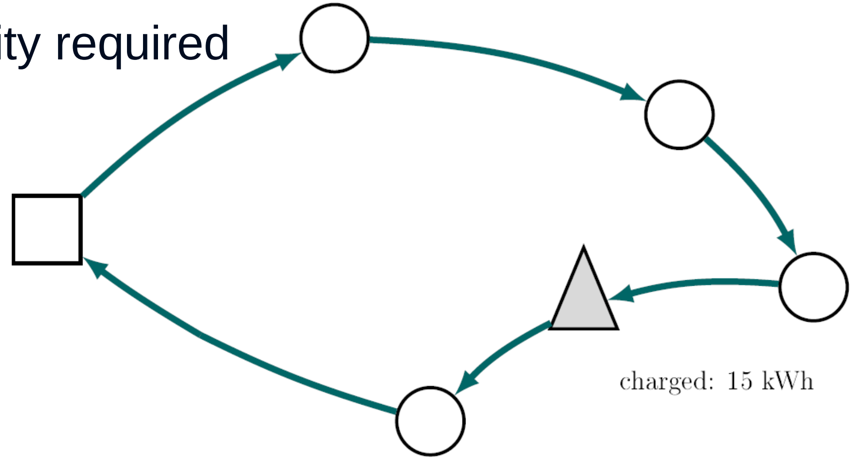
Fossil Fuel		Energy
ICEV	PHEV	BEV

Routing Problems

- Internal Combustion Engine Vehicles => VRPTW
  - well researched topic

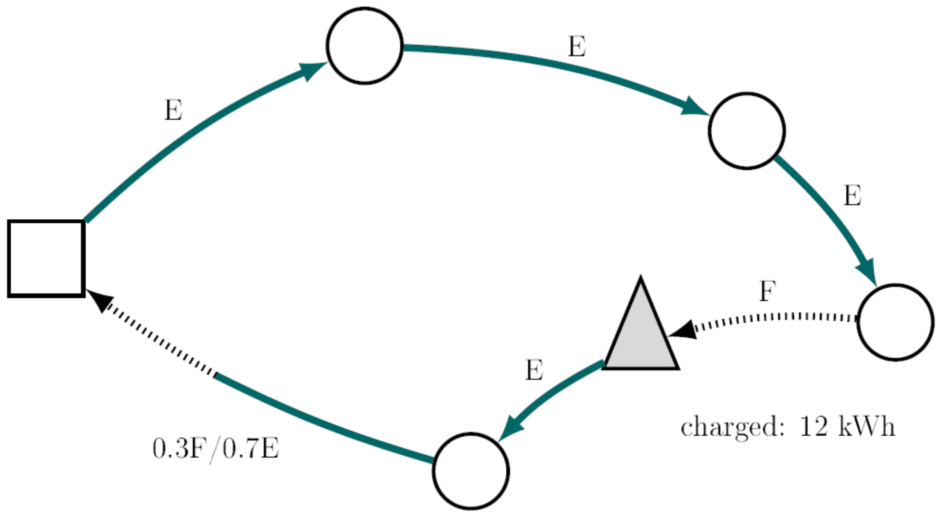


- Battery Electric Vehicles => E-VRPTW(PR)
  - visits to additional nodes (recharging stations) for recharging
  - partial recharging (PR)
    - no recharge to maximum capacity required
    - additional decision on the amount recharged per visit



Routing Problems

- Plug-in Hybrid Electric Vehicles
  - visits to additional nodes (recharging stations) for recharging
  - partial recharging assumed as well
  - decision when to use
    - pure electric engine
    - ICE
  - Assumption
    - use of energy is always better



How to optimize the combined problem?

- Alternatives
  - solve each problem separately – combine them afterwards

    \+ straight forward to implement

    \- no combined local improvement

  - combined with problem specific operators

    \+ likely to result in better solutions (no abstraction)

    \- high dependency / no extendibility (very specific)

How to optimize the combined problem?

- Our approach
  - use a layered, unifying view on the problems
    - find a common representation (top layer)
    - use optimization methods to solve specific aspects (to optimality) during evaluation (problem layers)

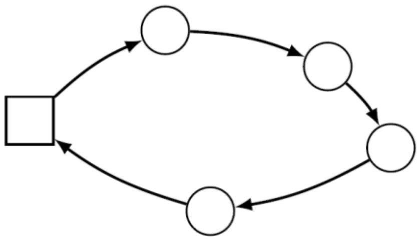
+ smaller solution space

+ modular design with replaceable parts

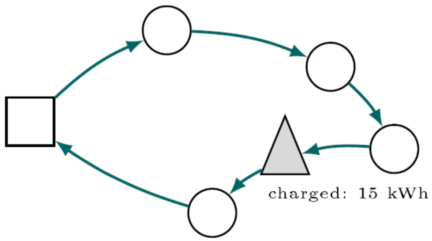
- runtime depend heavily on the specific sub-problem solver

Methodology – Decision Layers

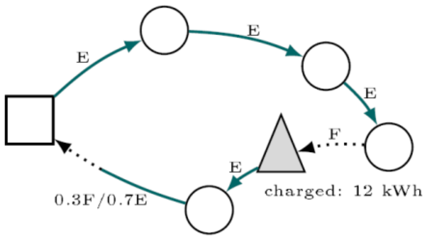
ICEV



BEV



PHEV

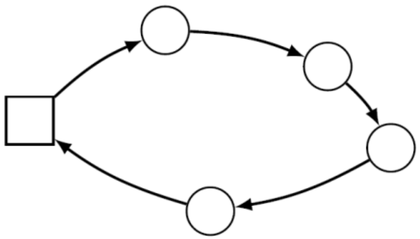


ICEV	BEV	PHEV
itinerary	itinerary	itinerary
	RS visits	RS visits
	charge in RS	charge in RS
		mode selection

(RS .. recharging station)

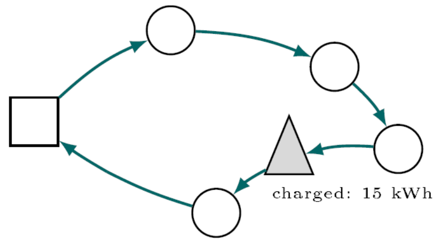
Methodology – Decision Layers

ICEV



itinerary

BEV

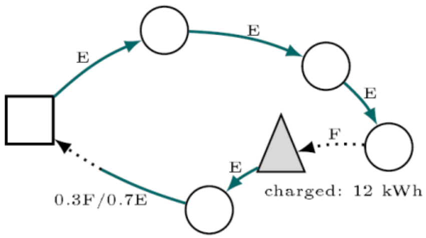


itinerary

RS visits

charge in RS

PHEV



itinerary

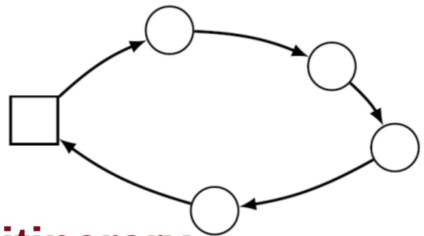
RS visits

charge in RS

mode selection

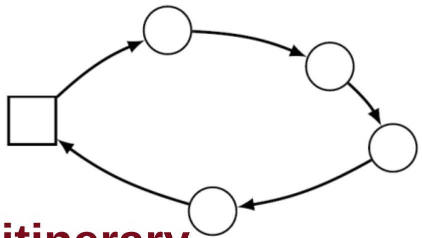
Methodology – Decision Layers

ICEV

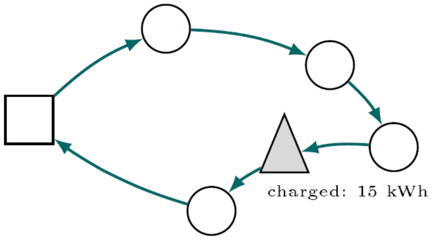


itinerary

BEV



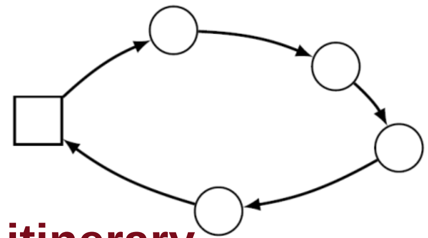
itinerary



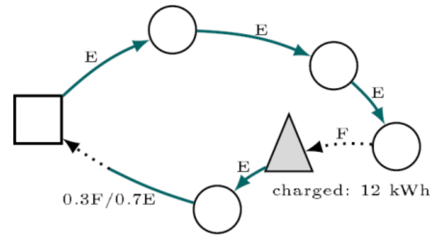
RS visits

charge in RS

PHEV



itinerary



RS visits

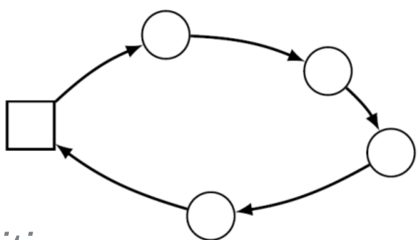
charge in RS

mode selection

Top Layer

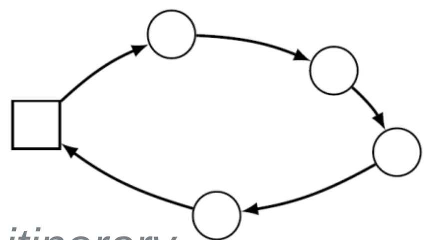
Methodology – Decision Layers

ICEV



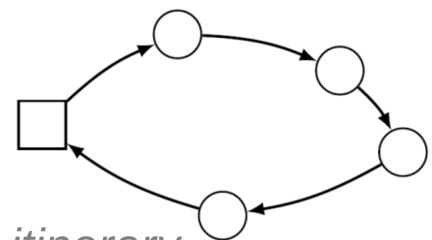
itinerary

BEV



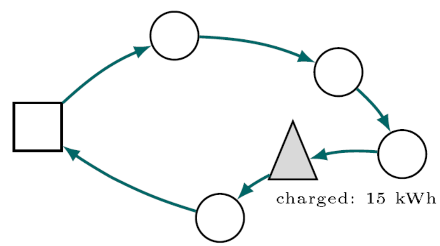
itinerary

PHEV



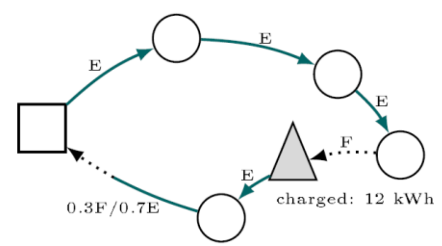
itinerary

Top Layer



RS visits

charge in RS



RS visits

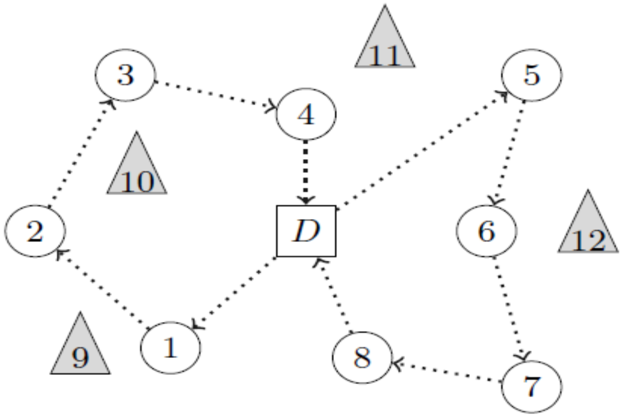
charge in RS

mode selection

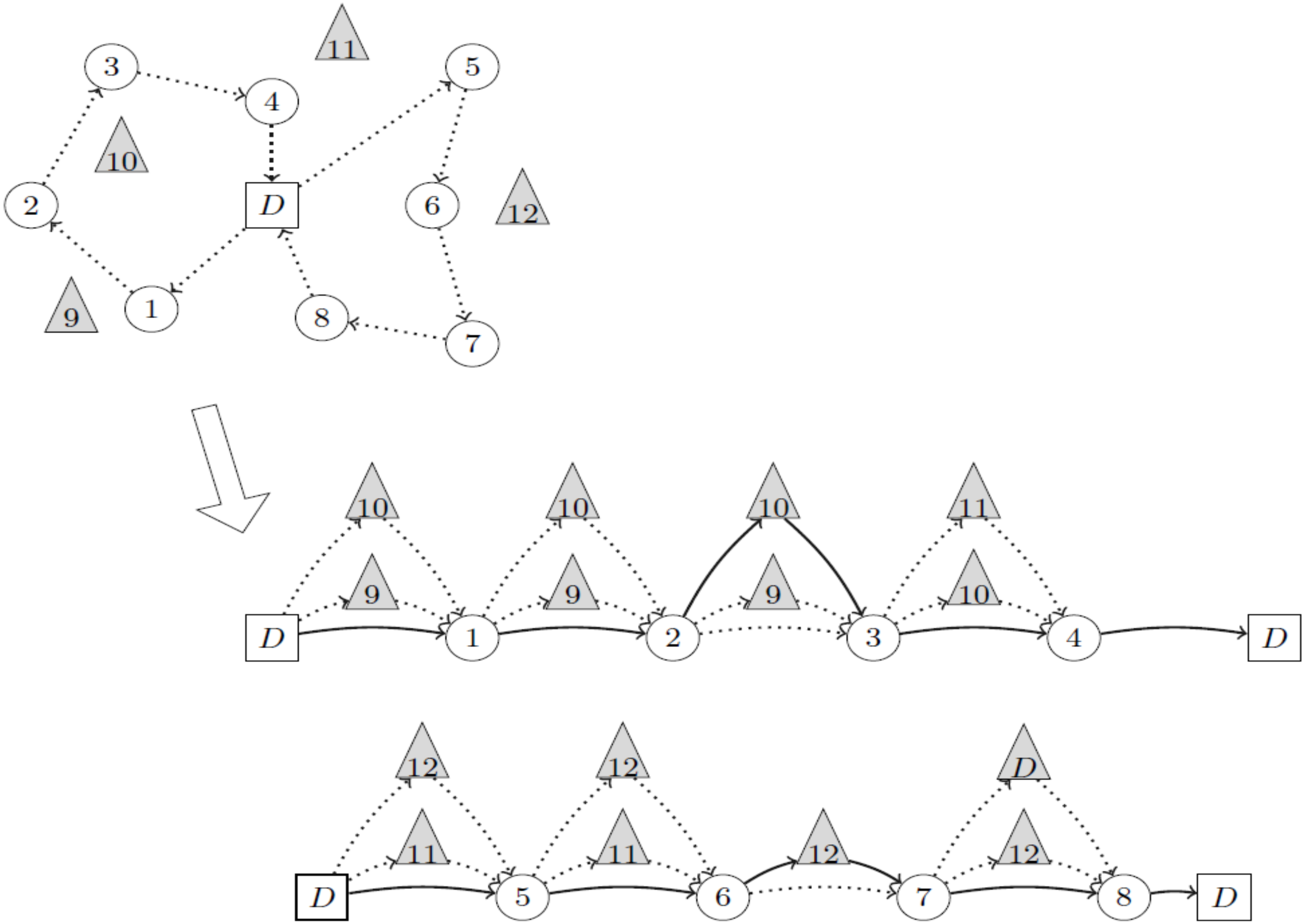
Recharging Stations Visits

- Explicit handling of recharging stations
  - insert a recharging station (RS) node into the route explicitly
  - special operators needed to handle insertion/removal of RS
- Implicit handling of recharging stations
  - RS are inserted into an auxiliary route for evaluation only
  - mapping of VRPTW ⇔ E-VRPTW
  - can be greedy or more intelligent
  - no special operators needed in the base route (VRPTW)
    - well-researched neighbourhood operators applicable
  - we use labelling for (optimal) RS insertion

Implicit handling of Recharging Stations



Implicit handling of Recharging Stations



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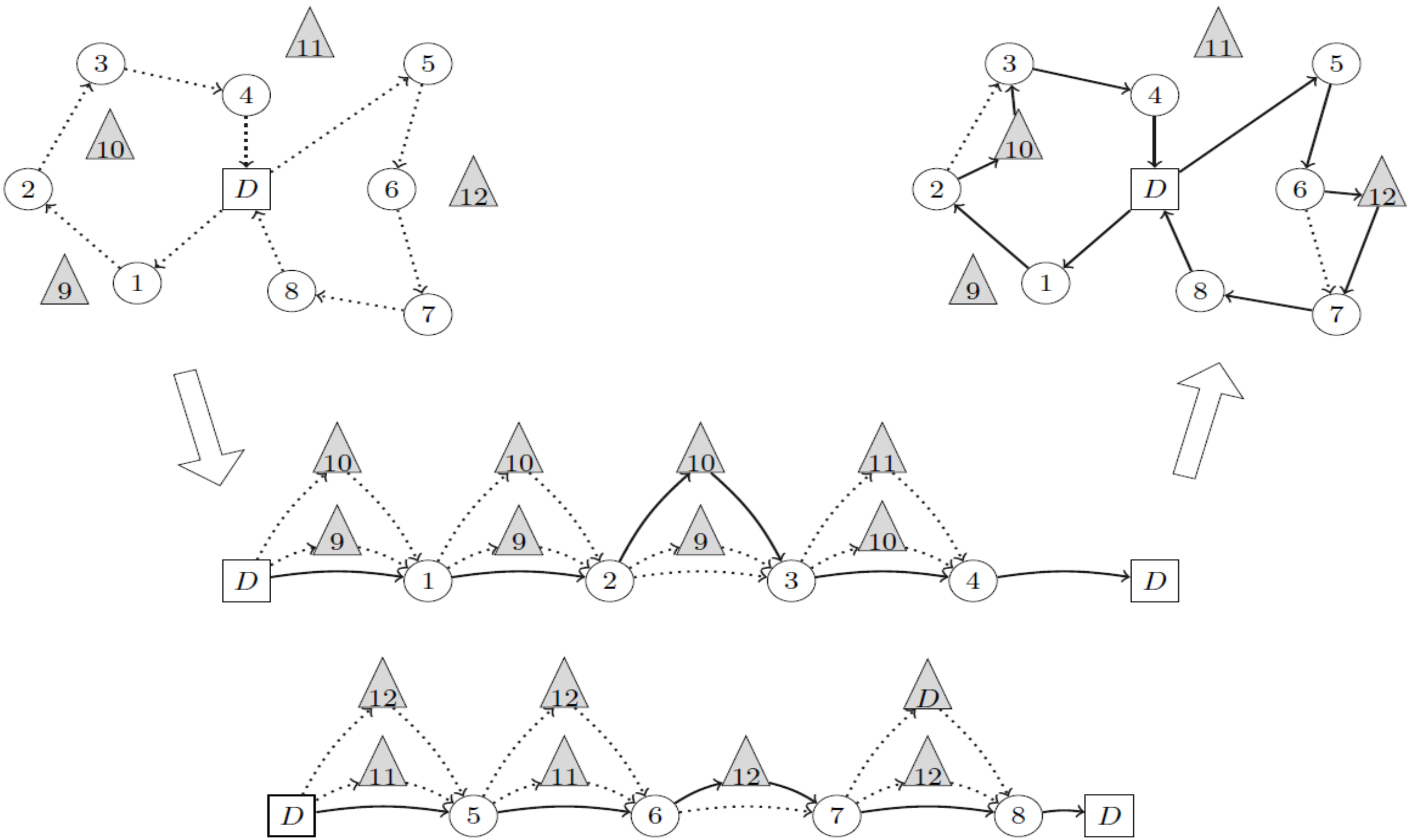
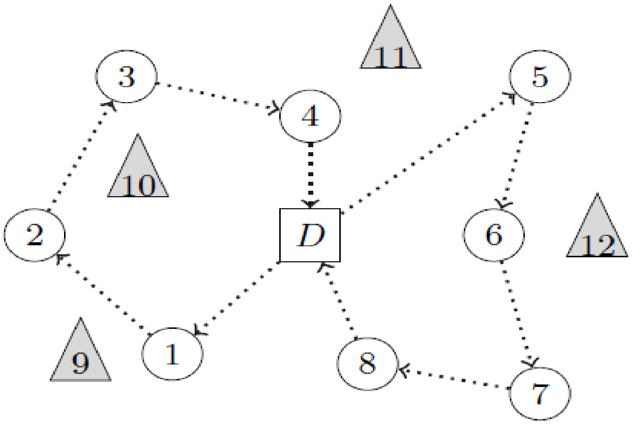


Implicit handling of Recharging Stations

Neighbourhood Search: Relocation Operator



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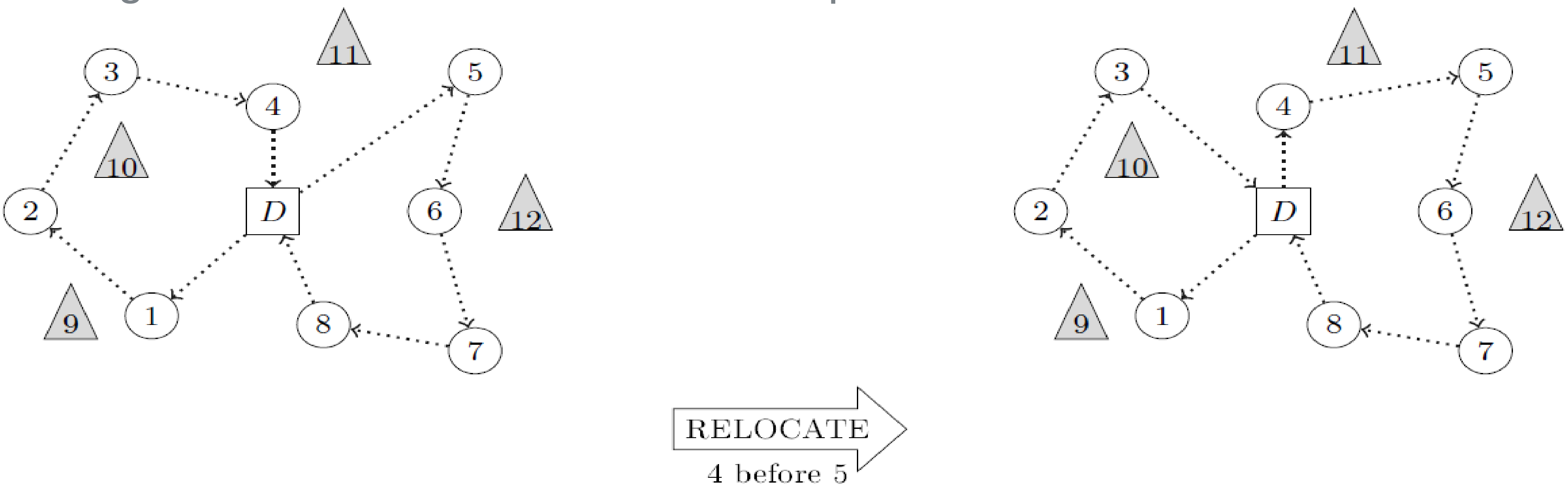

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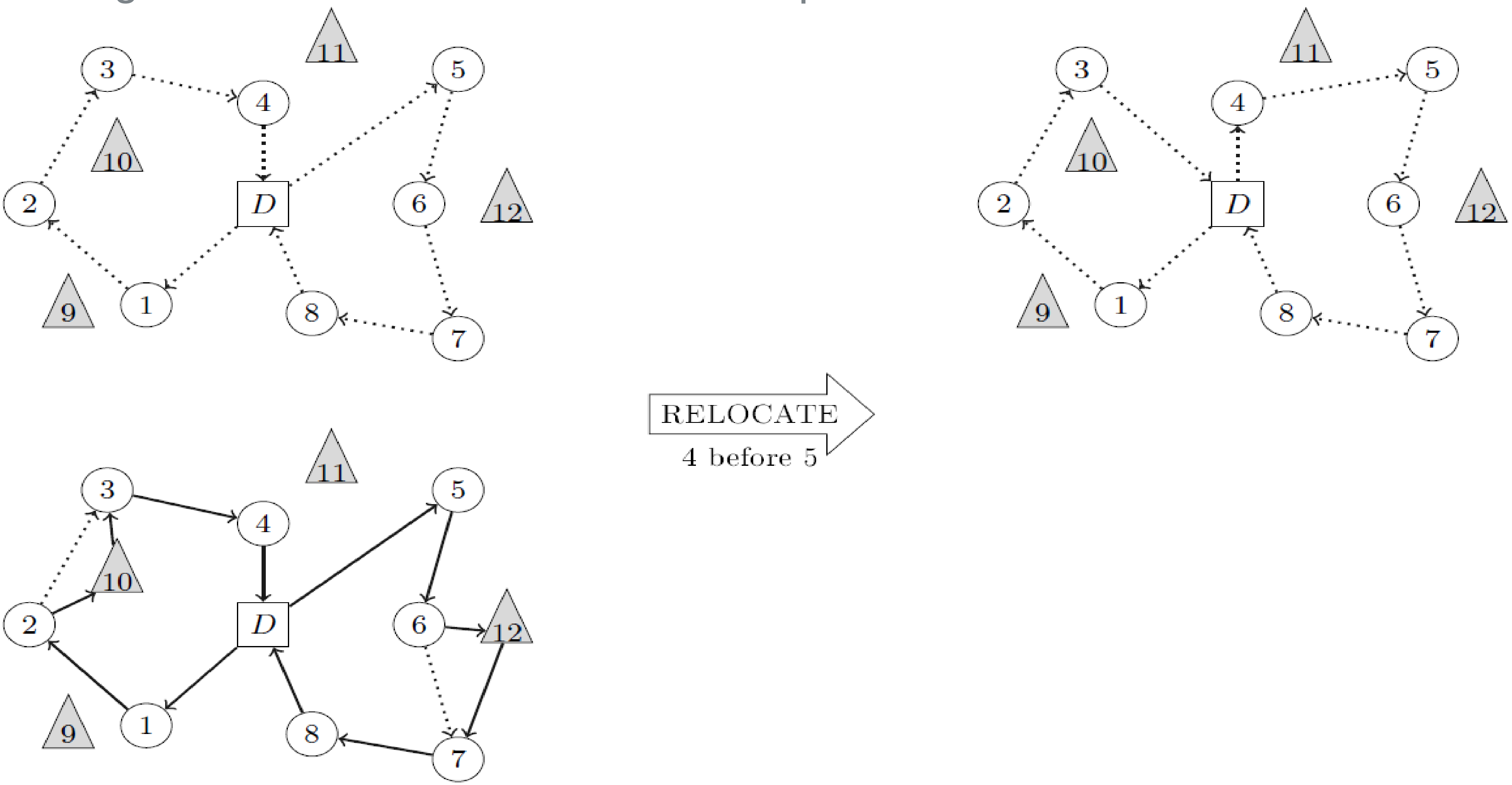

Implicit handling of Recharging Stations

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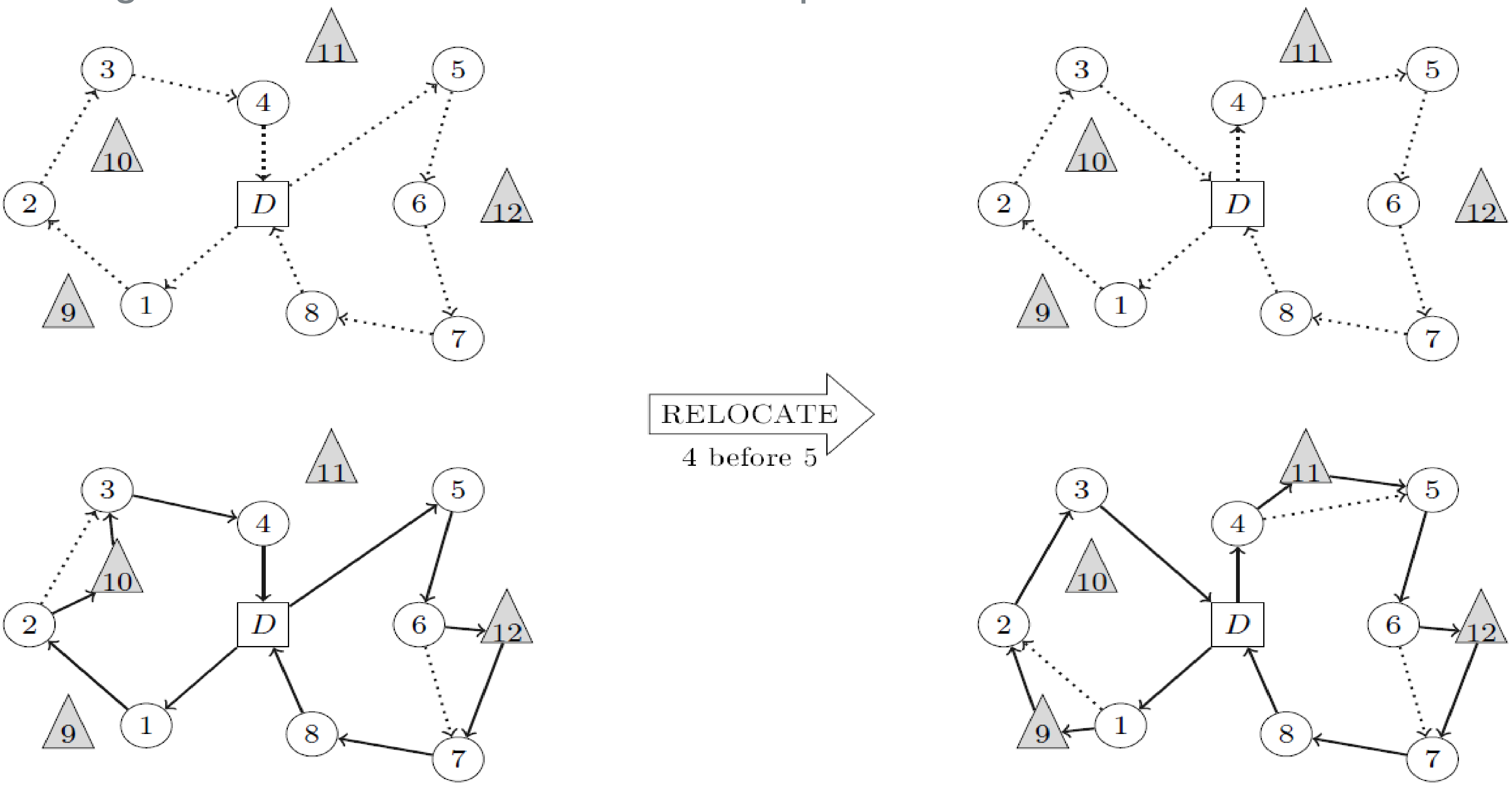
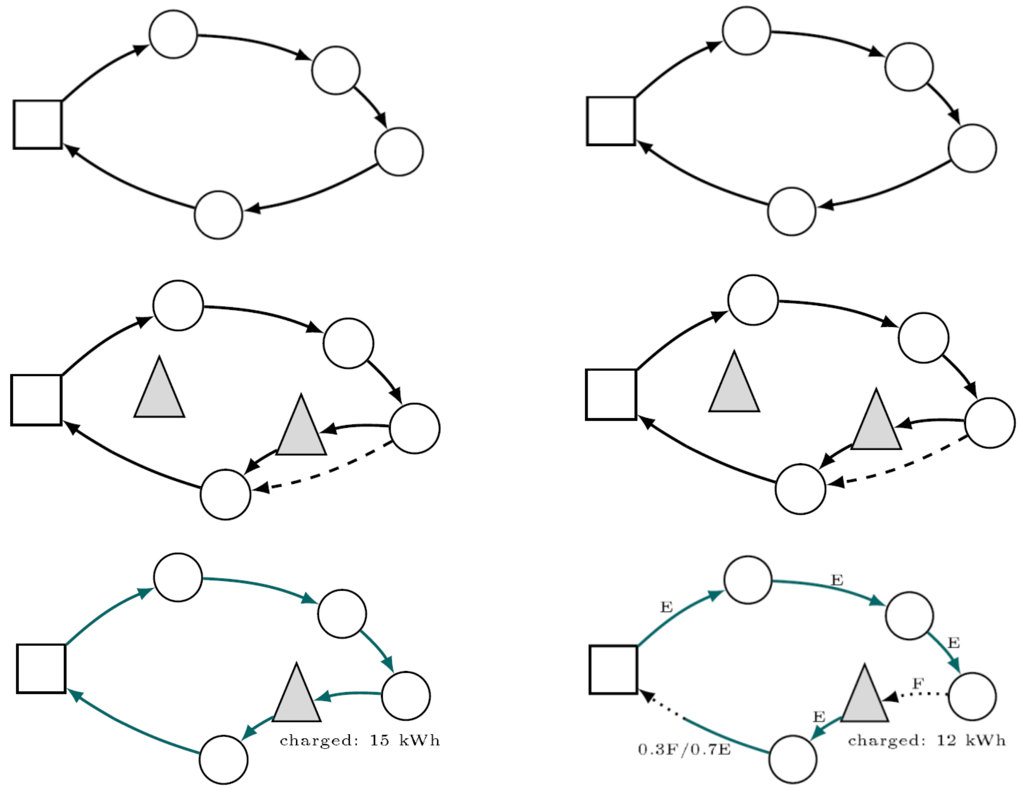


Methodology – Decision Layers

E-VRPTW | PH-VRPTW

itinerary

RS visits



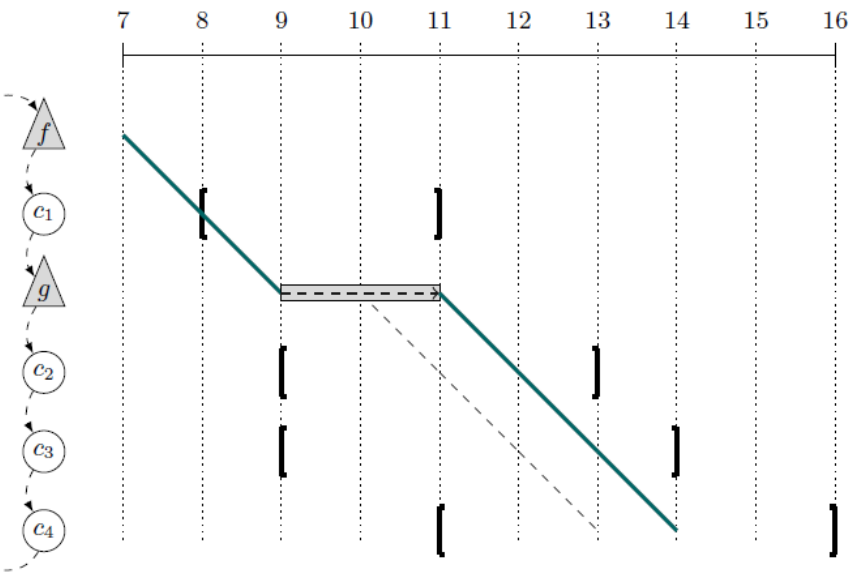
charge in RS

charge in RS

mode selection

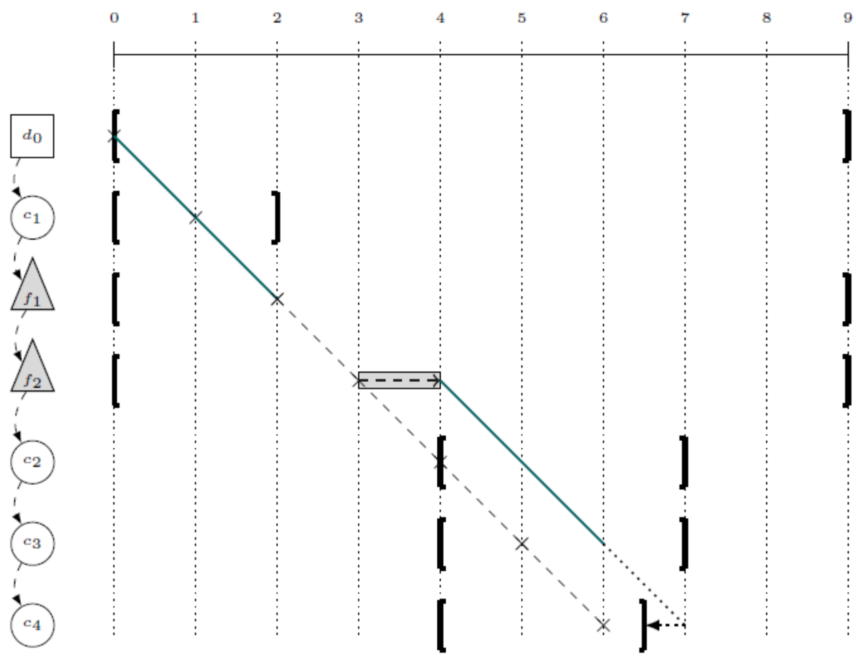
Evaluation for Battery Electric Vehicles

- Assumptions
  - recharging rate is linear (time)
  - energy consumption is also linear (distance)
- Decision
  - quantity to recharge
  - depends on the energy usage + previous recharges
- Greedy policy for the single recharging rate case:
  - charge only if necessary in the last visited recharging station
    → lazy recharging



Evaluation for Plug-in Hybrid Electric Vehicles

- Assumptions
  - recharging rate is linear (time)
  - energy consumption is also linear (distance)
  - no constraints or additional costs for mode switching
- Decision
  - quantity to recharge
  - which engine to use when or
  - how much is energy/fuel is needed
- Greedy policy
  1. energy ← time (lazy recharging)
  2. fuel → time (lazy engine switch)



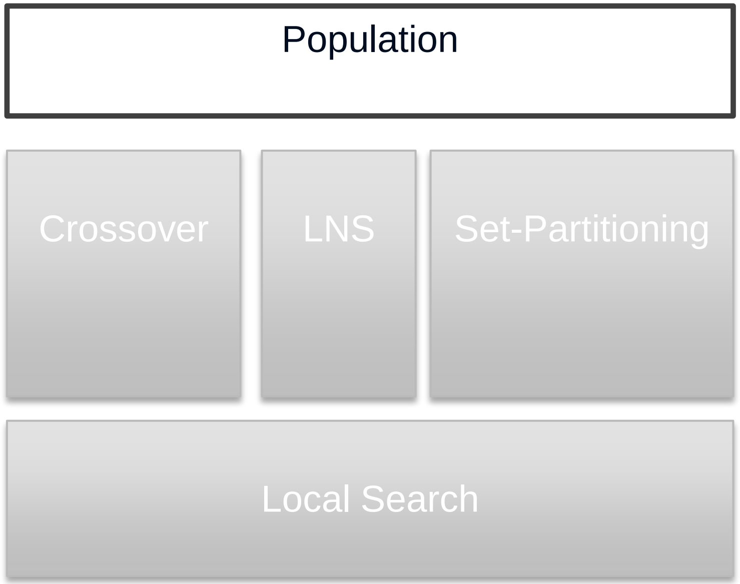
Heuristic Solver

- Population-based Metaheuristic (Hybrid Genetic Algorithm (Vidal et al., 2013))

- Individual (Chromosome) contains of
  - giant tour without route delimiter (and recharging stations)
  - full solution (list of complete tours)

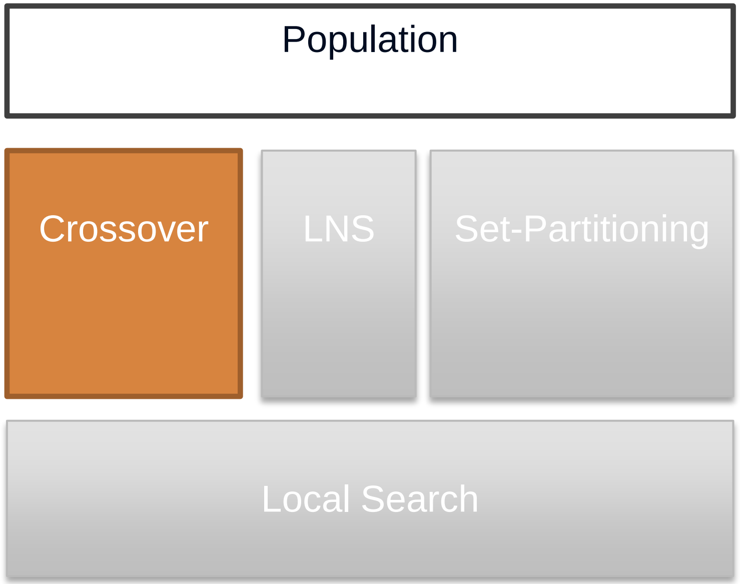
- Individual is selected using binary tournament selection

- Penalization
  - load capacity and time-window relaxation



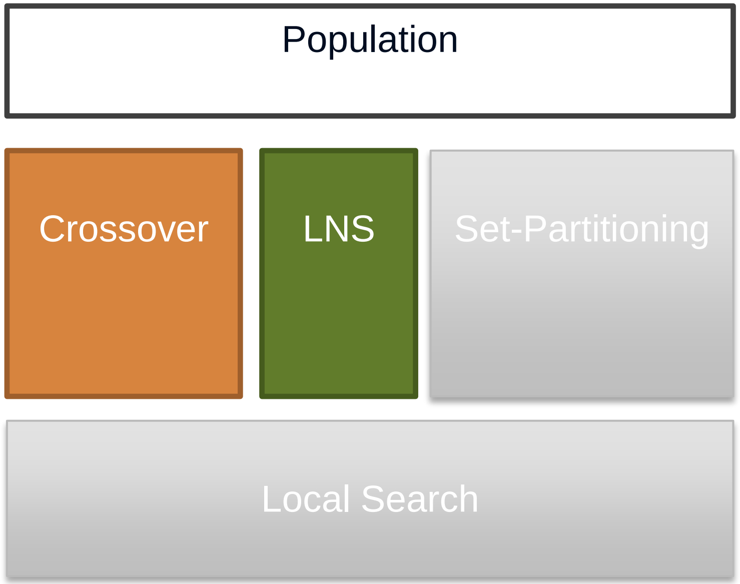
Heuristic Solver

- Population-based Metaheuristic (Hybrid Genetic Algorithm (Vidal et al., 2013))
- Crossover
  - selecting a second Individual using Binary Tournament as well
  - Ordered Crossover (OX) on the giant tours
  - using split procedure for decoding



Heuristic Solver

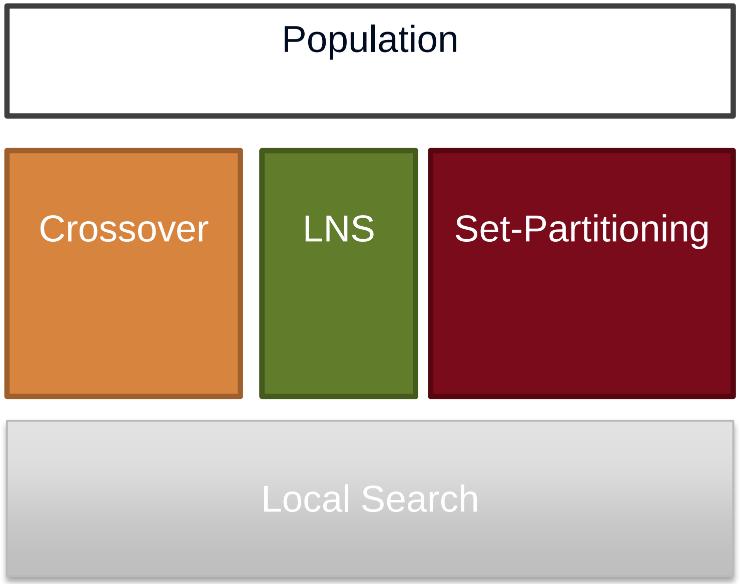
- Population-based Metaheuristic (Hybrid Genetic Algorithm (Vidal et al., 2013))
- Large Neighbourhood Search
  - set of destroy operators
    - random removal
    - similar (Shaw)
    - route removal
    - target
  - set of repair operators
    - greedy insertion
    - 2-regret insertion
  - random selection (roulette-wheel with equal probability)



Heuristic Solver

- Population-based Metaheuristic (Hybrid Genetic Algorithm (Vidal et al., 2013))

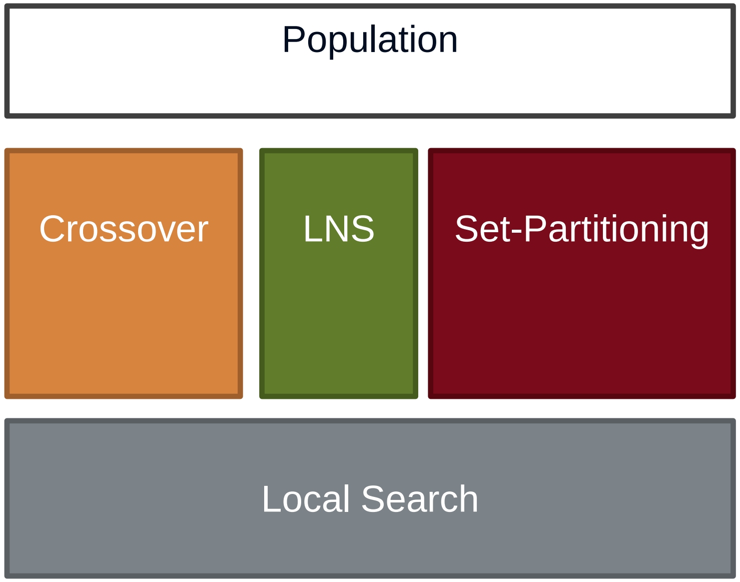
- Set Partitioning
  - pre-processed set of all 1-2 customer tours
  - store promising complete tours (> 2 customers) throughout the search
  - solve set partitioning problem



Heuristic Solver

- Population-based Metaheuristic (Hybrid Genetic Algorithm (Vidal et al., 2013))

- Local Search (Education)
  - 2Opt, 2Opt*
  - Relocate (1-2), Swap (0-2)
  - also used as a heuristic repair step (multiply penalties by 10/100)



Preliminary Experiments – Related Benchmark

- E-FSMVRPTW instances from previous work (2014)
  - combined E-VRPTW Instances with extended Liu&Shen vehicle type definition for the FSMVRPTW
  - only BEVs
  - solved using ALNS/LS/Labelling

Preliminary Experiments – Related Benchmark

- E-FSMVRPTW instances from previous work (2014)

instance	H14		HGA		Gap	
A,B,C	min	avg	min	avg	min	avg
C1	3784.49	3796.56	3780.47	3784.13	-0.083%	-0.389%
C2	2746.01	2763.62	2743.51	2743.81	-0.088%	-0.878%
R1	2514.76	2544.47	2499.86	2510.40	-0.410%	-1.226%
R2	1863.31	1884.47	1858.82	1863.48	-0.208%	-1,186%
RC1	2983.82	3022.68	2972.07	2984.83	-0.346%	-1.243%
RC2	2414.74	2437.14	2412.30	2419.19	-0.091%	-0.842%

Preliminary Experiments – New Instances

- Based on the E-VRPTW instances by Schneider et al. (2014)

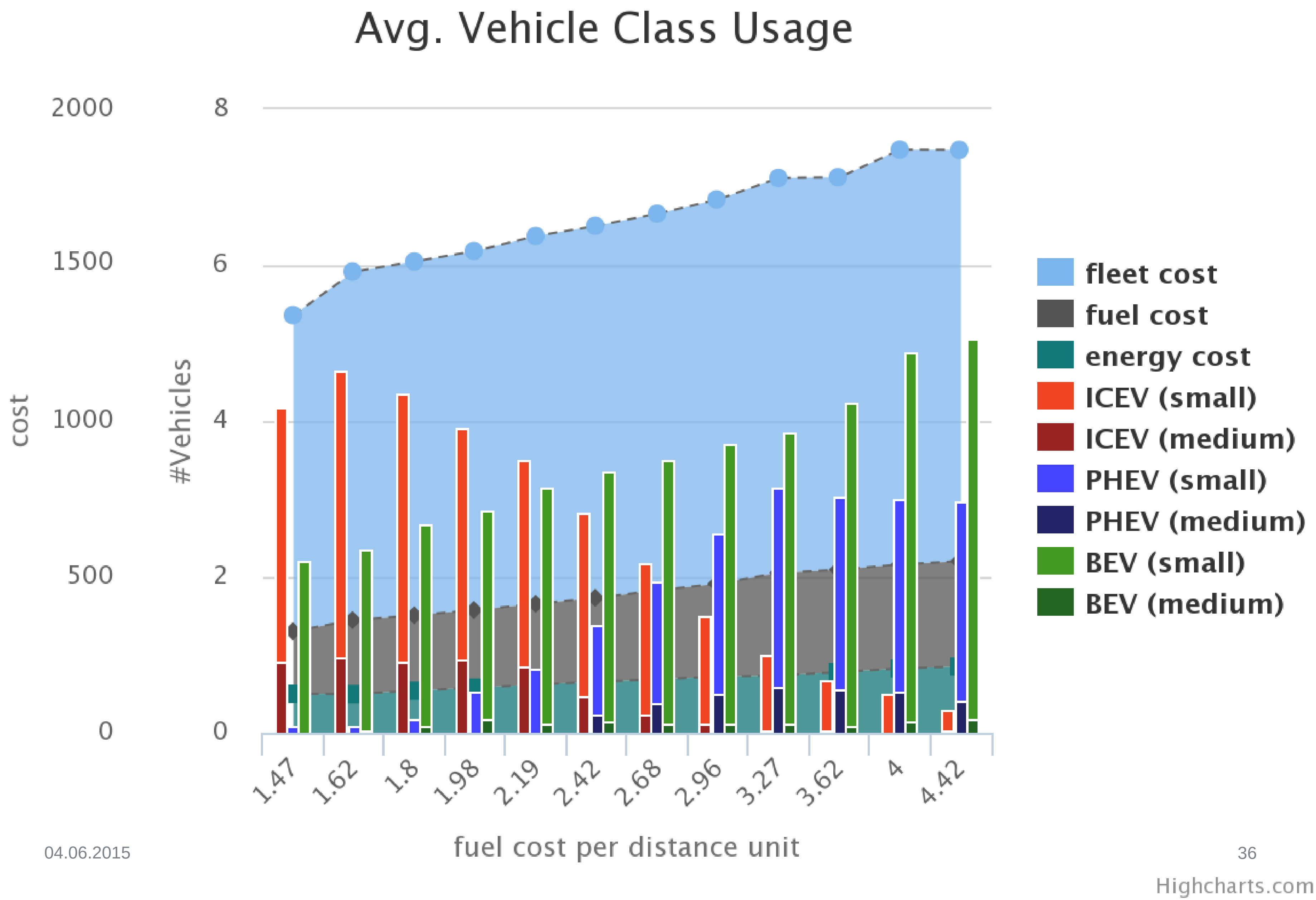
- Extended by additional fleet configuration file
  - 2 vehicles per class (ICEV,PHEV,BEV) – one small, one medium sized
  - parameters based on Fraunhofer study (Plötz et al. 2013)
    - daily utility cost
      - (acquisition cost – reselling gain)
      - maintenance
      - driver wage
    - capacity and consumption
      - only relative values (based on the study)
      - actual values depend on the E-VRPTW instance

Preliminary Experiments – Fleet Configuration

- Parameters from the E-VRPTW instance files:
  - load capacity C
  - battery capacity Q
  - energy consumption r

- Fleet configuration:

class	ICEV		PHEV		BEV	
type	S	M	S	M	S	M
load	0.8*C	1.0*C	0.8*C	1.0*C	0.8*C	1.0*C
fuel	0.23*r	0.28*r	0.26*r	0.33*r	0.0	0.0
battery	0.0	0.0	0.29*Q	0.42*Q	0.83*Q	1.0*Q
energy	0.0	0.0	0.84*r	1.03*r	0.90*r	1.10*r
cost	155	163	158	170	157	167



Avg. Vehicle Class Usage
2000
1500
1000
500
0
8
6
4
2
0
cost
#Vehicles
1.47
1.62
1.8
1.98
2.19
2.42
2.68
2.96
3.27
3.62
4
4.42
fuel cost per distance unit
fleet cost
fuel cost
energy cost
ICEV (small)
ICEV (medium)
PHEV (small)
PHEV (medium)
BEV (small)
BEV (medium)
Highcharts.com

Summary

- Fleet Mixing Problem with ICEV, PHEV and BEV

- Methodology
  - Modular design for handling problem specific sequence attributes
  - Labelling to use well-studied neighbourhoods directly
    - may be time consuming
    - can be replaced with other (greedy) procedure without modifying the neighbourhood operators
  - Directly applicable in a competitive metaheuristic framework

- Results
  - higher fuel prices => more electric vehicles
  - lower fixed cost still a major advantage of ICEVs

Future work

- Instances using real street graphs
  - to better reflect urban settings

- Analysis of the metaheuristic components
  - contribution of set-partitioning, LNS and crossover
  - heuristic and exact labelling

- Introducing City Center restrictions
  - prohibited / restricted use of fossil fuel to travel from / to a customer in the center
  - promotes the use of (hybrid) electric vehicles
  - more on this topic at the VeRoLog 2015

Thank you for your attention!

Acknowledgement

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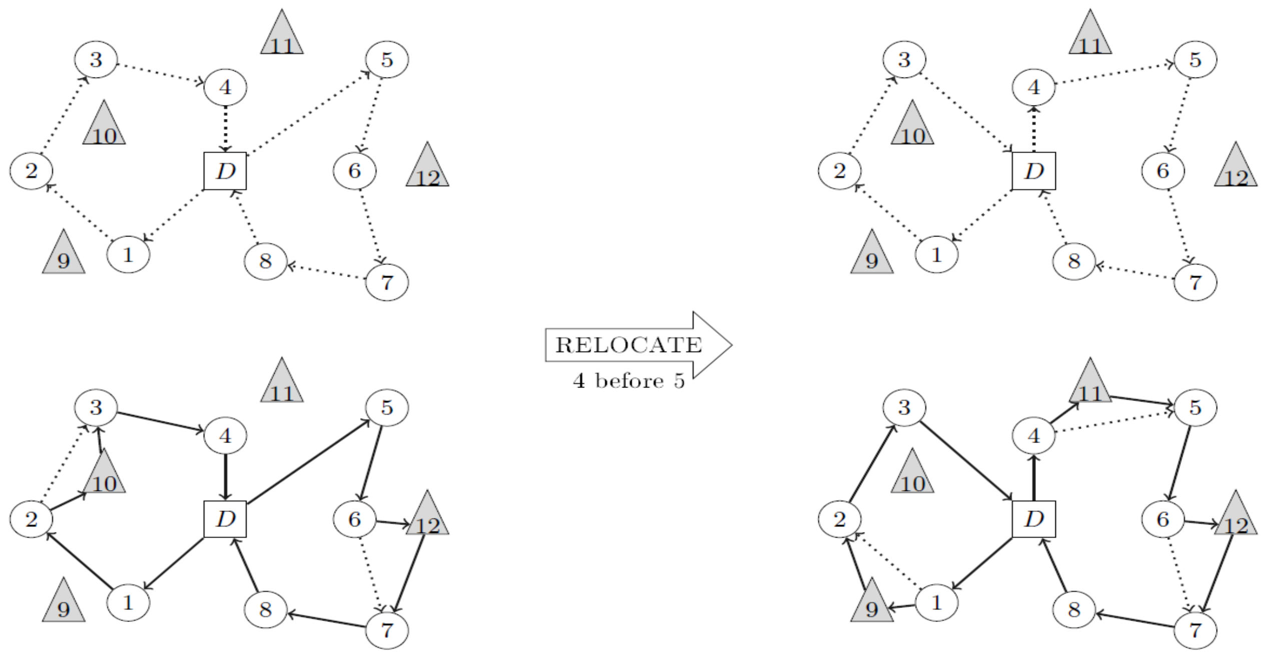
Additional Slides

Implicit handling of Recharging Stations

Neighbourhood Search: Relocation Operator

i	$dist_{0,i}$	$dist_{i-1,i}$
1	4	/
2	4	3
3	5	5
4	2	4
5	4	3
6	3	3
7	5	3
8	3	3
$dist_{i,j} = dist_{j,i}$		
other distances $= \infty$		

	$dist_{i,j}$			
$i \backslash j$	9	10	11	12
0	5	4	3	6
1	2	5	/	/
2	3	3	/	/
3	/	3	5	/
4	/	4	2	/
5	/	/	2	3
6	/	/	4	2
7	/	/	/	4
8	5	/	/	5



σ	$dist(\sigma)$
(0, 1, 2, 10, 3, 4, 0)	19
(0, 5, 6, 12, 7, 8, 0)	19
(0, 1, 9, 2, 3, 0)	16
(0, 4, 11, 5, 6, 12, 7, 8, 0)	21

other properties
$tt_{i,j} = dist_{i,j}$
$[e_i, l_i] = [0, \infty]$
$Y = 10$
$r = 1.0, g = 1.0$