Dynamic EV Routing with Uncertain Availability: Heuristics and Lower Bounds

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e-VRO
Electric Vehicle Routing Optimization

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Outline

- Motivation
- Problem description
- Literature review
- Dynamic routing model
- Solution methods: Policies
- Lower bounds for the dynamic routing model*
- Information penalties & tighter bounds*
- Summary

Motivation

Motivation

Electric vehicles (EVs)

- Reducing petroleum dependency in shift to sustainable transport
- Increased the use of EVs in their operations : La Poste, EDF, Coca Cola, UPS, …

Motivation

Why do EVs lead to new VRPs?

- New technological constraints
  - Limited battery capacity & range → More frequent charging
  - Longer charging times
  - Fewer charging stations

  → Greater impact of queueing

Motivation

Why do EVs lead to new VRPs?

More frequent charging

+

Greater impact

of queueing

1. Charge only at depot
   - Additional travel time
   - Less queueing time
2. Mid-route recharging
   - Less travel time
   - Additional queueing time

Motivation

Montoya (2015) — ENEDIS & Mid-route recharging

Motivation

Montoya (2015) — ENEDIS & Mid-route recharging

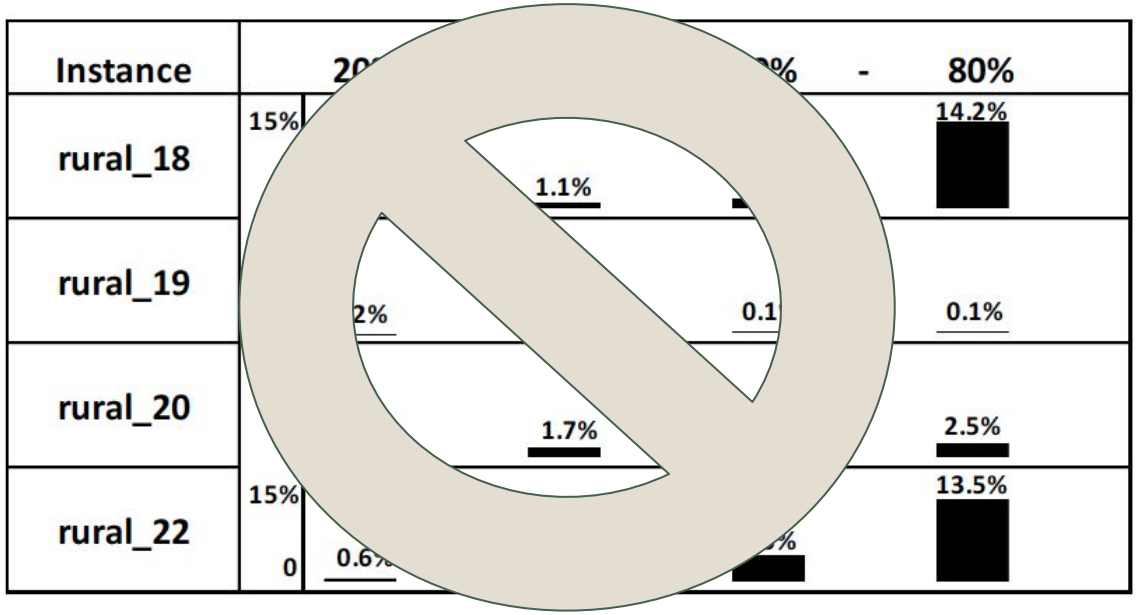
- Results
  - Mid-route recharging offered cost savings

Instance	20% - 40% - 60% - 80%
rural_18	15% 0 — 0.8% — 1.1% — 1.7% — 14.2%
rural_19	15% 0 — 0.2% — 0.1% — 0.1% — 0.1%
rural_20	15% 0 — 0.8% — 1.7% — 1.2% — 2.5%
rural_22	15% 0 — 0.6% — 2.7% — 4.6% — 13.5%

Motivation

Montoya (2015) — ENEDIS & Mid-route recharging

- Results
  - Mid-route recharging offered cost savings
  - ENEDIS chose not to employ mid-route recharging
    - Uncertainty in access to CS



Motivation

Montoya (2015) — ENEDIS

- Results
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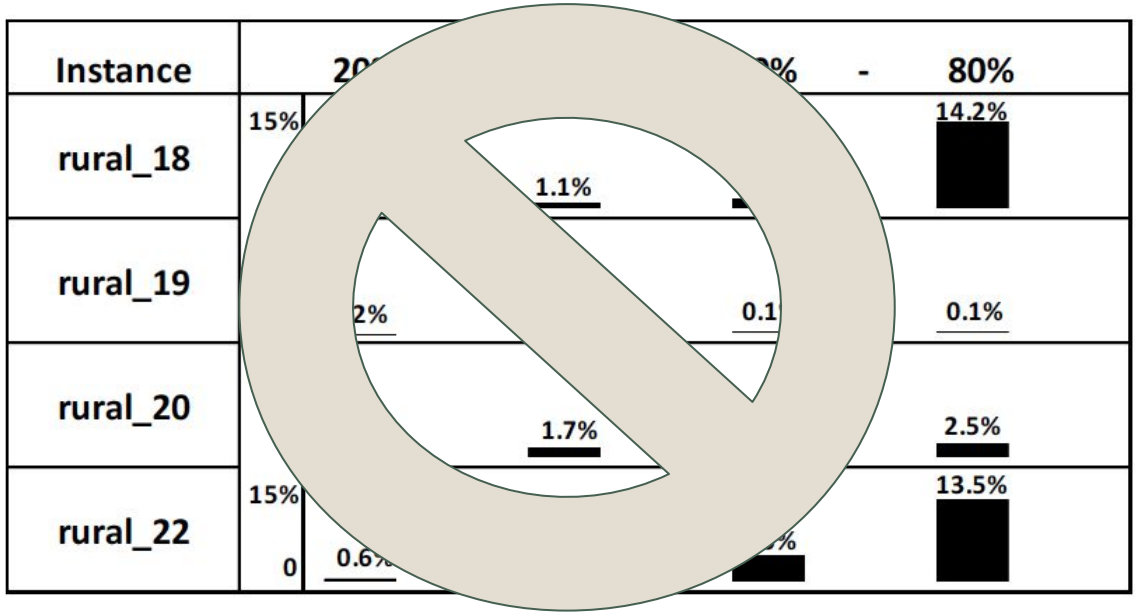
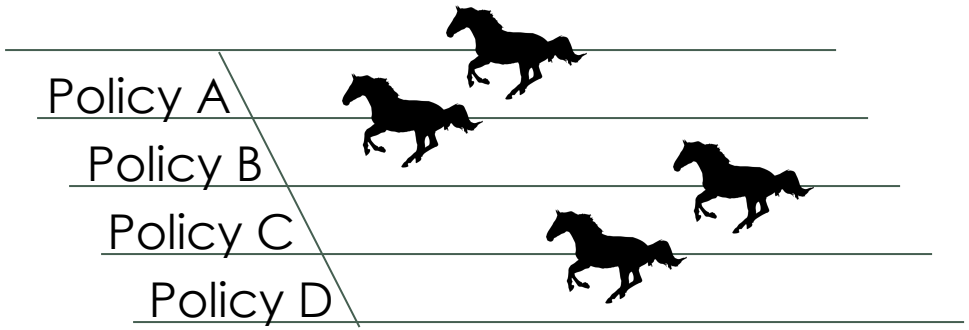


- Solution should consider
  - Mid-route recharging | CS uncertainty | **Dynamic routing**

Motivation

A few words on dynamic routing

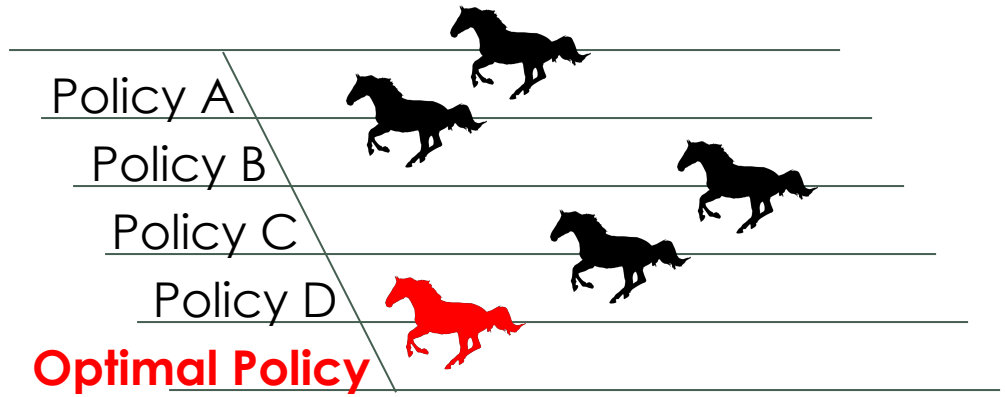
- Common drawback
  - "Horse race" method of comparing solutions
  - Benchmarks, but how much better can we do?



Motivation

A few words on dynamic routing

- Common drawback:
  - "Horse race" method of comparing solutions
  - Benchmarks, but how much better can we do?
- In this work:
  - Lower bounds via information relaxation & information penalties
  - Evidence for goodness of policies



Problem description: EVRP-MRUA

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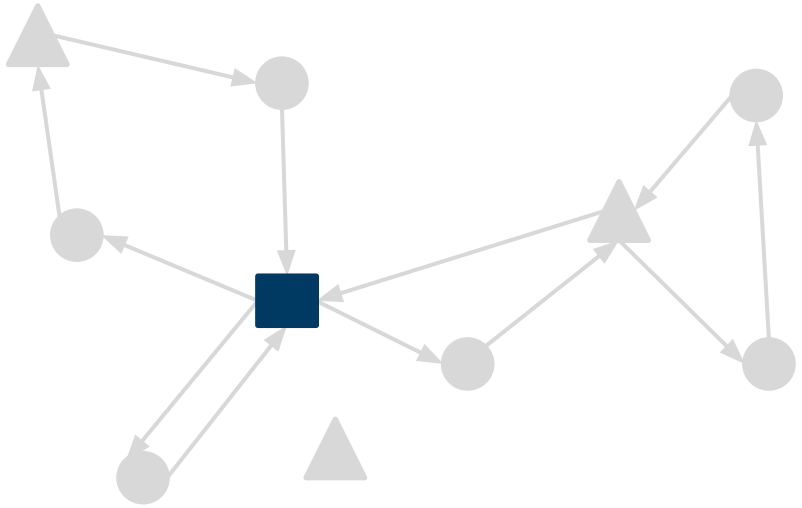
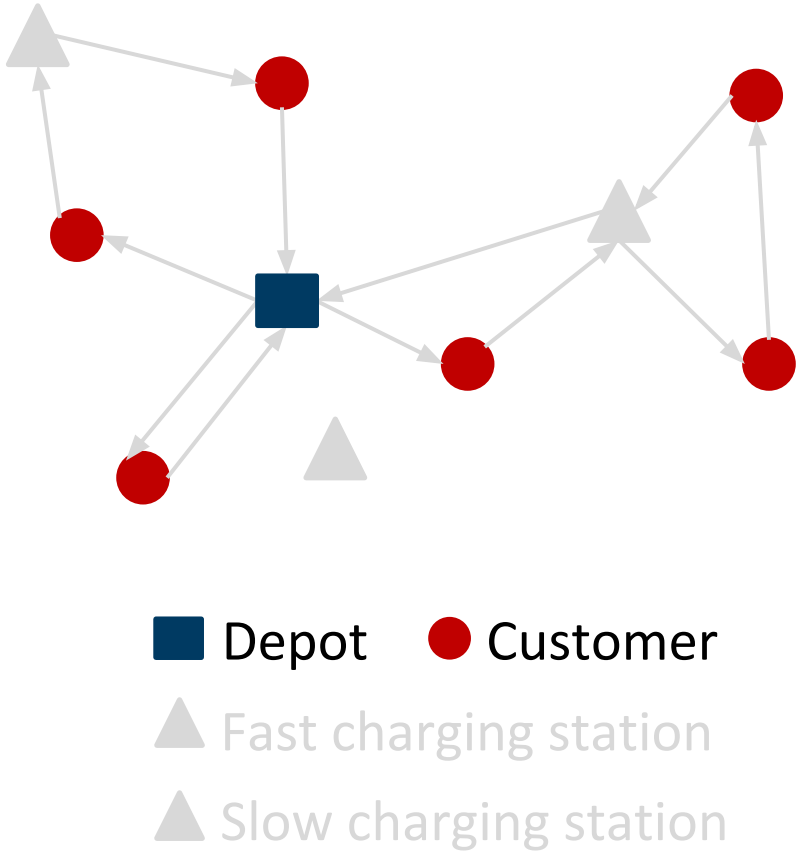
- One depot



Depot
Customer
Fast charging station
Slow charging station

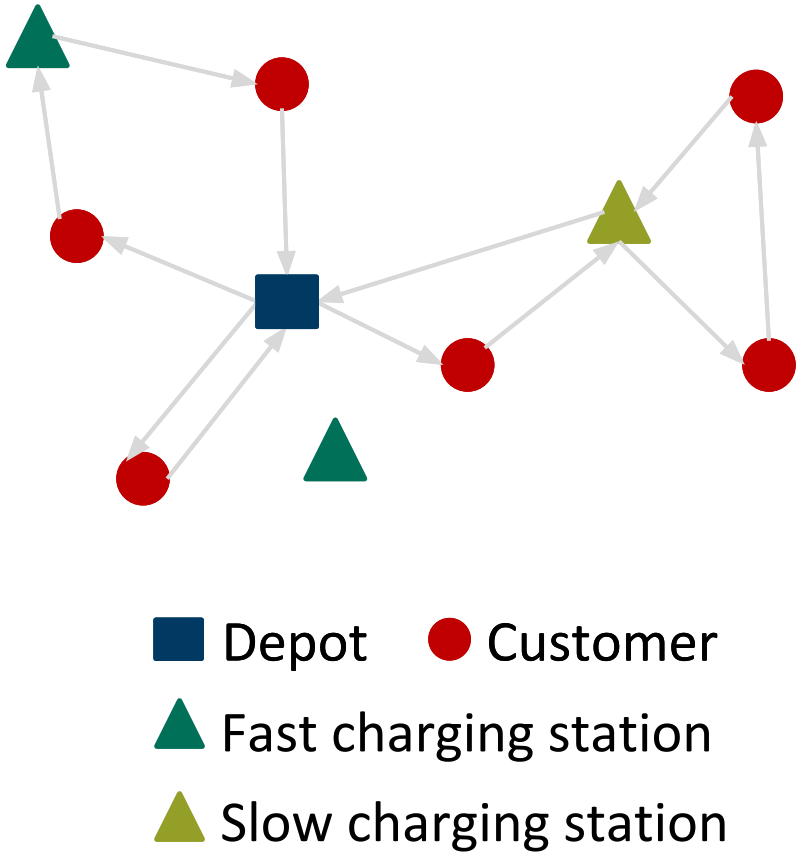
Problem description: EVRP-MRUA

- One depot
- *n* customers



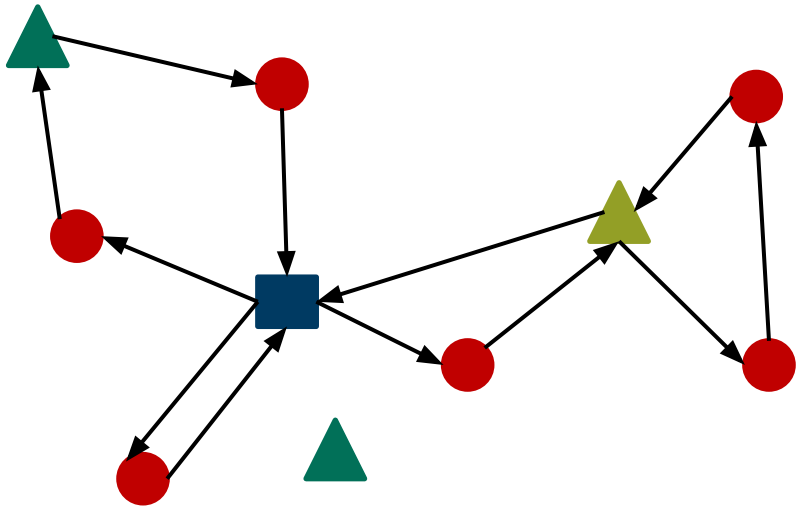
Problem description: EVRP-MRUA

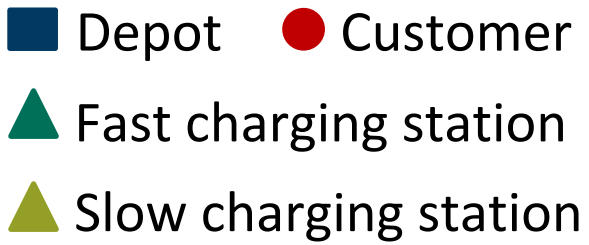
- One depot
- *n* customers
- *m* charging stations
  - Fast, medium, slow
  - Queues unknown prior to arrival
  - Geom/Geom/s



Problem description: EVRP-MRUA

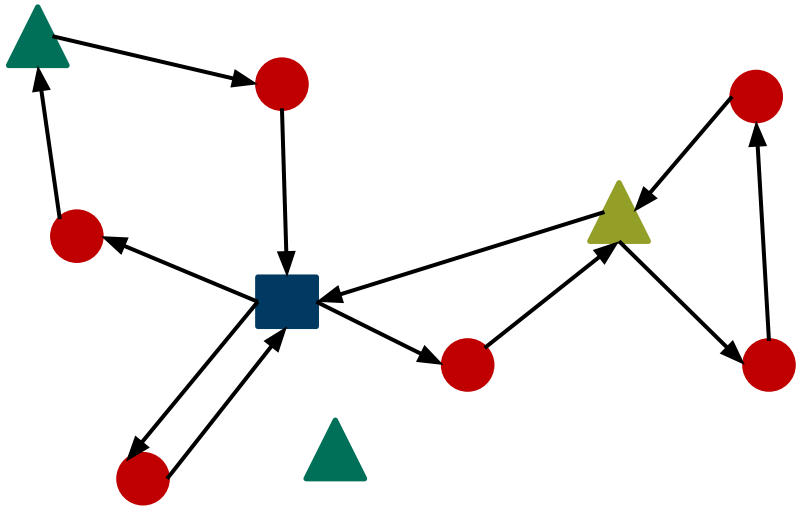
- One depot
- *n* customers
- *m* charging stations
- For each arc (*i*,*j*):
  - d_{ij} distance
  - $\propto$ e_{ij} energy consumption
  - $\propto$ t_{ij} time





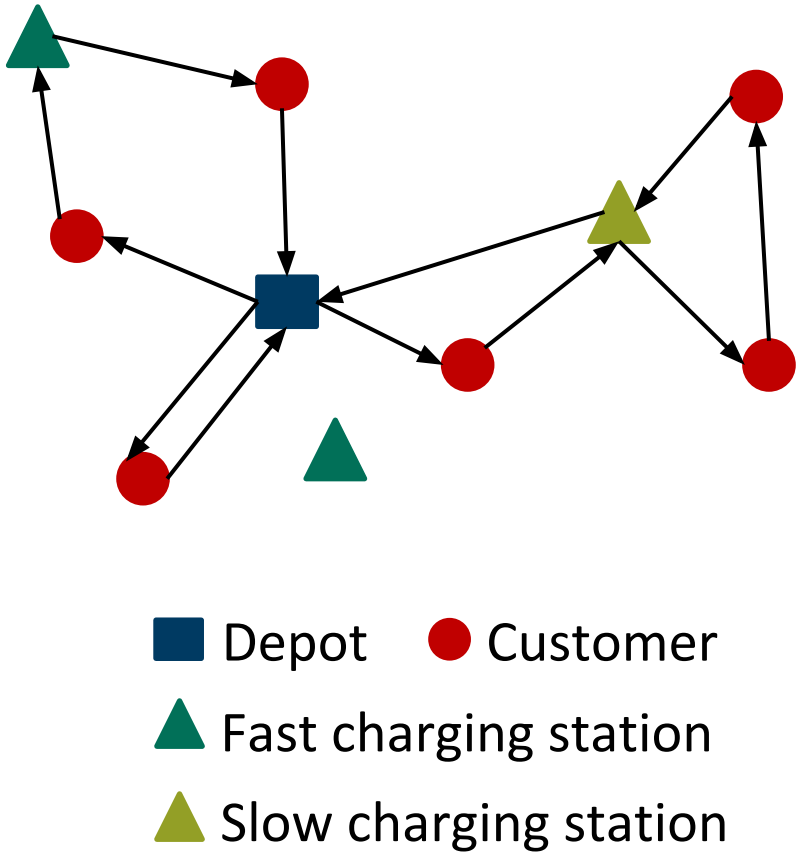
Problem description: EVRP-MRUA

- One depot
- *n* customers
- *m* charging stations
- For each arc (*i*,*j*):
- Single vehicle
  - Battery capacity Q
  - Non-linear charging function
  - Discrete charging decisions



Problem description: EVRP-MRUA

- One depot
- *n* customers
- *m* charging stations
- For each arc (*i*,*j*):
- Single vehicle
- Objective: Minimize time to serve all customers and return to depot



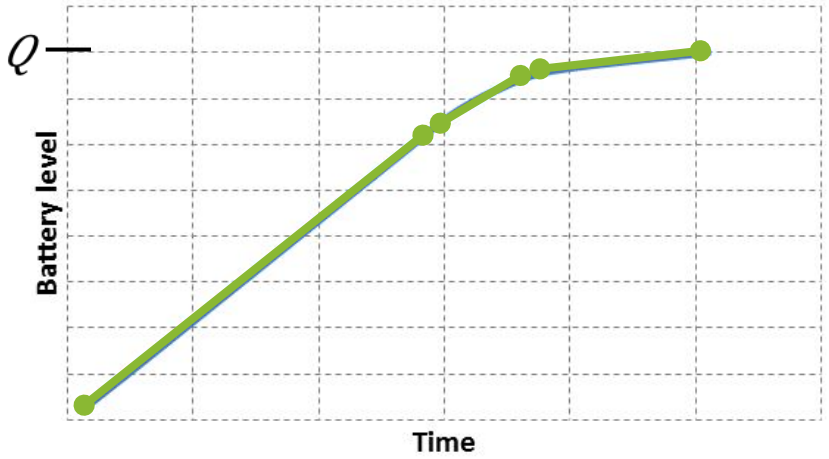
Field work

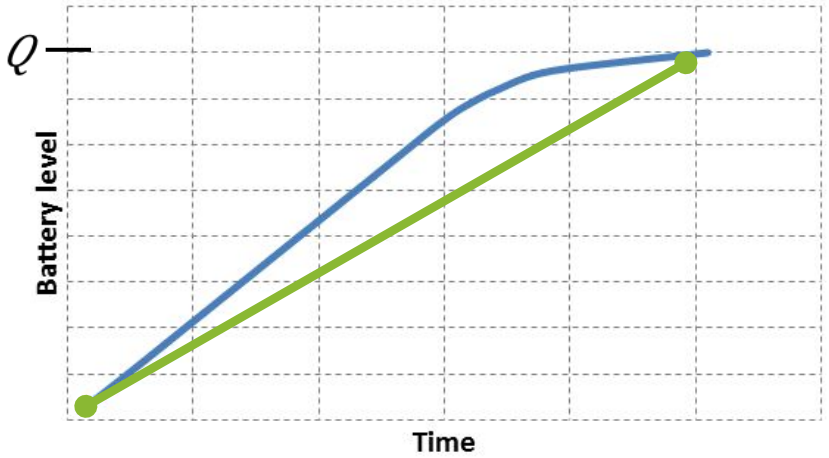
Validating Assumptions

Literature

Literature

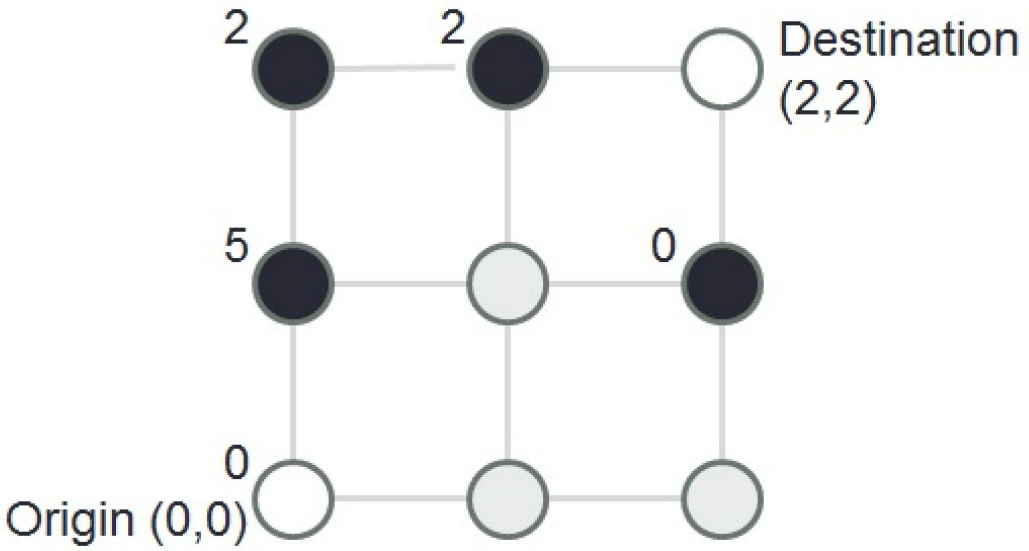
- **Partial charging & non-linear charging function**
  - Montoya et al. (2016b)
  - Pelletier, et al. (2017)
  - Pelletier, Jabali, Laporte (2017)





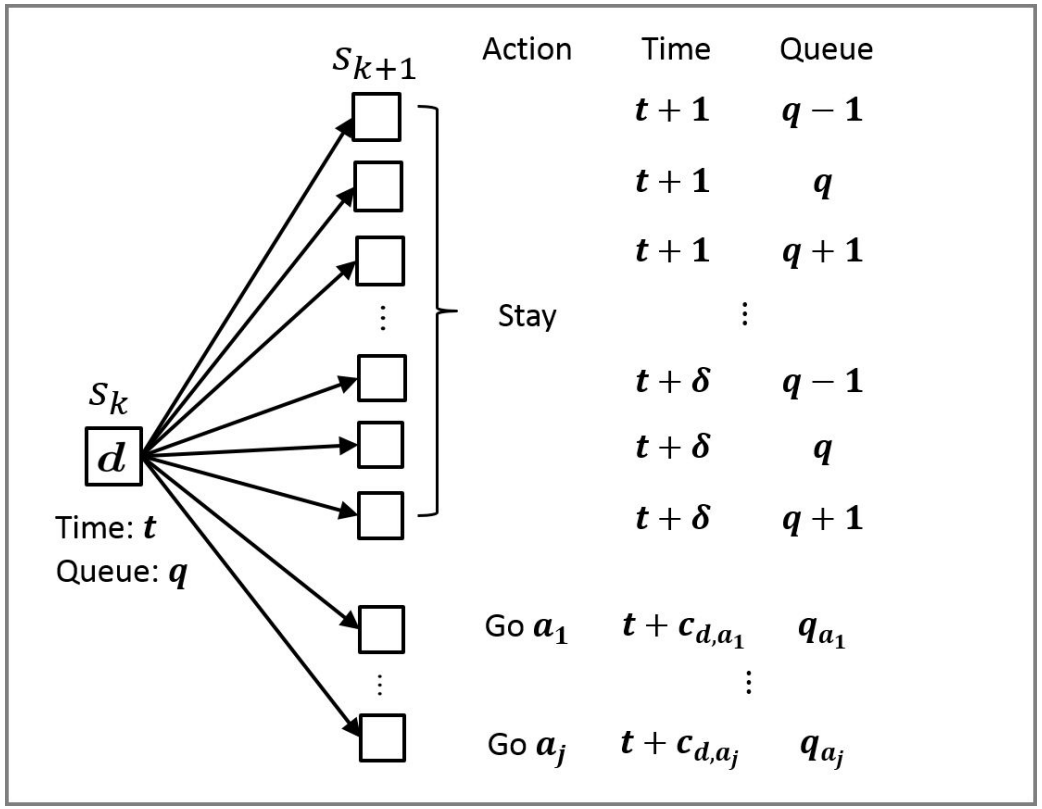
Literature

- Partial charging & non-linear charging function
- **Dynamic EV routing with uncertain CS availability**
  - Adler, Mirchandani (2014)
  - Sweda, Dolinskaya, Klabjan (2015)



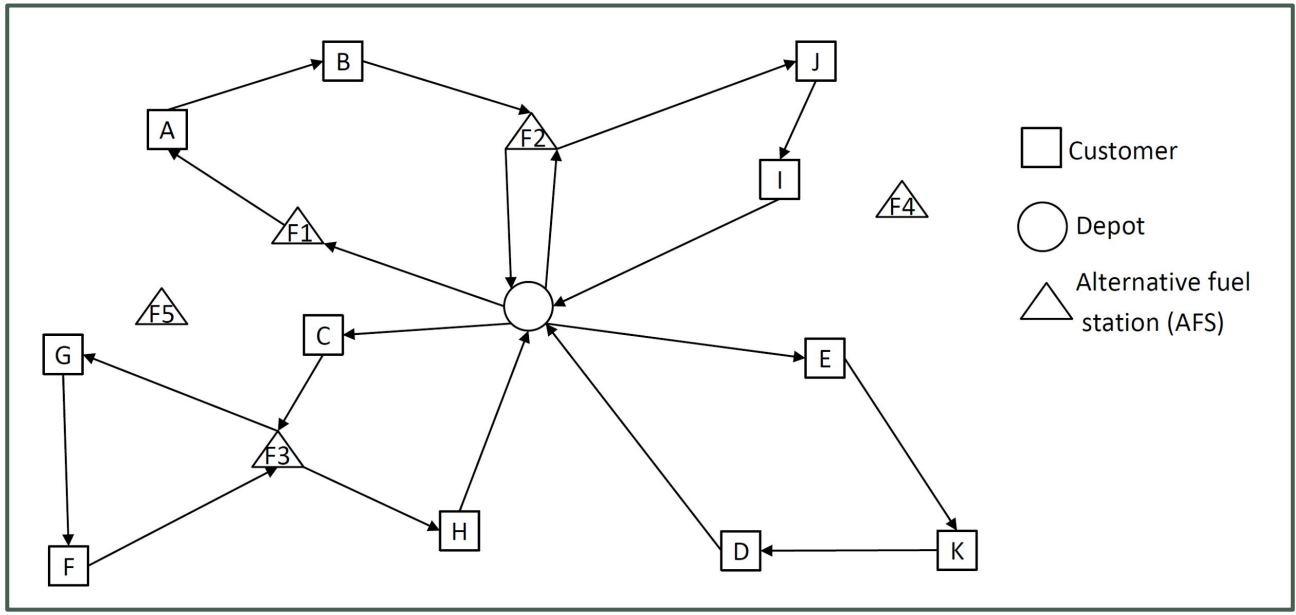
Literature

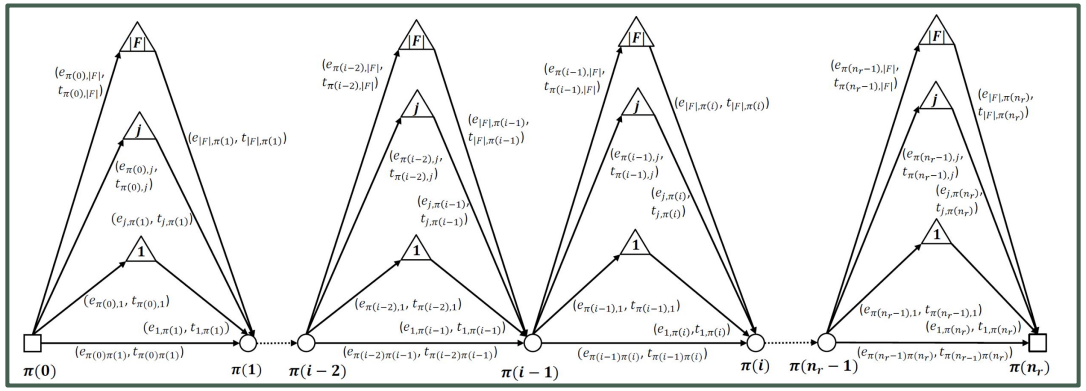
- Partial charging & non-linear charging function
- Dynamic EV routing with uncertain CS availability
- **Dynamic routing over network of queues**
  - Zhang, Ohlmann, Thomas (2015)



Literature

- Partial charging & non-linear charging function
- Dynamic EV routing with uncertain CS availability
- Dynamic routing over network of queues
- **EV routing over network of customers & CSs**
  - Erdoğan, Miller-Hooks (2012)
  - Montoya et al. (2016)

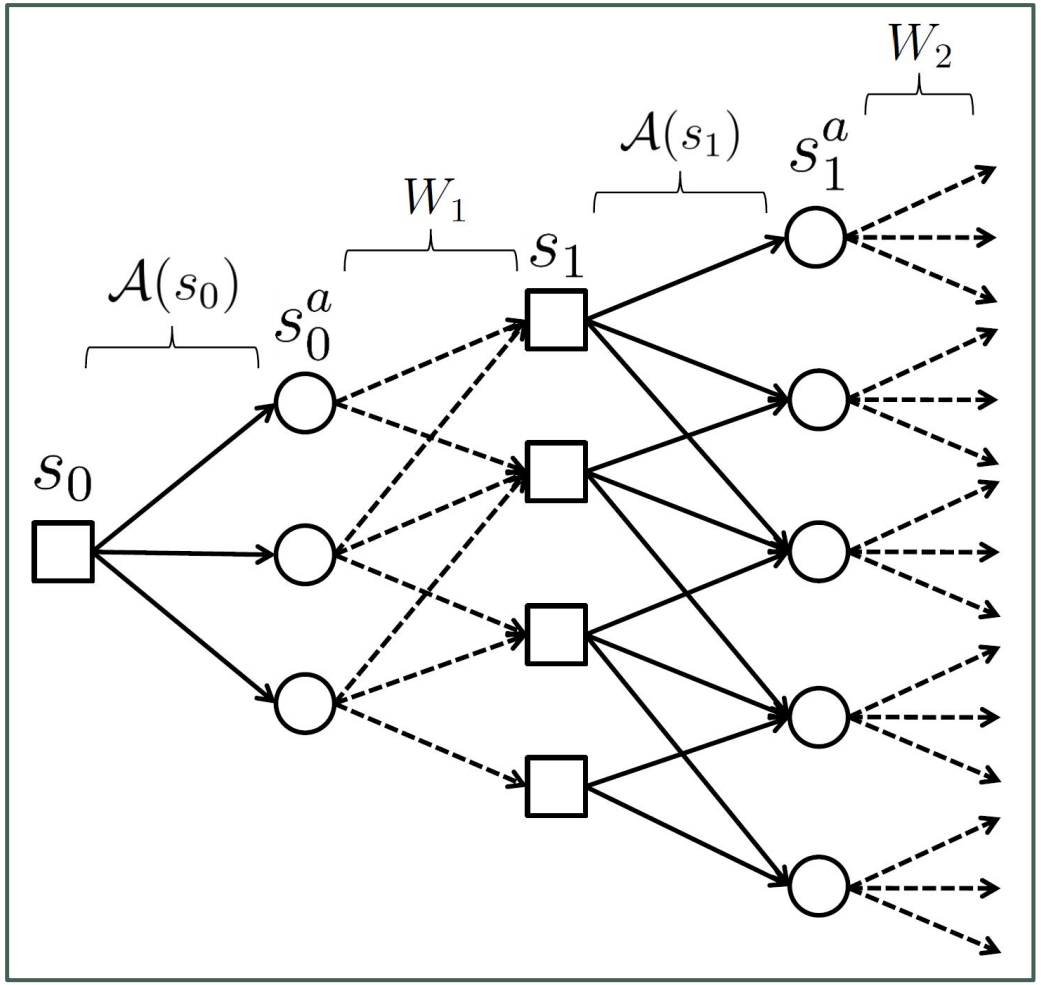




Dynamic Routing Model

Dynamic Routing Model

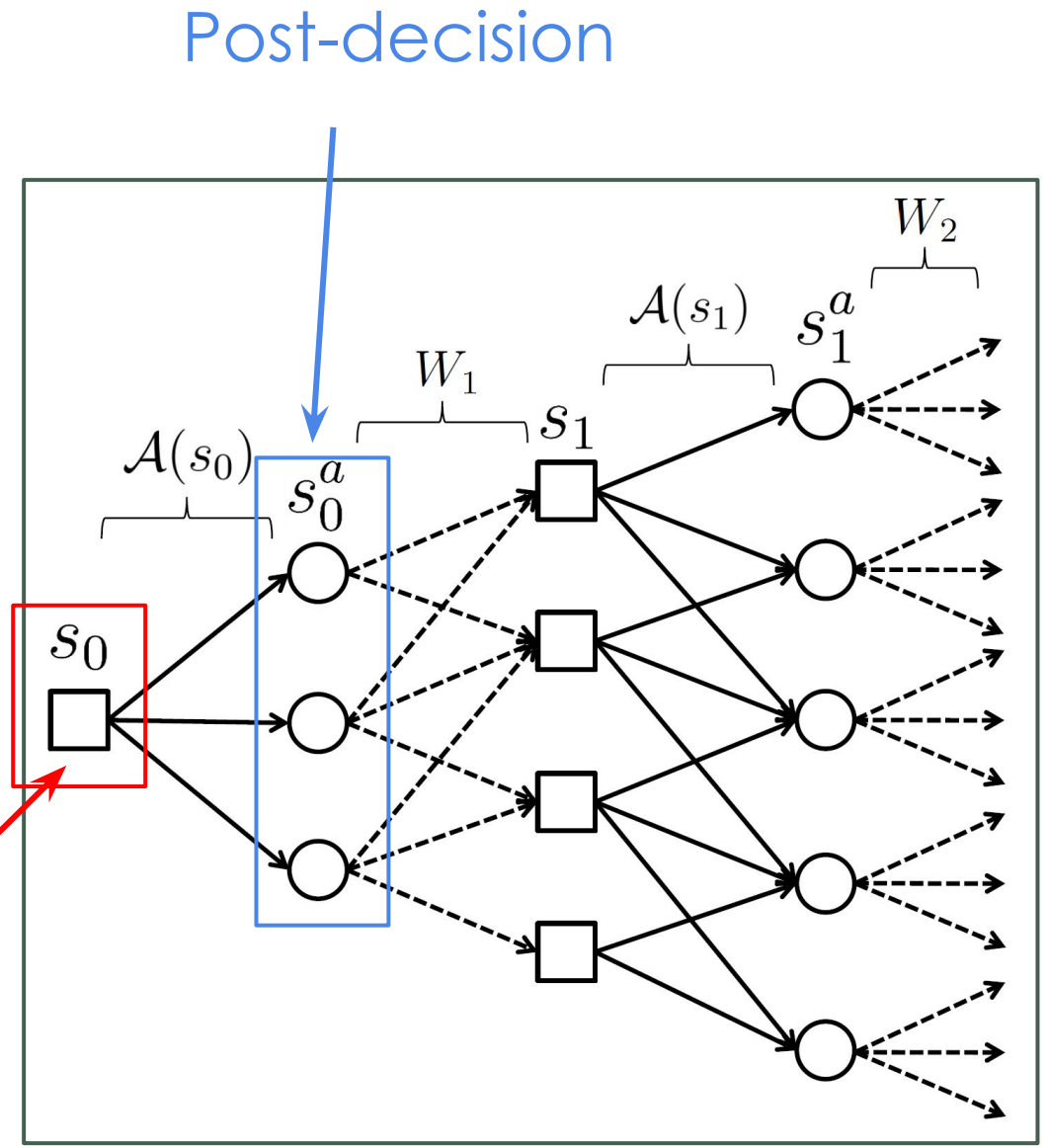
Stochastic dynamic program



Dynamic Routing Model

Stochastic dynamic program

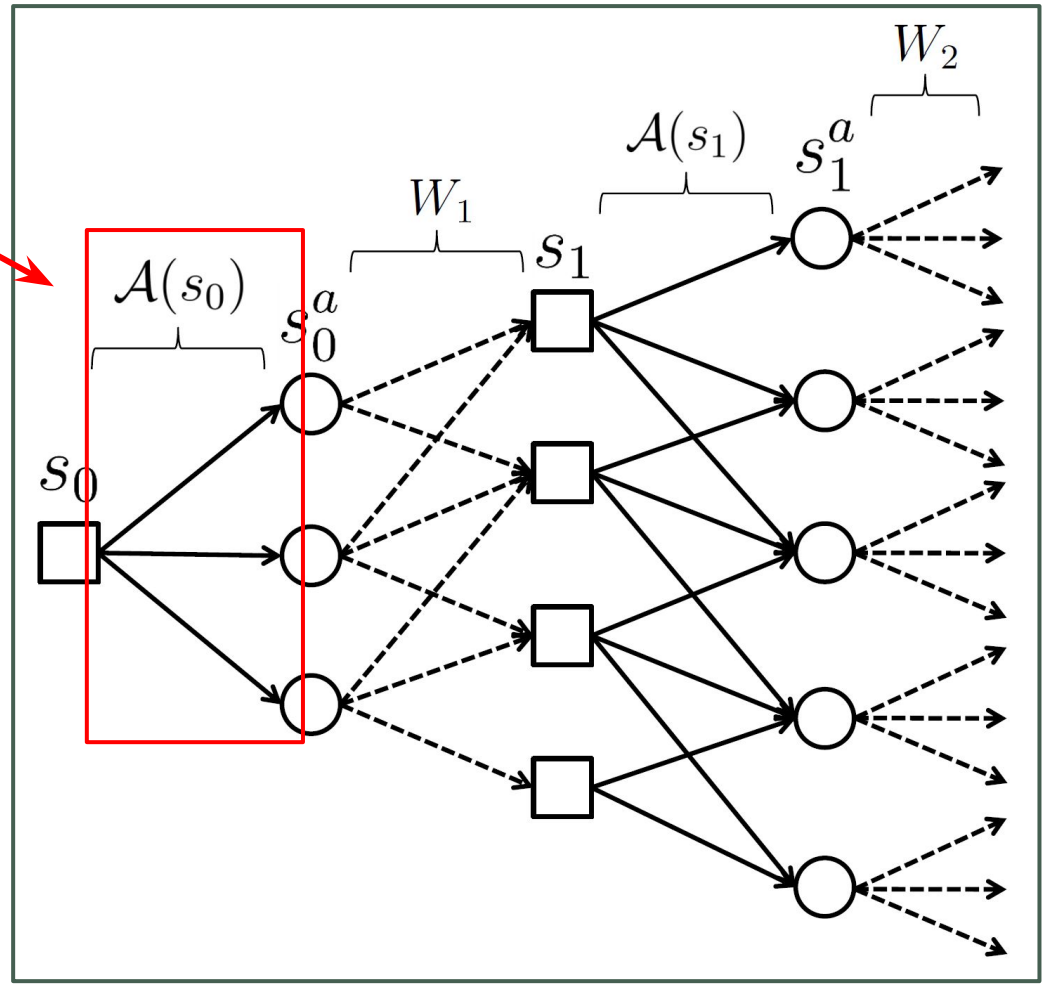
- States
  - State of charge (SoC)
  - Time
  - Location
  - Unvisited customers
  - Queue length



Dynamic Routing Model

Stochastic dynamic program

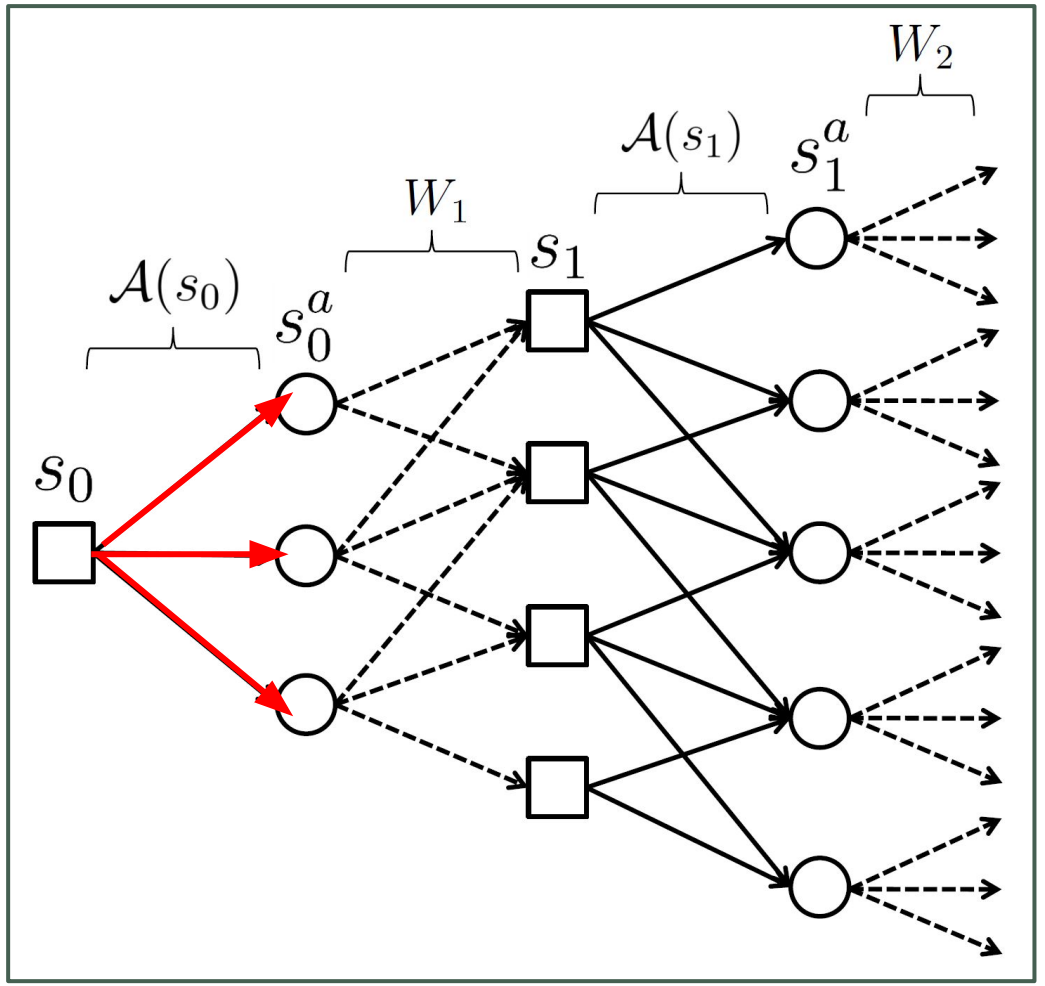
- States
- Action space
  - Move
  - Join queue & wait
  - Charge



Dynamic Routing Model

Stochastic dynamic program

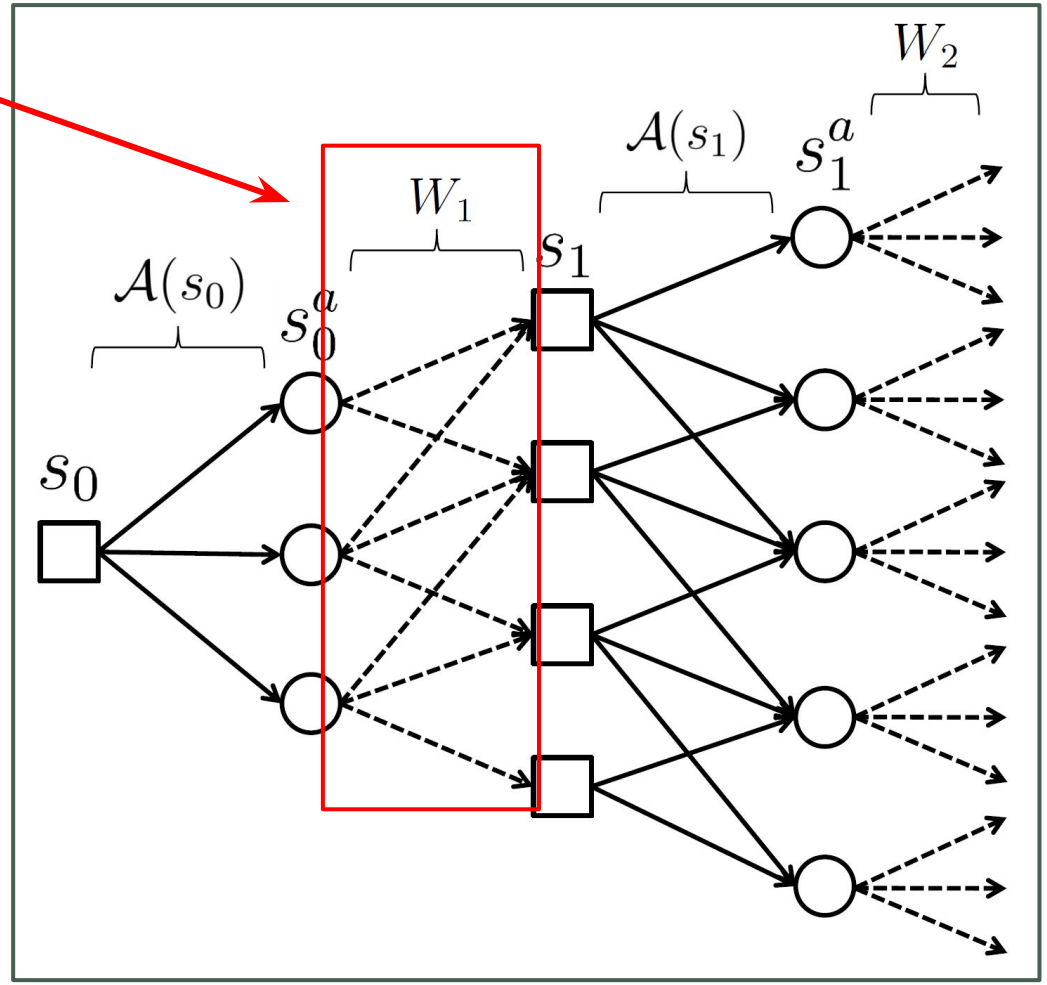
- States
- Action space
- Actions
  - Destination
  - SoC



Dynamic Routing Model

Stochastic dynamic program

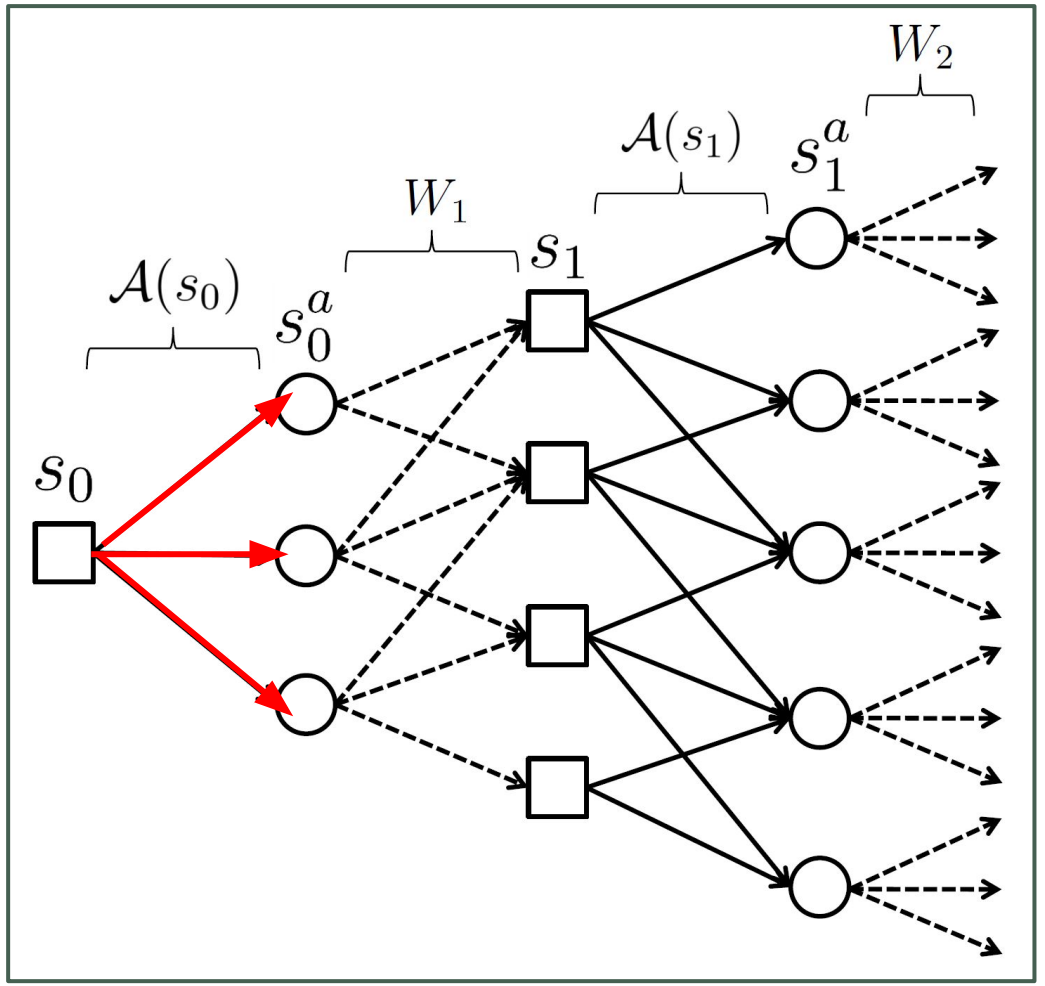
- States
- Action space
- Actions
- Exogenous information
  - Queue lengths (upon arrival to CS)
  - Time until we enter service (after electing to join queue)



Dynamic Routing Model

Stochastic dynamic program

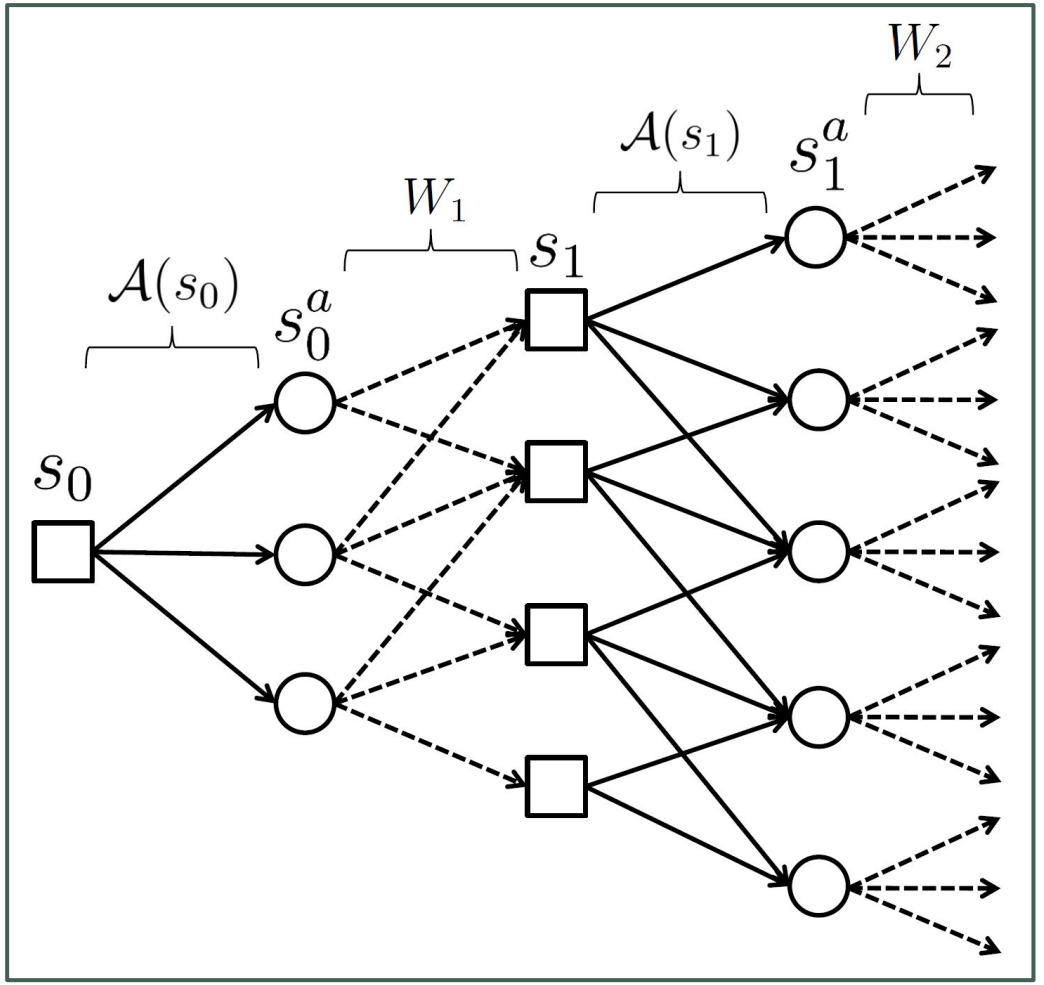
- States
- Action space
- Actions
- Exogenous information
- Contributions (costs)
  - Expected time until next epoch



Dynamic Routing Model

Stochastic dynamic program

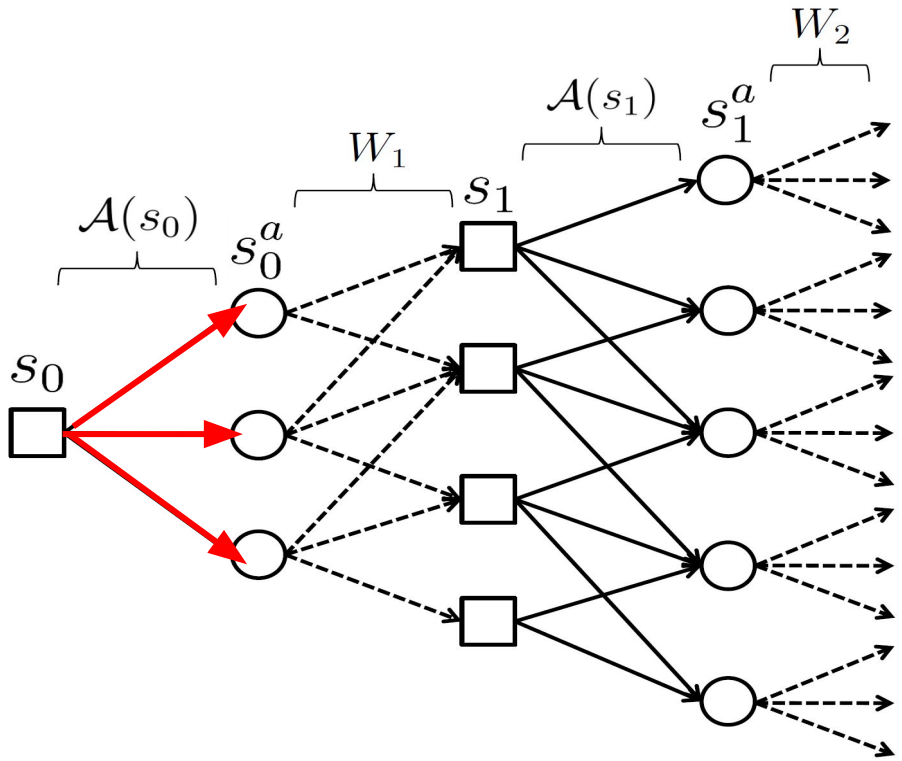
- States
- Action space
- Actions
- Exogenous information
- Contributions (costs)
- Objective function
  - Minimize expected time to reach terminal state



Solution methods: Policies

Solution methods

Policies - what is a policy?



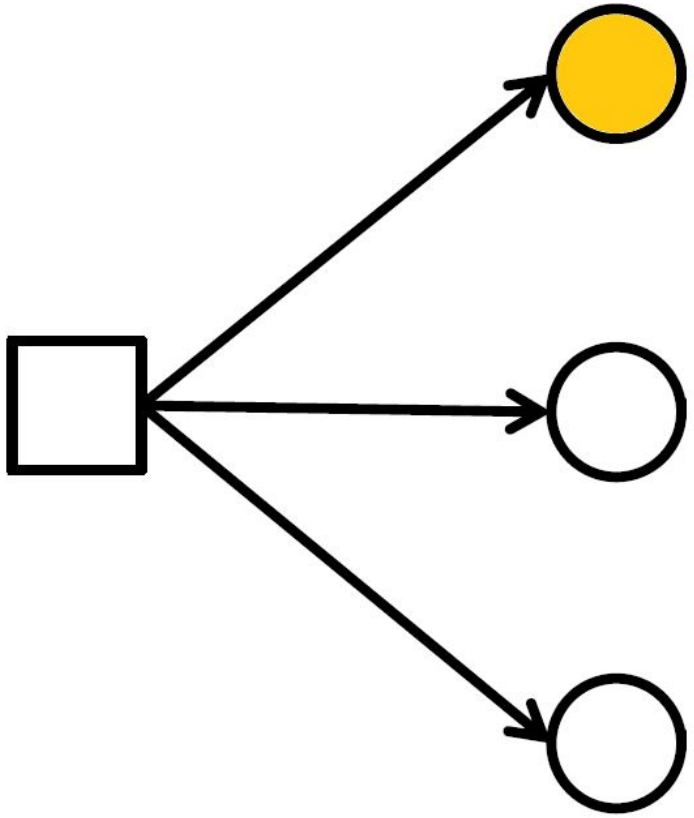
$$s_k \mapsto \mathcal{A}(s_k)$$

Solution methods

Policies	Type
1. Myopic	Dynamic
2. Rollout + myopic	Dynamic
3. Fixed route	Static
4. Rollout + fixed route	Dynamic

Solution methods

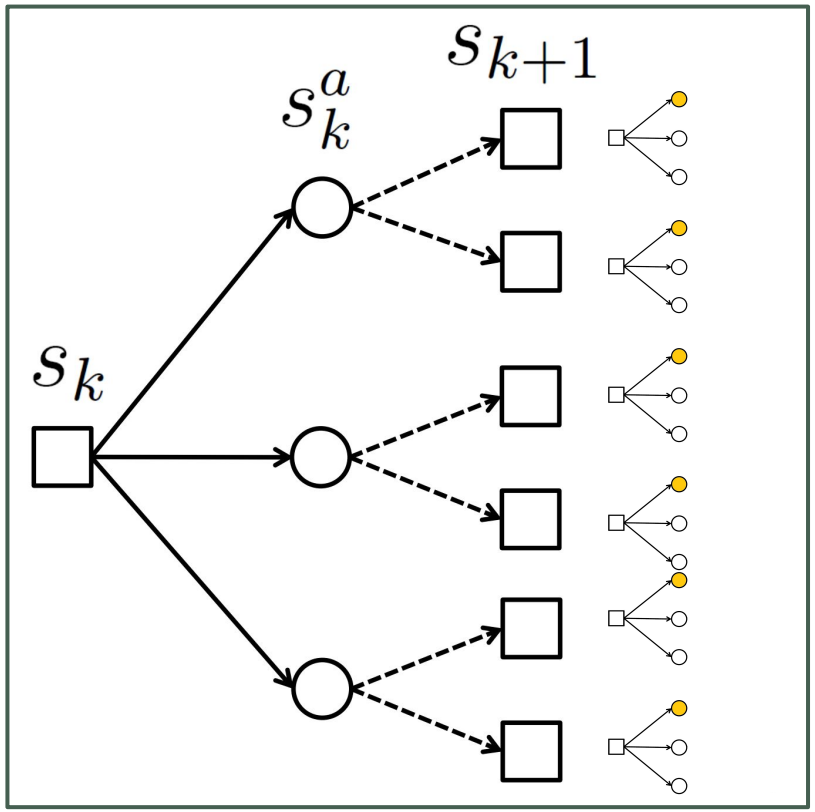
1) Myopic policy (dynamic)



$$\text{argmin}_a\{C(s_k, a)\}$$

Solution methods

2) One-step rollout with myopic base policy (dynamic)



$$\text{argmin}_a \left\{ C_k(s_k, a) + \mathbb{E}\left[\sum_{i=k+1}^{K} C_i\left(s_i, \delta_i^{\pi_{\mathcal{H}}(s_{k+1})}\right) \,\middle|\, s_k \right] \right\}$$

Solution methods

3) Fixed Route Policy

- Static (non-dynamic) policy
- Fix sequence of customers and charging stations
- Policy:
  - Follow tour, charge, wait as required

Solution methods

3) Fixed Route Policy - fixing sequence

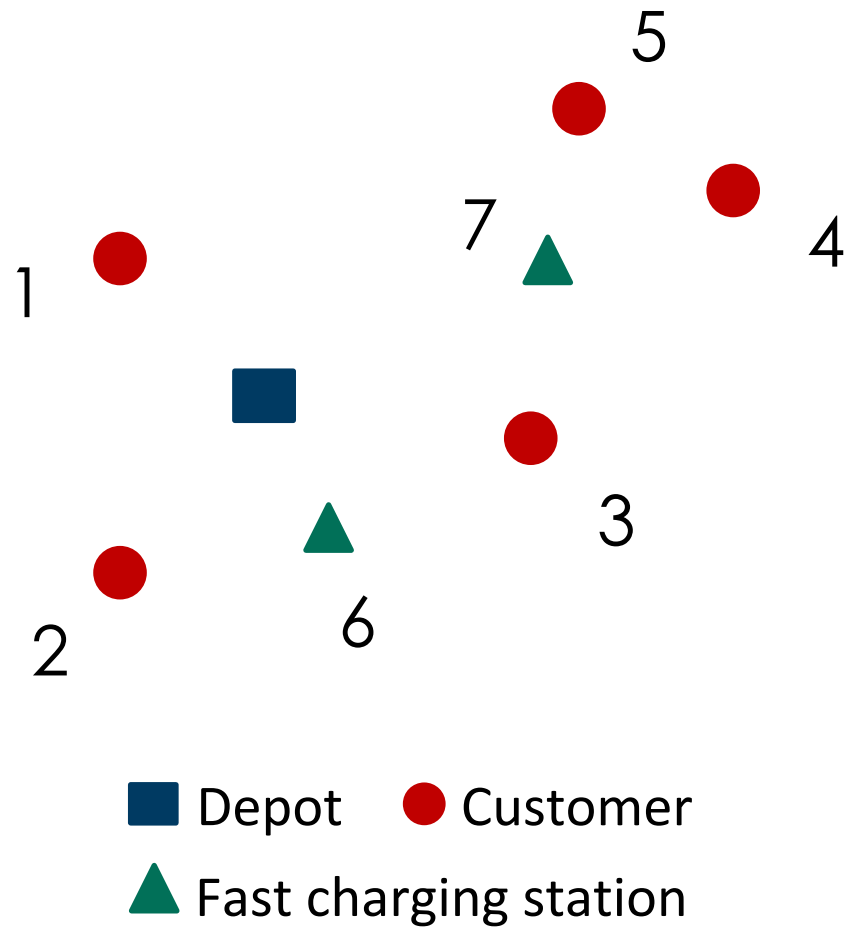
Initial state s_0

Nodes

Depot {0}

Customer set {1,2,3,4,5}

CS set {6,7}

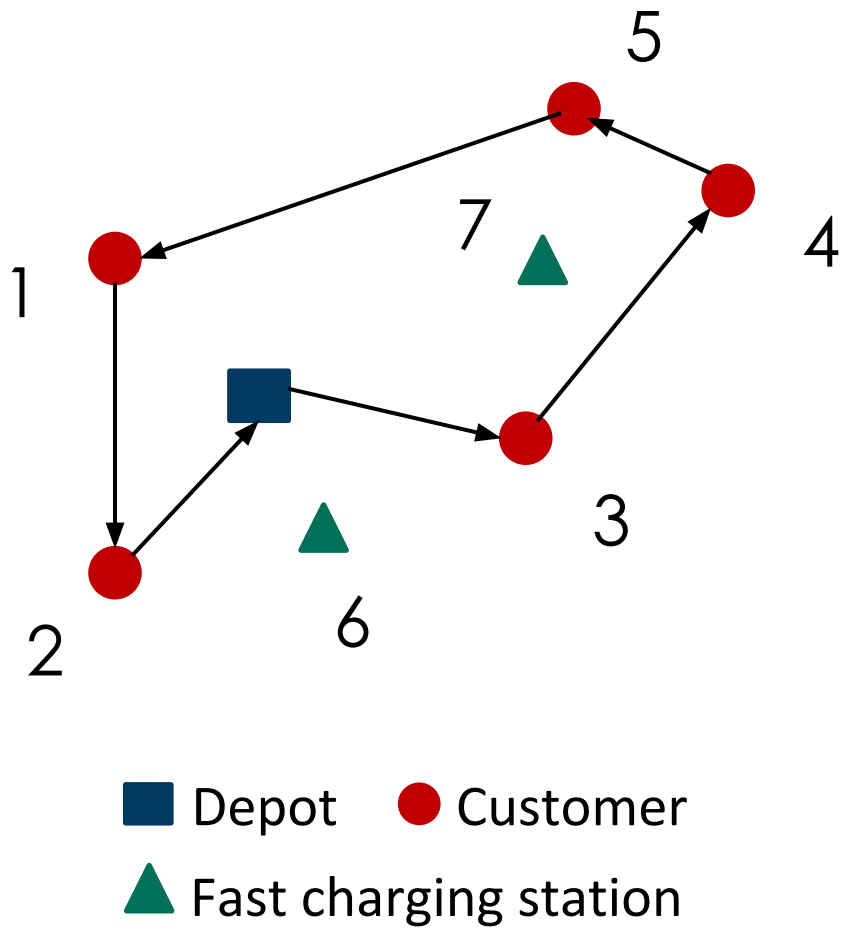


Solution methods

3) Fixed Route Policy - fixing sequence

Heuristic search:

Customer sequence 0-3-4-5-1-2-0



Solution methods

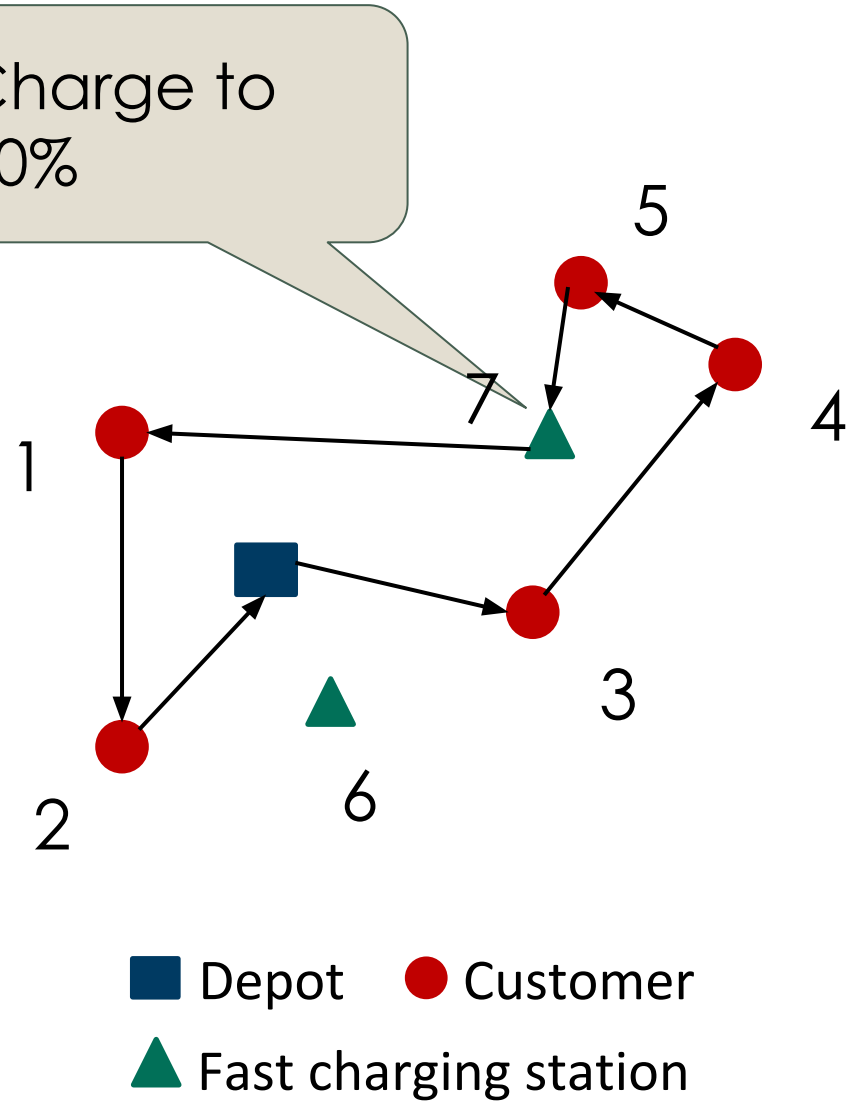
3) Fixed Route Policy - fixing sequenc

Heuristic search:

Customer sequence 0-3-4-5-1-2-0

Mid-route recharging MIP:

Energy feasible 0-3-4-5-**7**-1-2-0



Solution methods

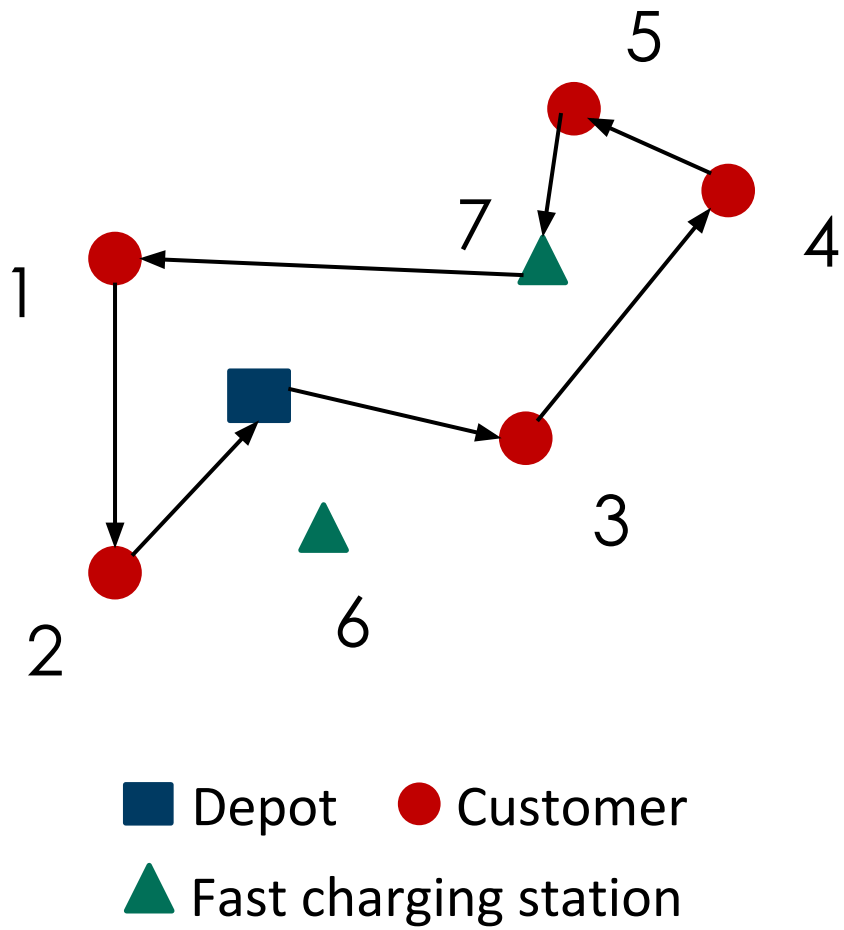
3) Fixed Route Policy - fixing sequence

Heuristic search:

Customer sequence 0-3-4-5-1-2-0

Mid-route recharging MIP:

Energy feasible 0-3-4-5-**7**-1-2-0



Policy:

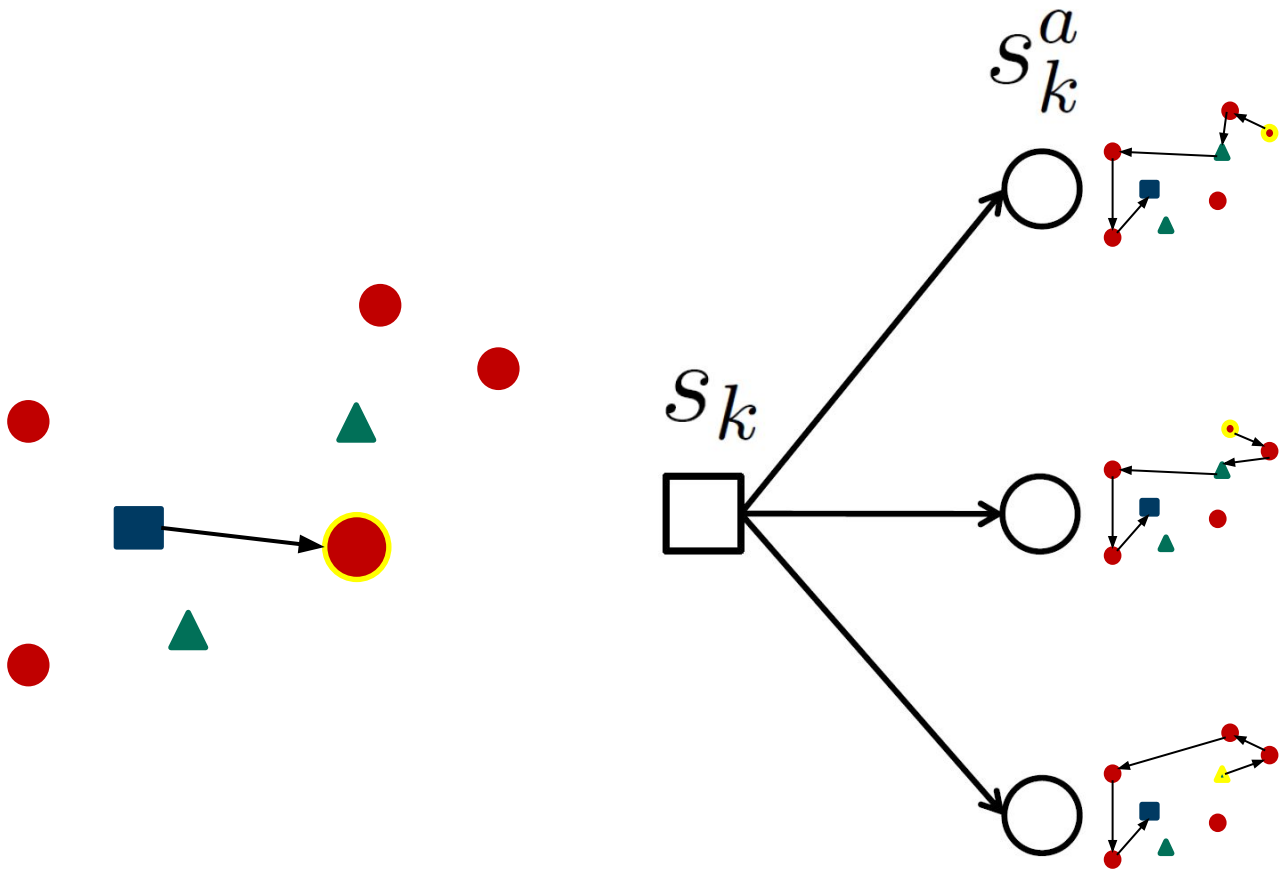
- Follow tour, charge, wait as required

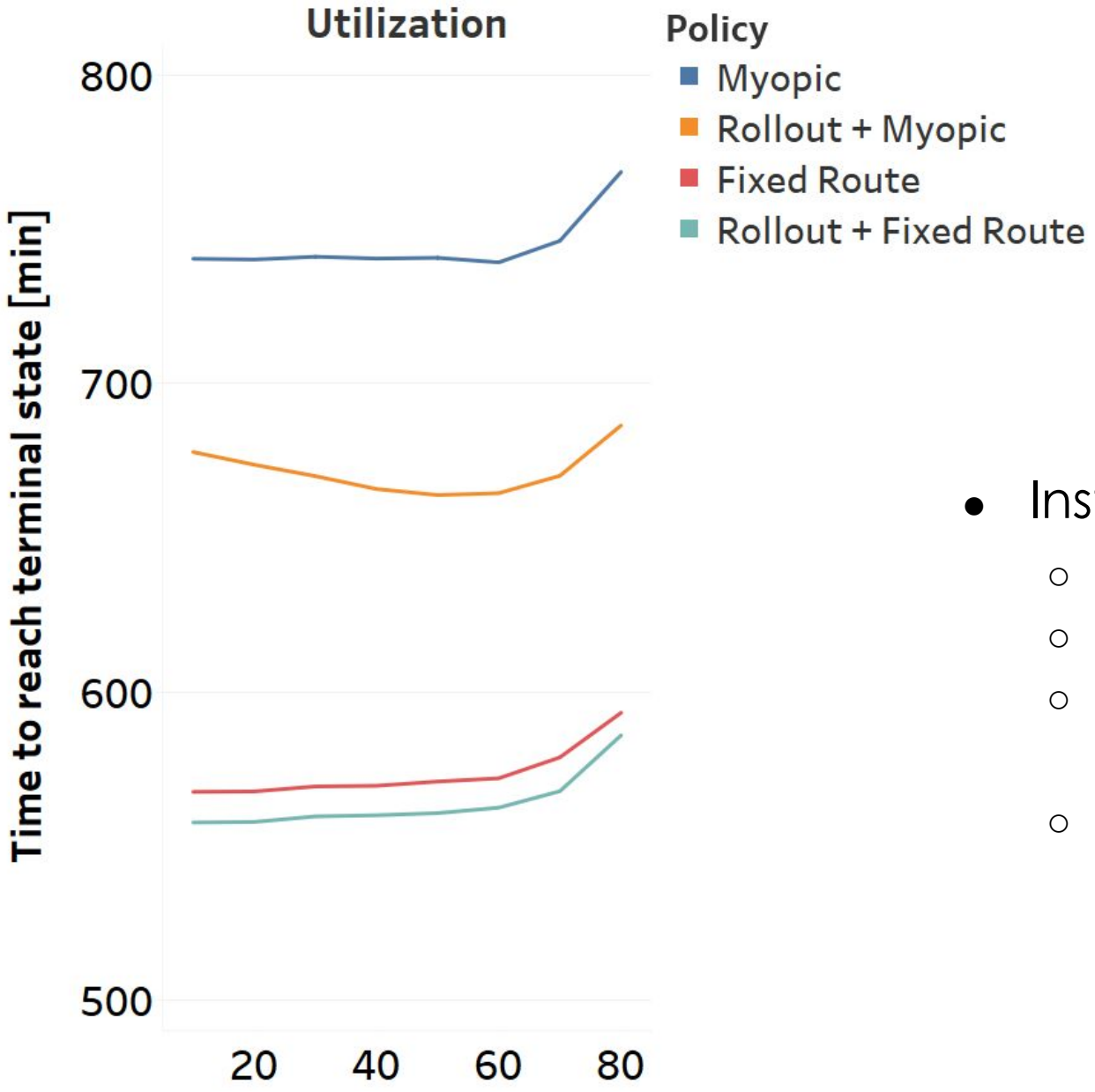
Solution methods

4) Post-decision rollout with fixed-route base policy

Solution methods

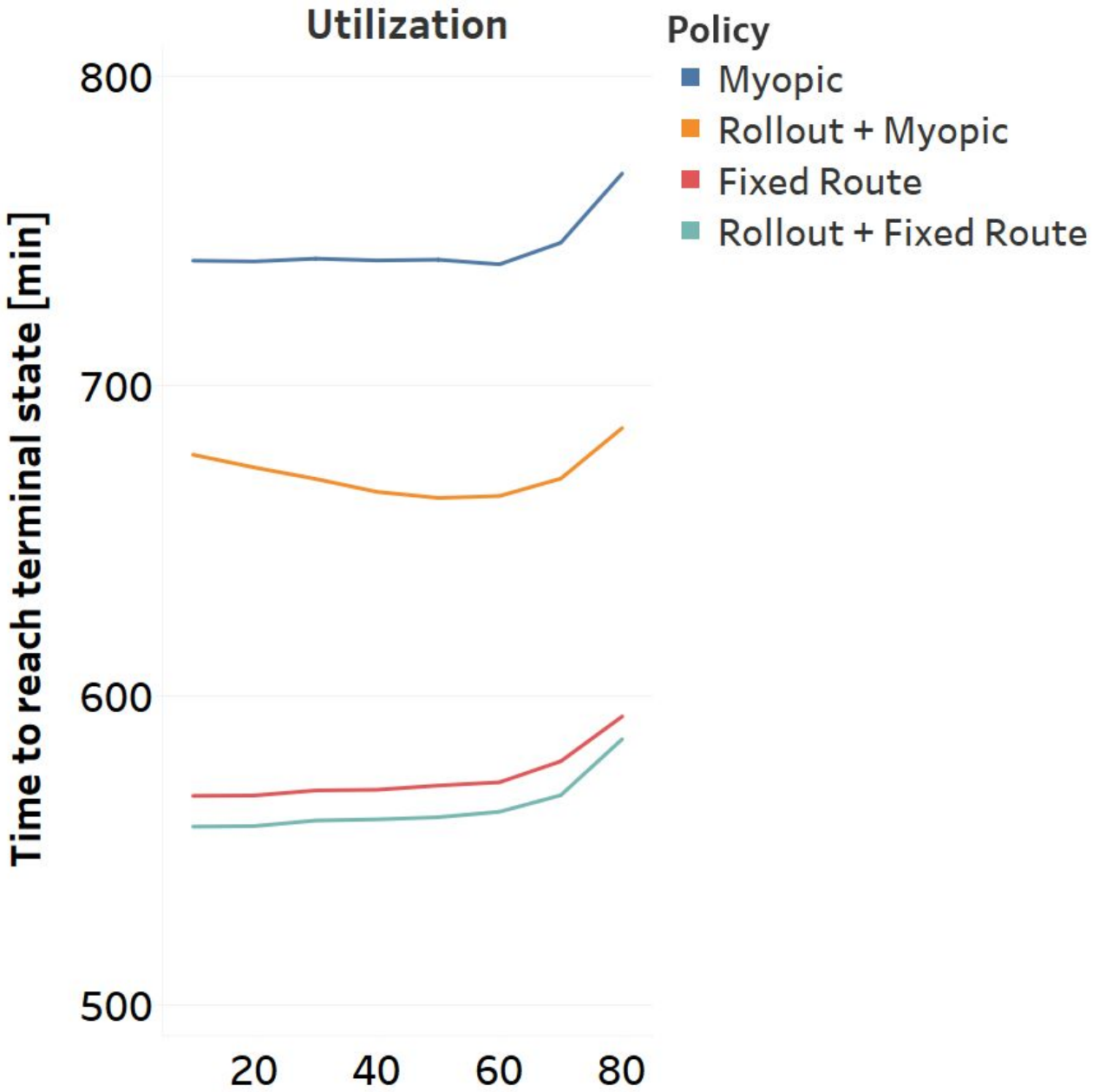
4) Post-decision rollout with fixed-route base policy

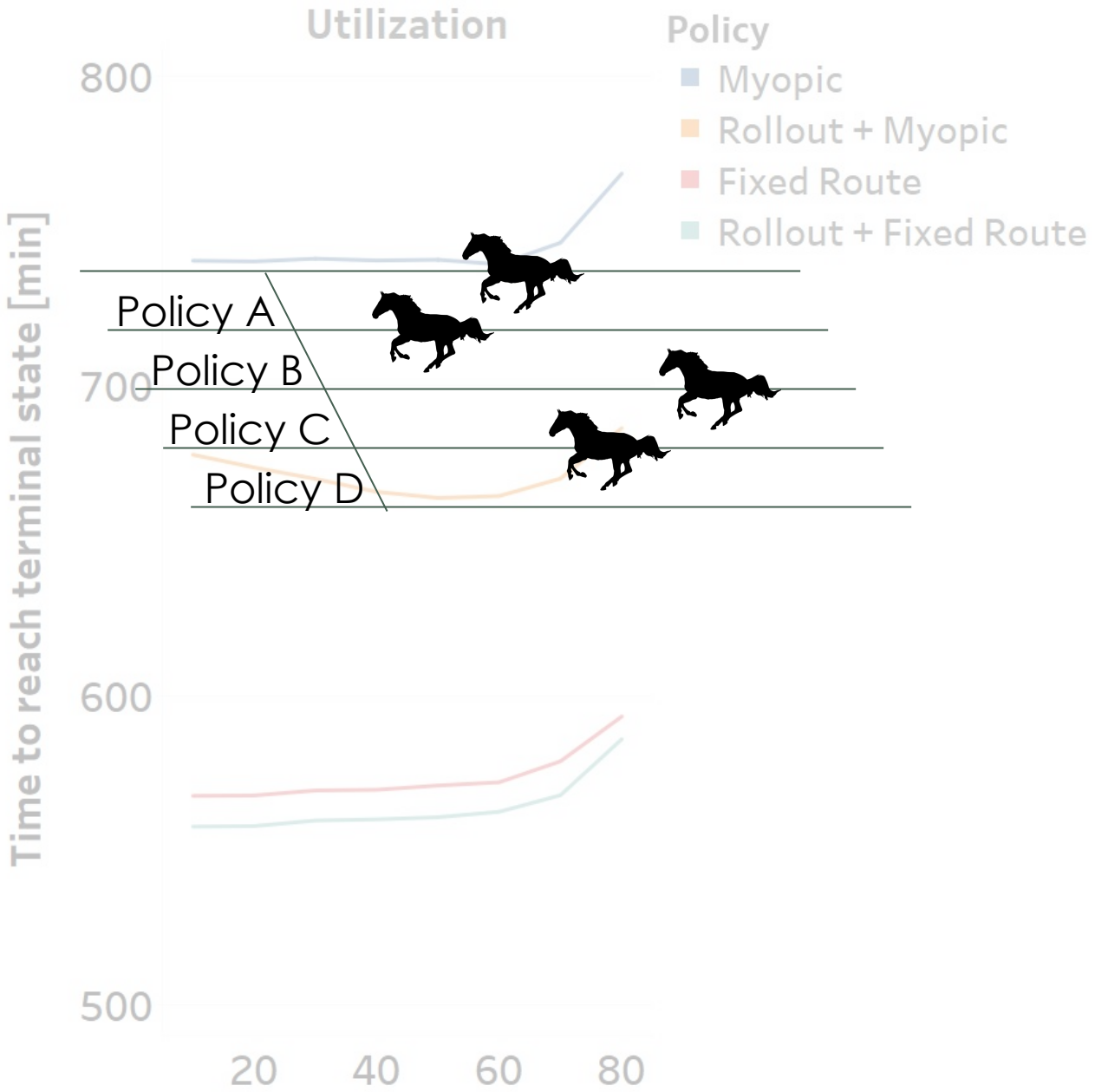


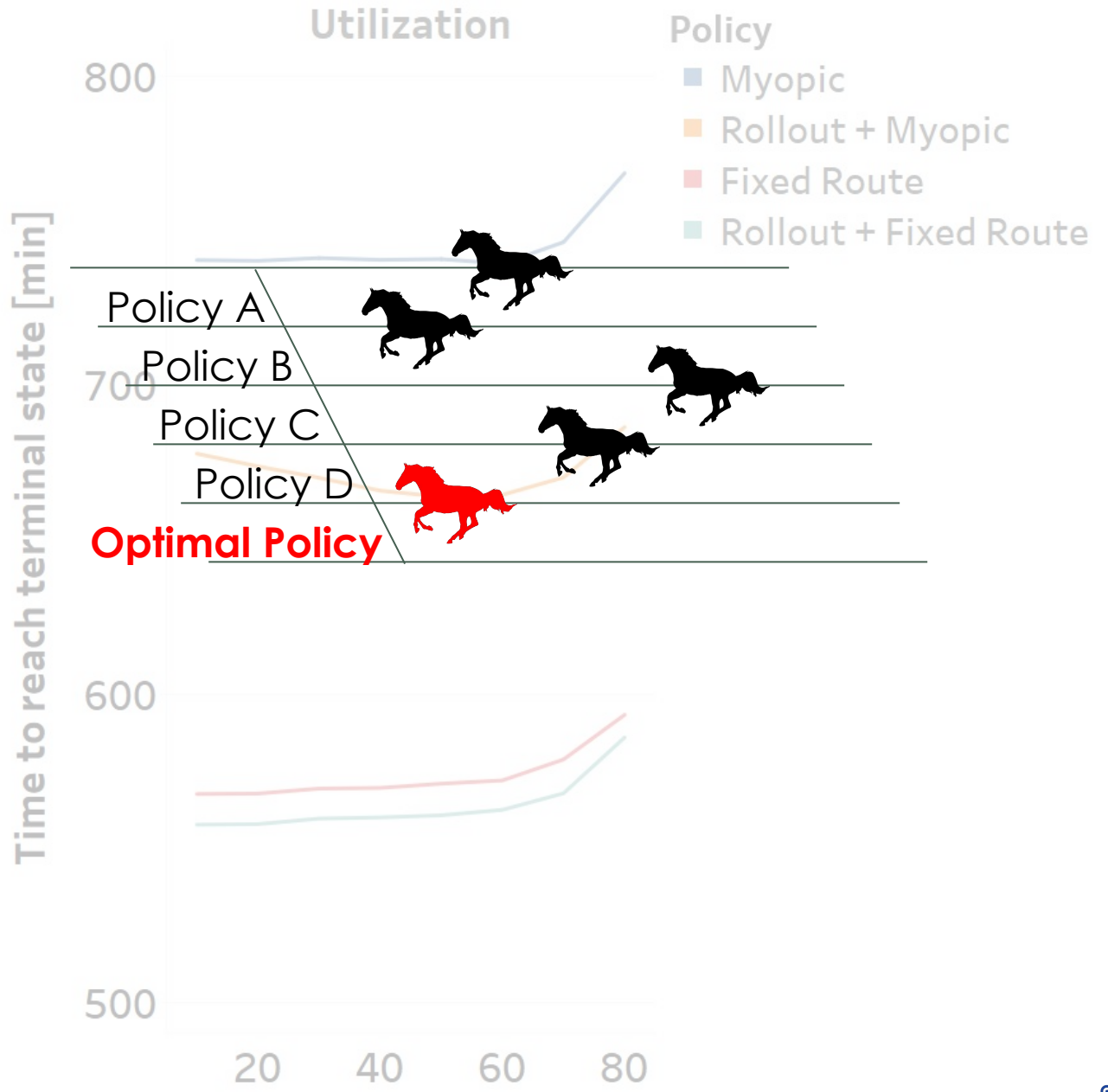


- Instances:
  - 10-20 customers
  - 2-3 CSs
  - 3 customer location methods (random, clustered, mixed)
  - 8 levels of utilization (10%, 20%, ..., 80%)

Derivation of lower bounds: Information relaxation


Utilization
Policy
Myopic
Rollout + Myopic
Fixed Route
Rollout + Fixed Route
Time to reach terminal state [min]
800
700
600
500
20
40
60
80


Utilization
Policy
Myopic
Rollout + Myopic
Fixed Route
Rollout + Fixed Route
Time to reach terminal state [min]
800
700
600
500
20
40
60
80
Policy A
Policy B
Policy C
Policy D


Utilization
Policy
Myopic
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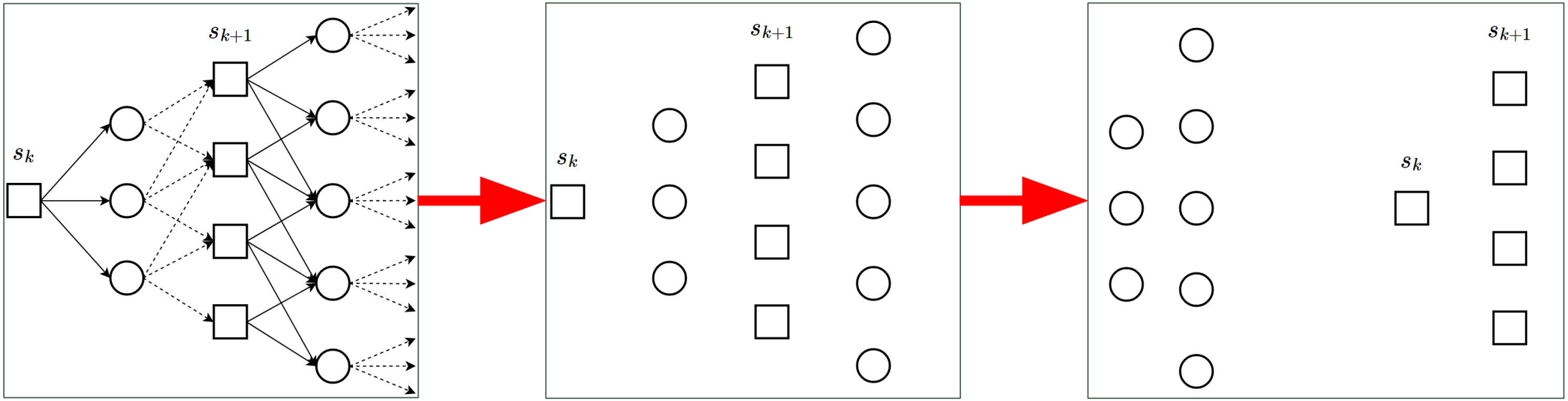
Fixed Route
Rollout + Fixed Route
Time to reach terminal state [min]
800
700
600
500
20
40
60
80
Policy A
Policy B
Policy C
Policy D
Optimal Policy

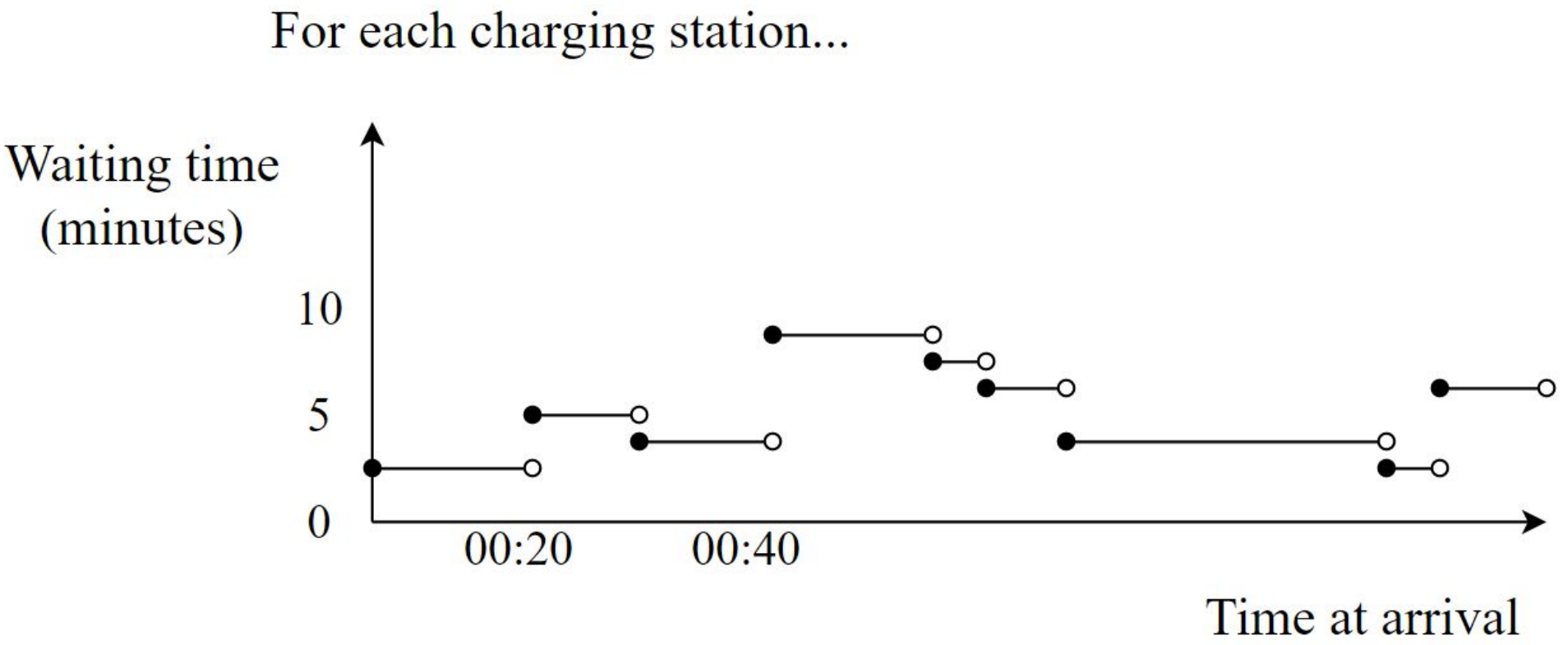
Information relaxation

Perfect information



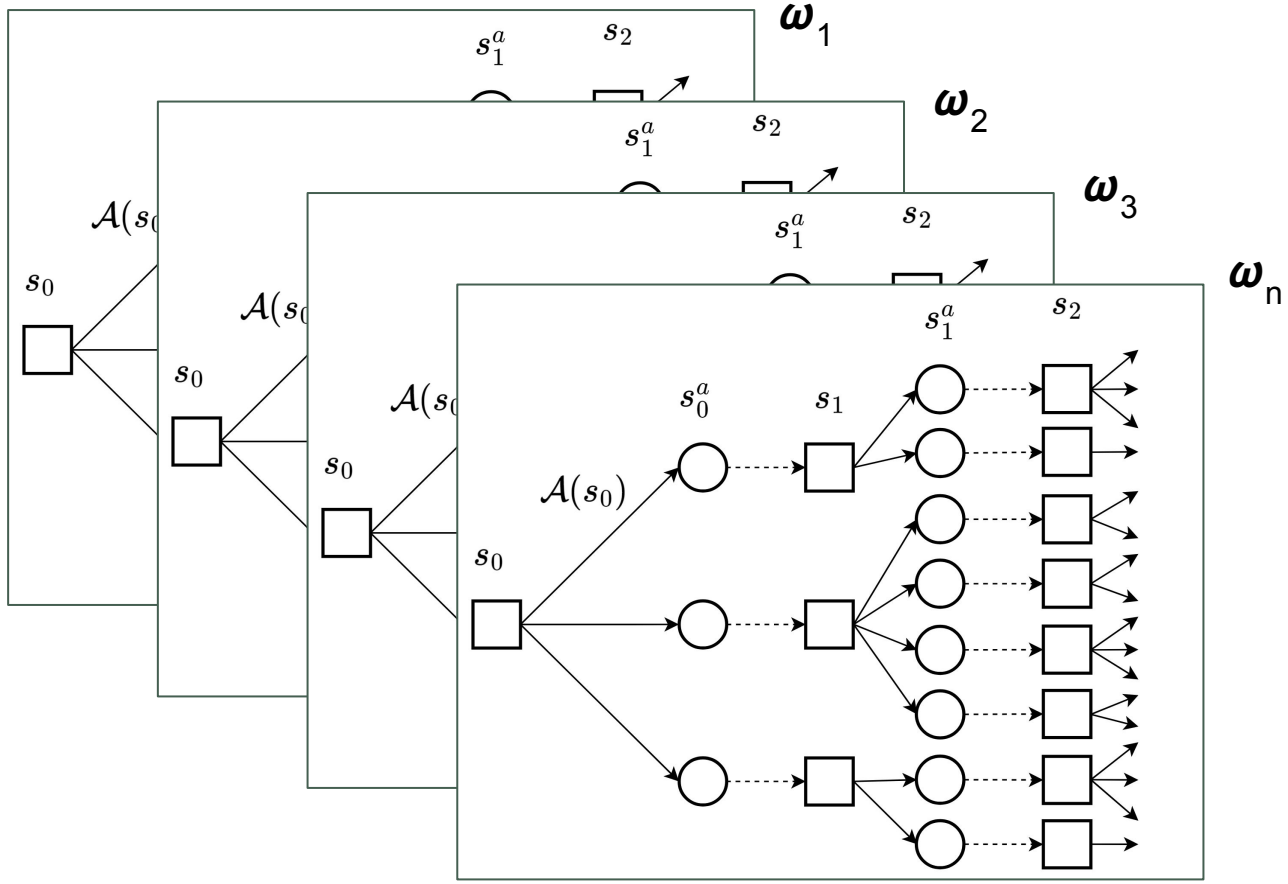
Information relaxation

What does perfect information look like?



Information relaxation

Solving for optimal solution with perfect information



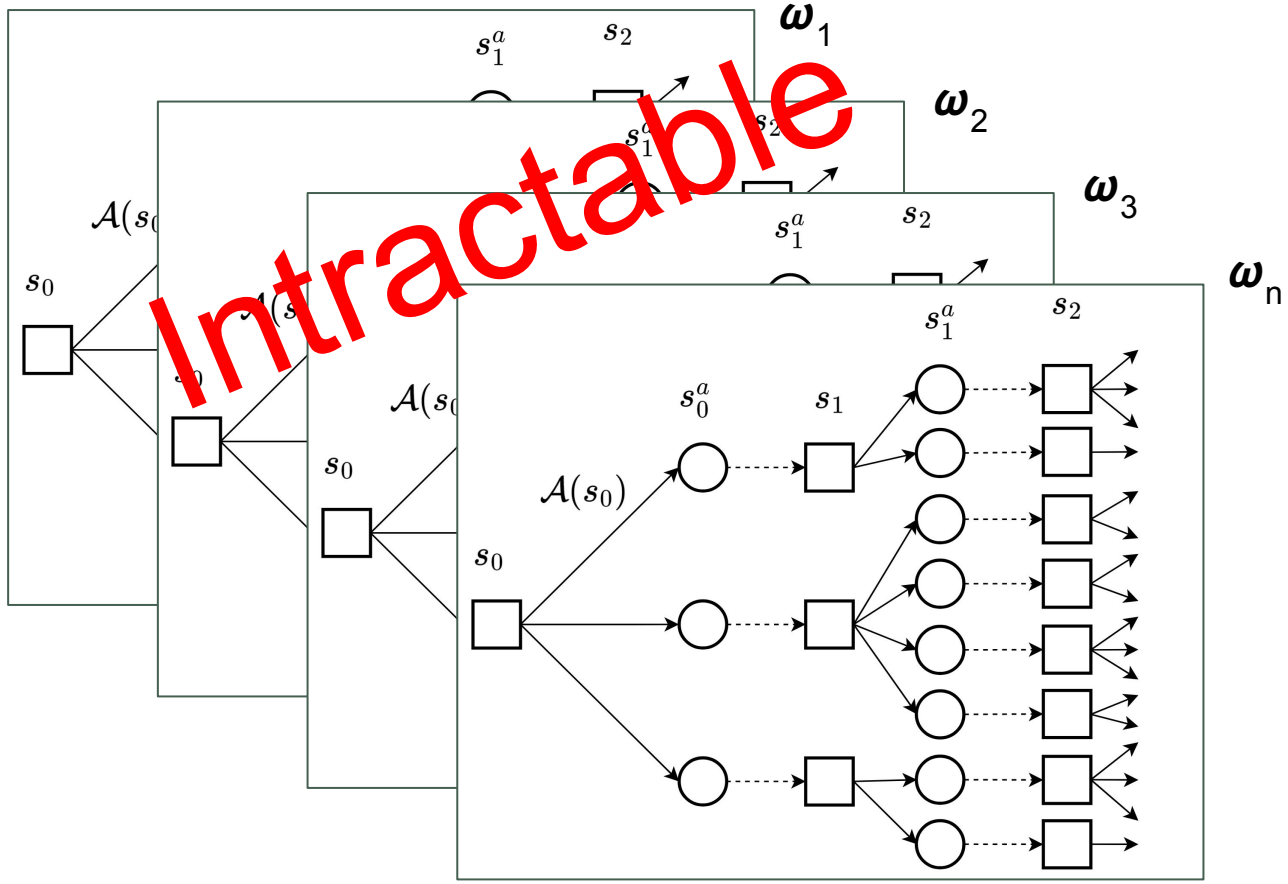
For *n* realizations:

- Build tree, solve recursively

Average results to get unbiased estimator of objective with perfect information

Information relaxation

Solving for optimal solution with perfect information



For *n* realizations:

- Build tree, solve recursively

Average results to get unbiased estimator of objective with perfect information

Information relaxation

Solving for optimal solution with perfect information

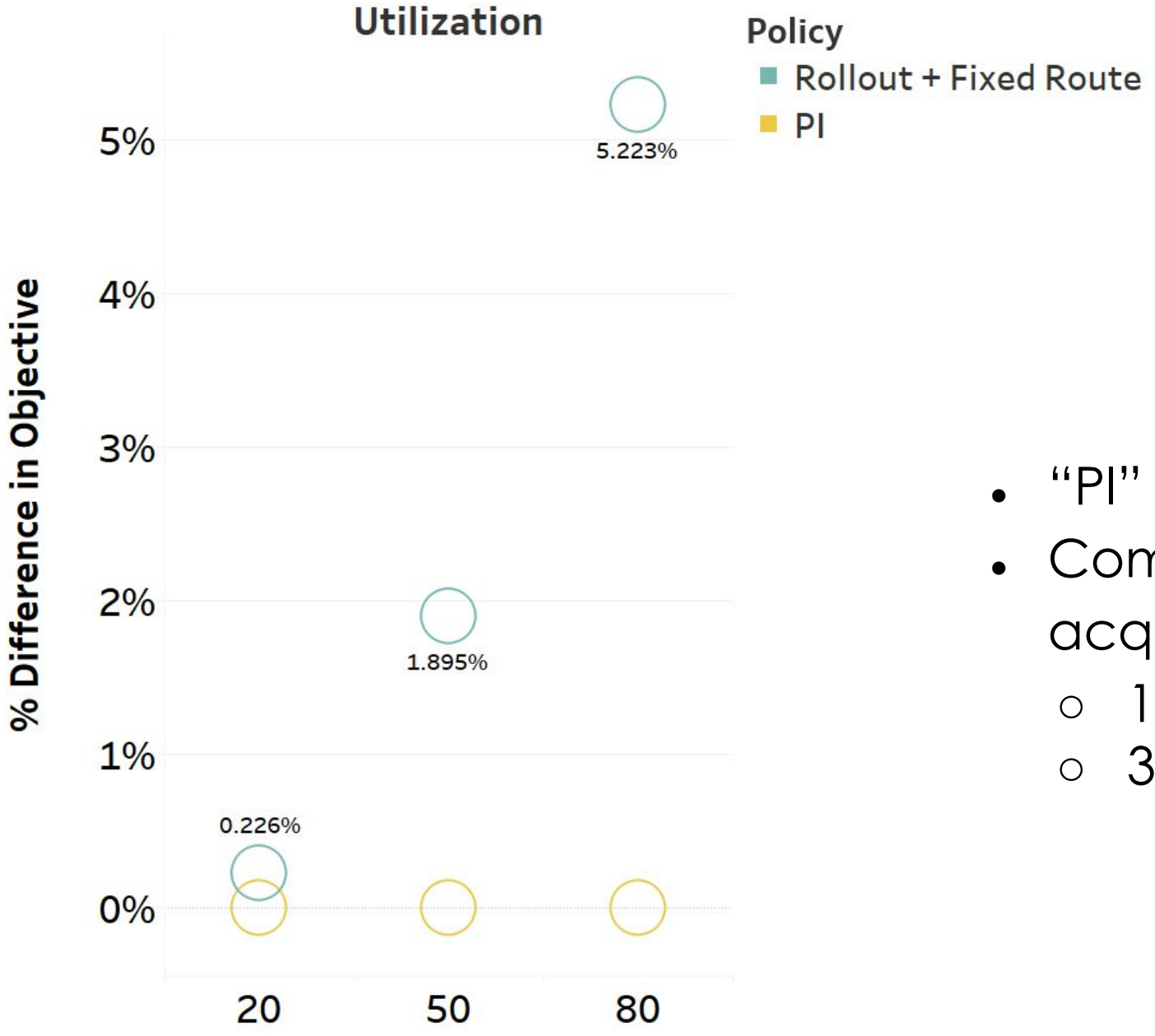
Alternatively, we can formulate an equivalent MIP

Information relaxation

Solving for optimal solution with perfect information

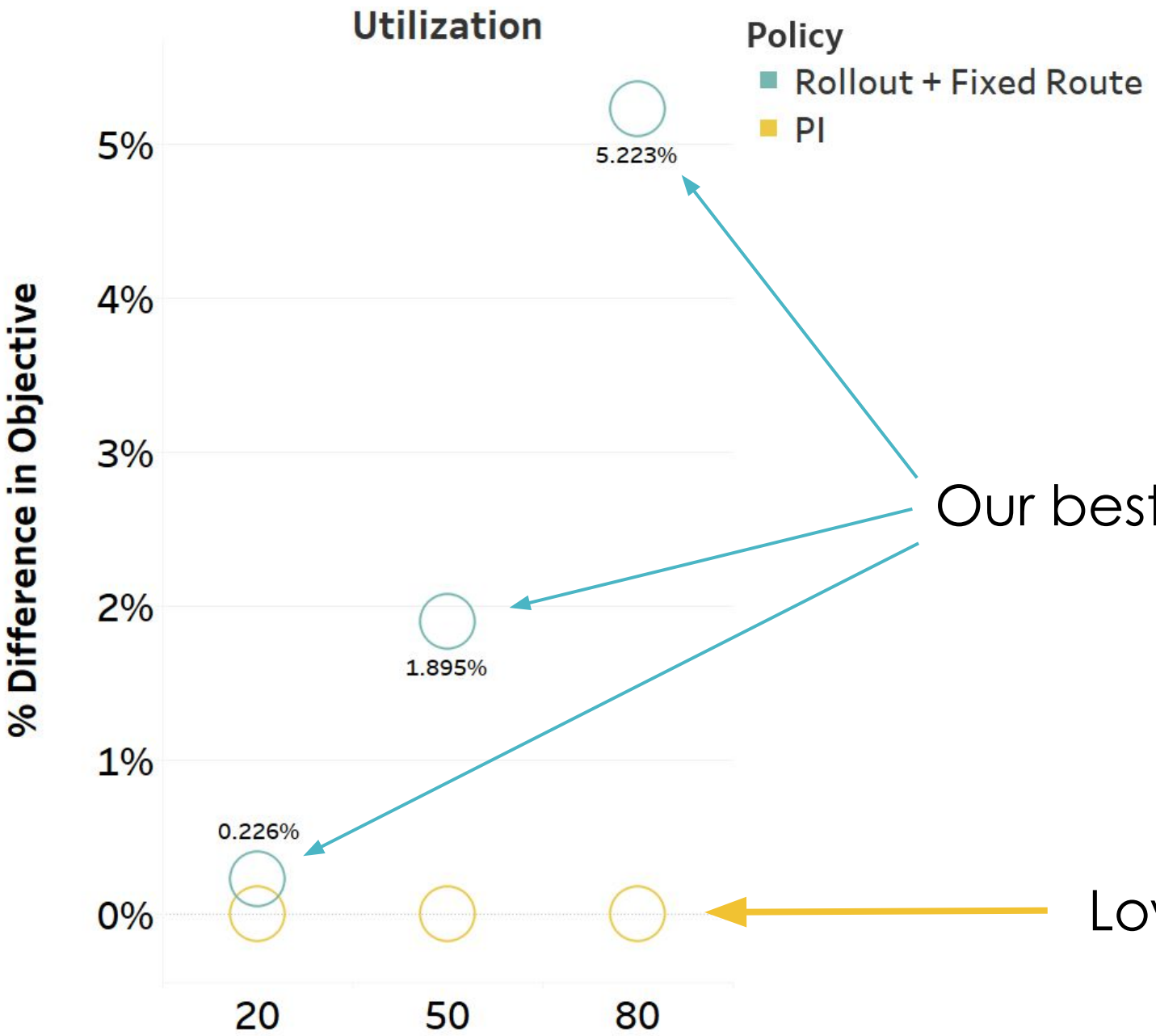
Alternatively, we can formulate an equivalent MIP

- Minimize expected time to reach terminal state
  (visit all customers, return to depot)
- TSP with charging/waiting decisions



- "PI" = Perfect Information
- Computationally intensive to acquire
  - 10 customers, 2 CSs
  - 3 levels of utilization

Tightening lower bound: Information penalties

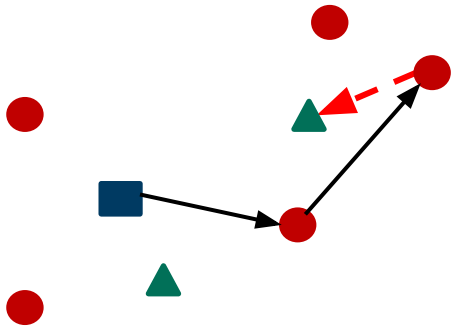


Our best dynamic policy

Poor policy or loose bound?

Lower bound

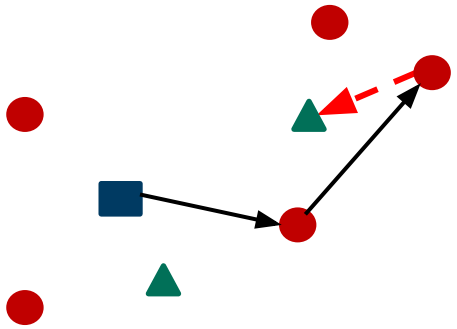
Information penalties



Information penalties

I think I'll have to wait 25 min

I can tell you… For a price



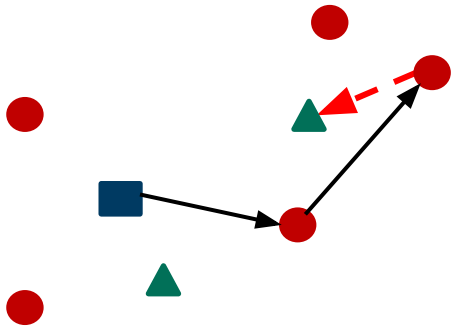
Information penalties

I think I'll have to wait 25 min

$$

"40 min"

I can tell you… For a price



Information penalties

Naturally available to DM

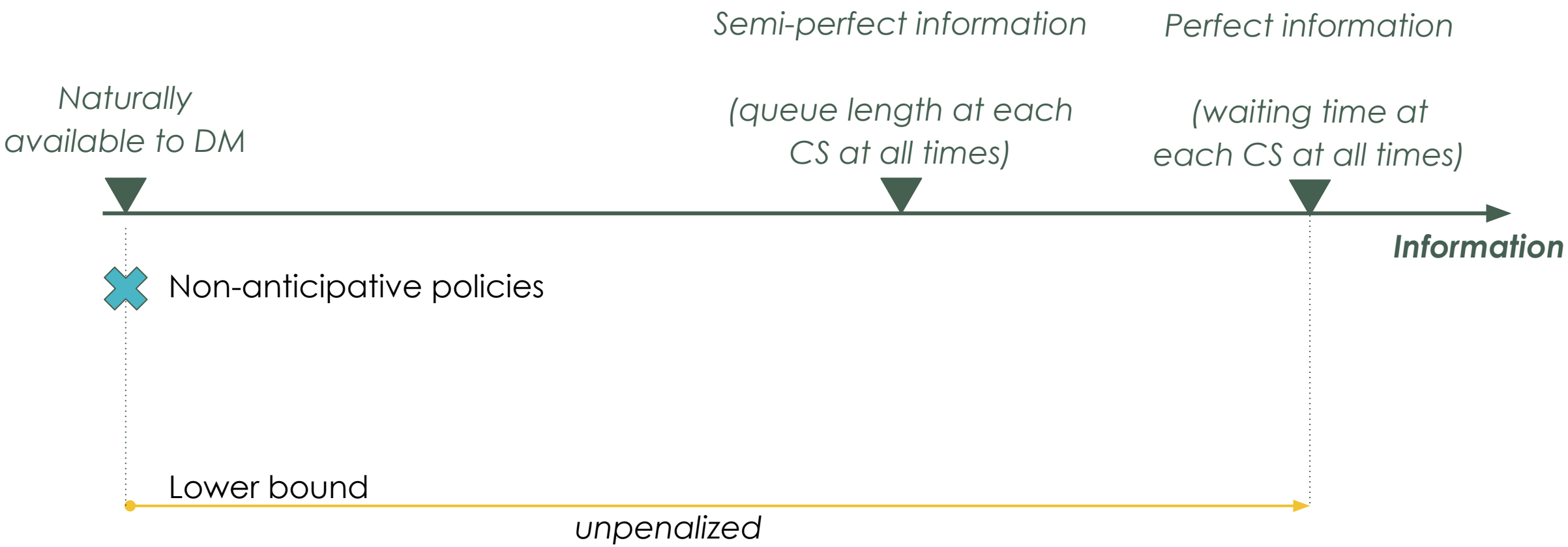
Information

Information penalties

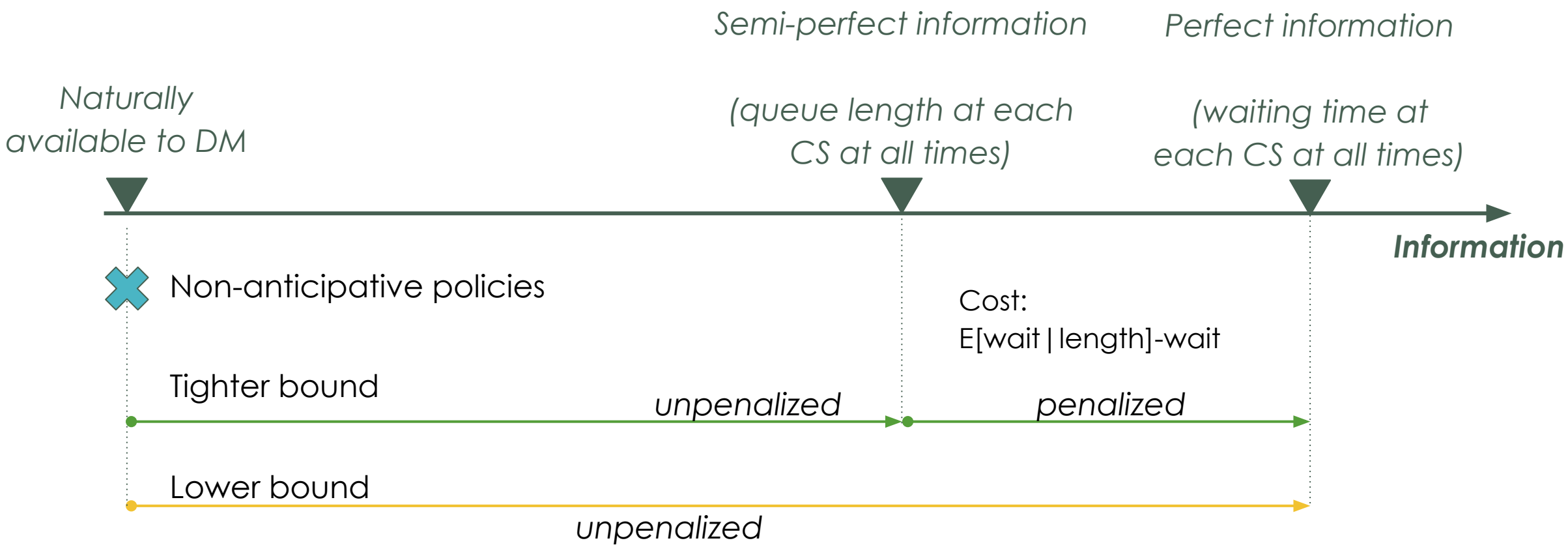
Information penalties

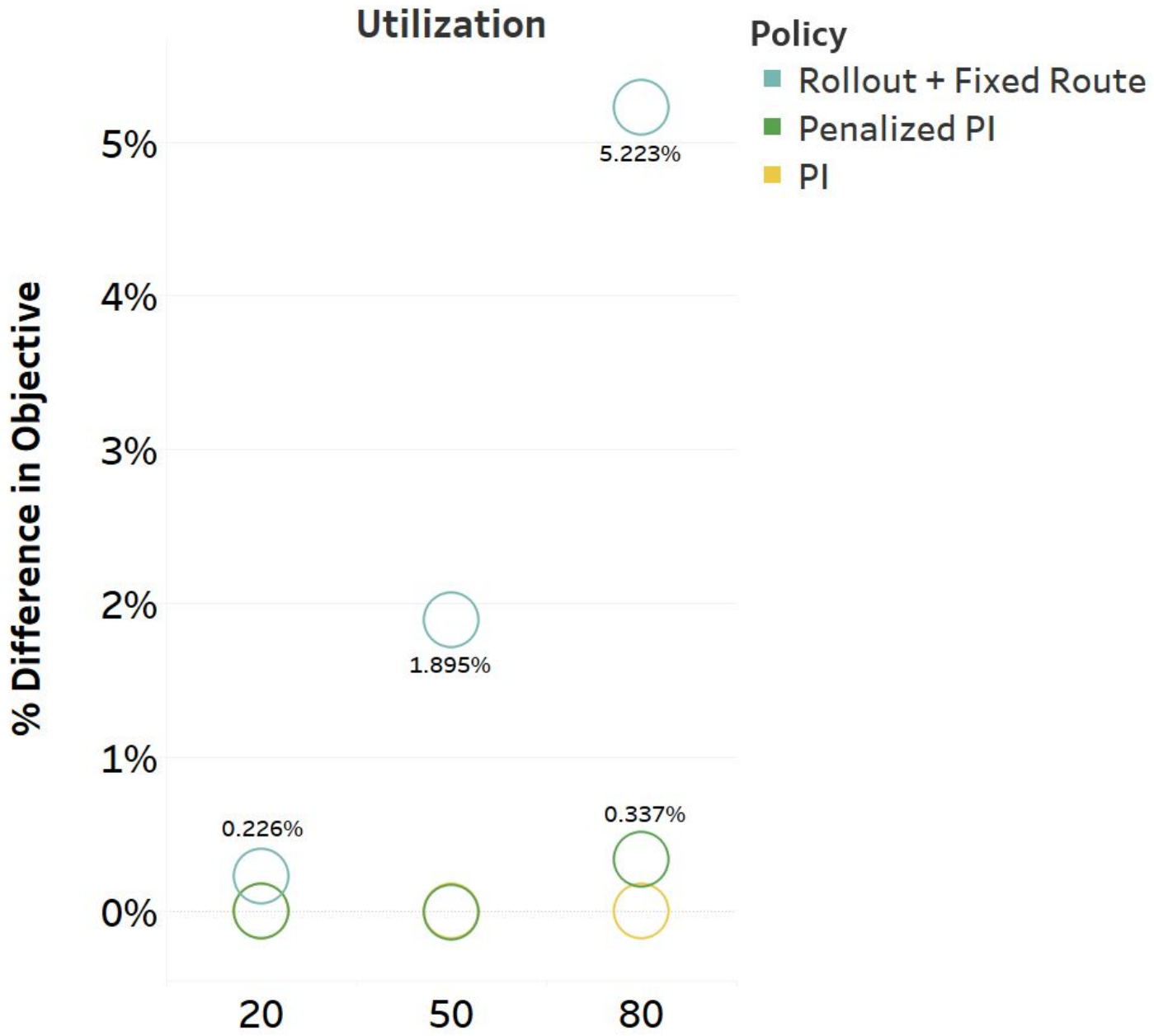
Information penalties

Information penalties



Information penalties




Utilization
Policy
Rollout + Fixed Route
Penalized PI
PI
% Difference in Objective
5%
4%
3%
2%
1%
0%
5.223%
1.895%
0.226%
0.337%
20
50
80

Summary

Summary

- Introduced and solved new eVRP variant
- Derived lower bounds for dynamic routing model
- Imposed penalties to tighten lower bounds
- Showed for subset of problem instances that our policies perform within 5% of the optimal policy

Thank you