UNIVERSITY OF TWENTE.

LONG-HAUL FREIGHT SELECTION FOR LAST-MILE COST REDUCTION

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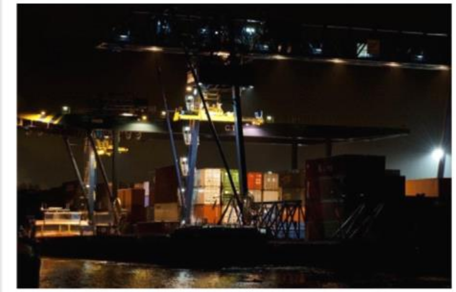
OUTLINE

- Case introduction
- The long-haul freight selection problem
- Solution approaches
  - *Mixed-Integer Linear Programming*
  - *Dynamic Programming*
  - *Approximate Dynamic Programming*
- Our approach
- What to remember


MAERSK
MAERSK

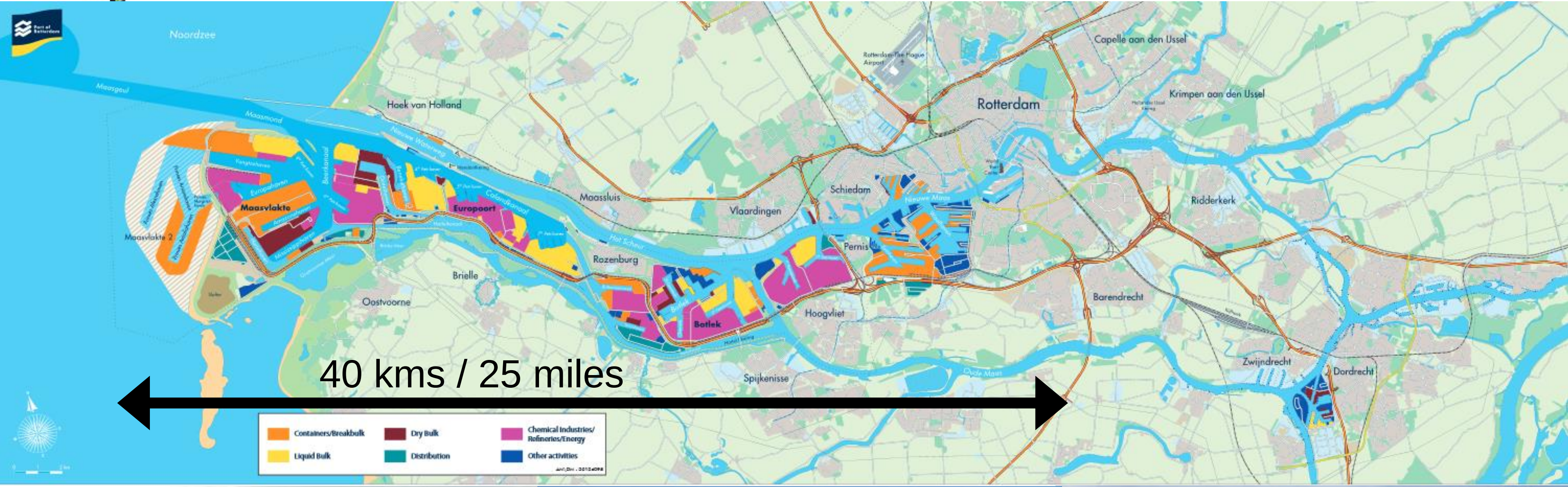

MAERSK
CHINA SHIPPING


FIGEE
CTT
LYS-LINE
LYS-LINE
ZALTBOMMEL
CTT
INTERMODAAL TRANSPORT

THE COMPANY

CTT INTERMODAAL TRANSPORT

- Core business is the transportation of ***containers to and from Rotterdam***.
- Long-haul of the transportation is done ***using barges through Dutch waterways***.
- More than 150k containers per year (more than 300 per day).
- There are 30 terminals regularly visited in Rotterdam.



Noordzee
Hoek van Holland
Rotterdam
Capelle aan den IJssel
Krimpen aan den IJssel
Maasvlakte
Maasvlakte 2
Europoort
Maassluis
Schiedam
Vlaardingen
Ridderkerk
Pernis
Rozenburg
Brielle
Oostvoorne
Botlek
Hoogvliet
Barendrecht
Spijkenisse
Zwijndrecht
Dordrecht
40 kms / 25 miles
Containers/Breakbulk
Dry Bulk
Chemical Industries/ Refineries/Energy
Liquid Bulk
Distribution
Other activities

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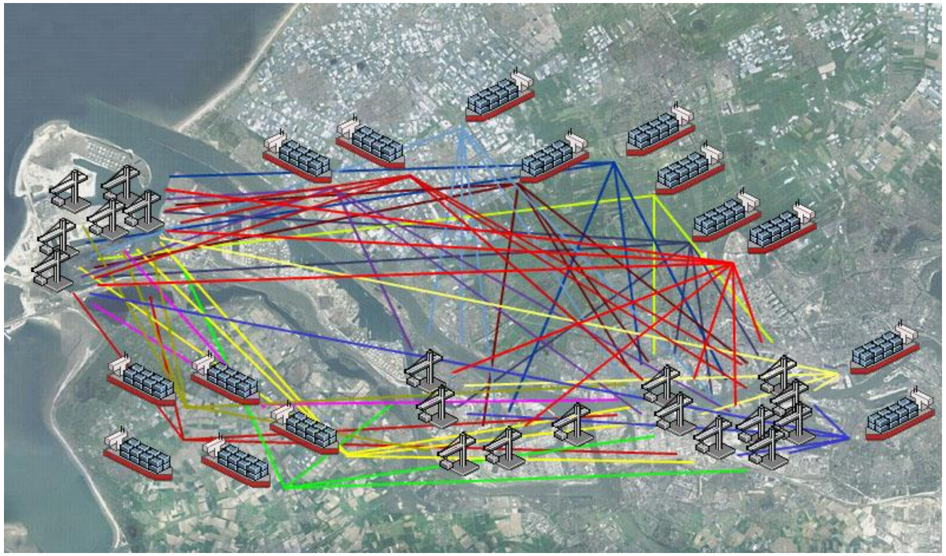
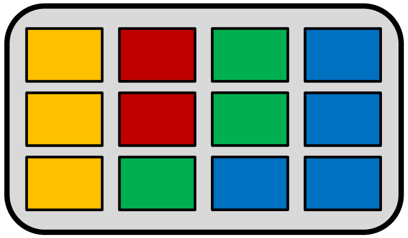
THE COMPANY'S COMPLAINT

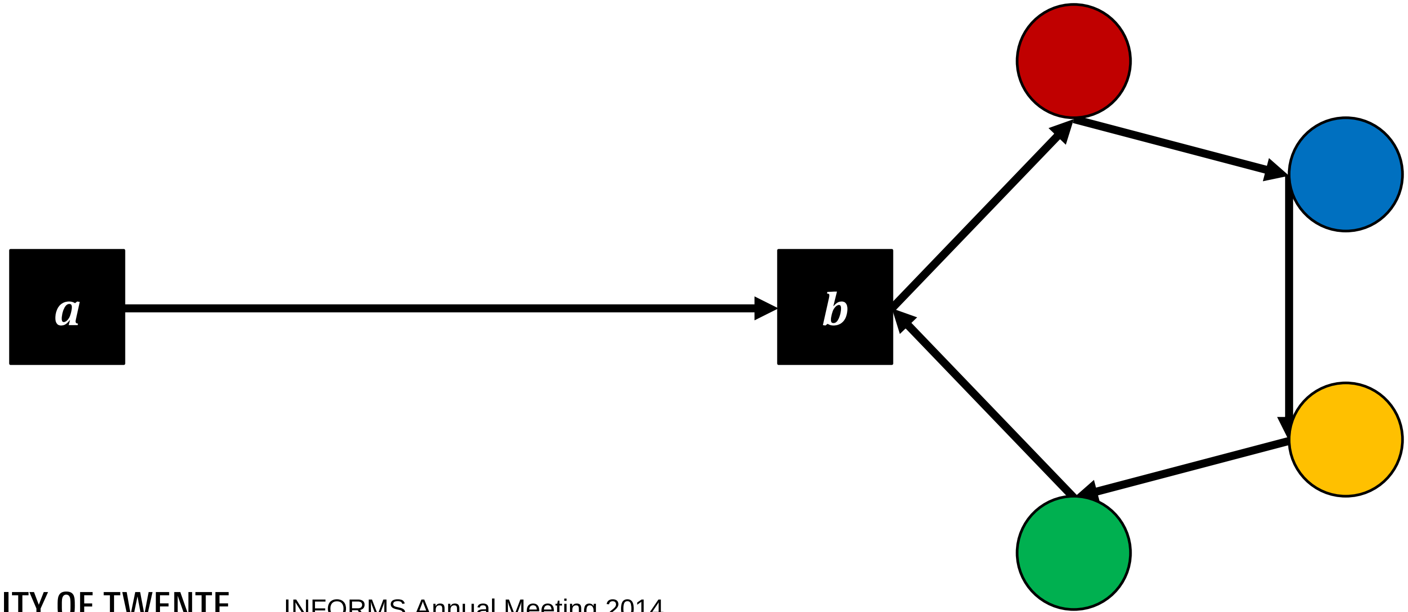
- Barges spend around two days ***waiting and sailing between terminals in Rotterdam*** due to changes in appointments (e.g., unavailable berths, deep sea vessel arrival, etc.)



THE LONG-HAUL FREIGHT SELECTION PROBLEM



Today



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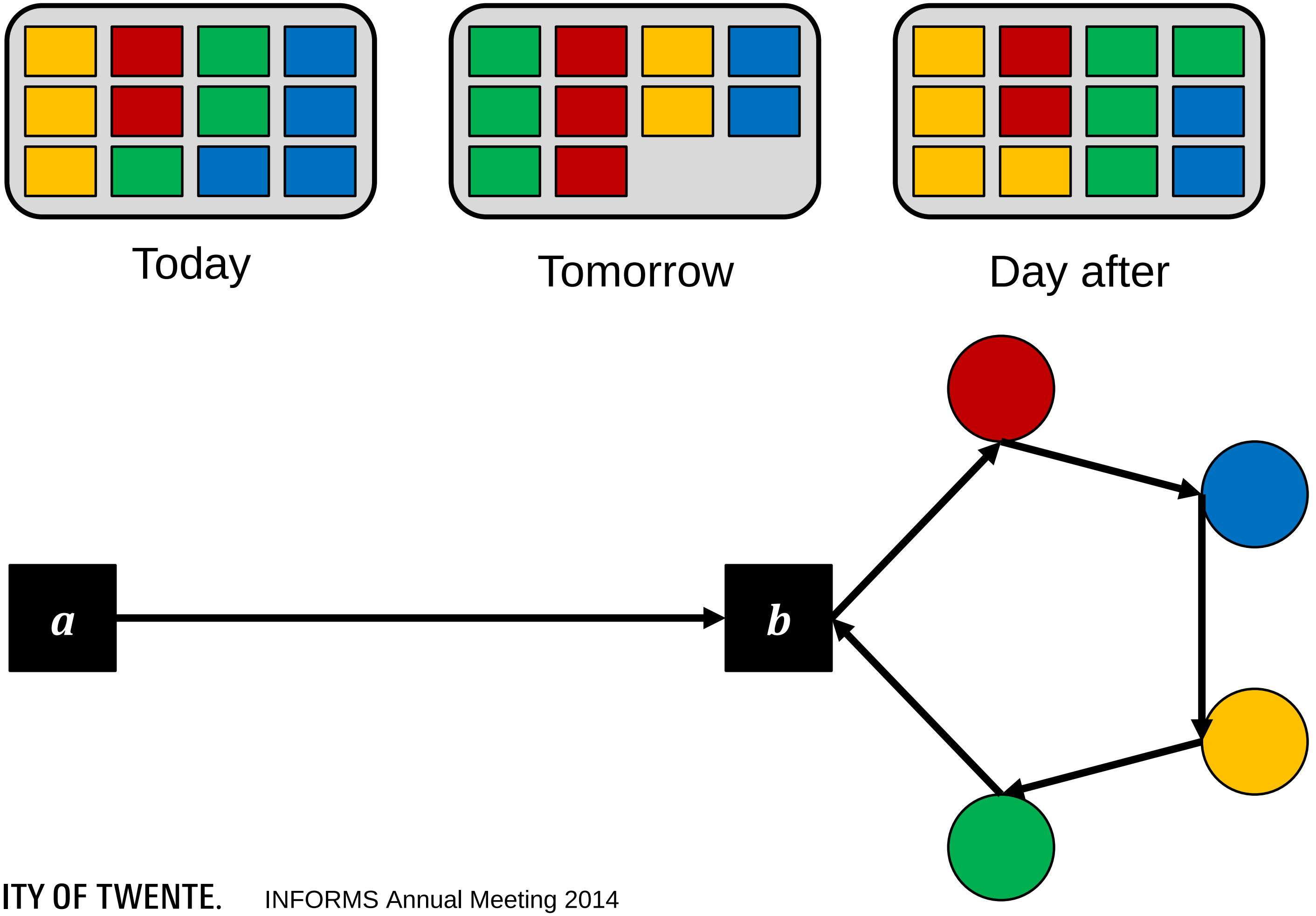

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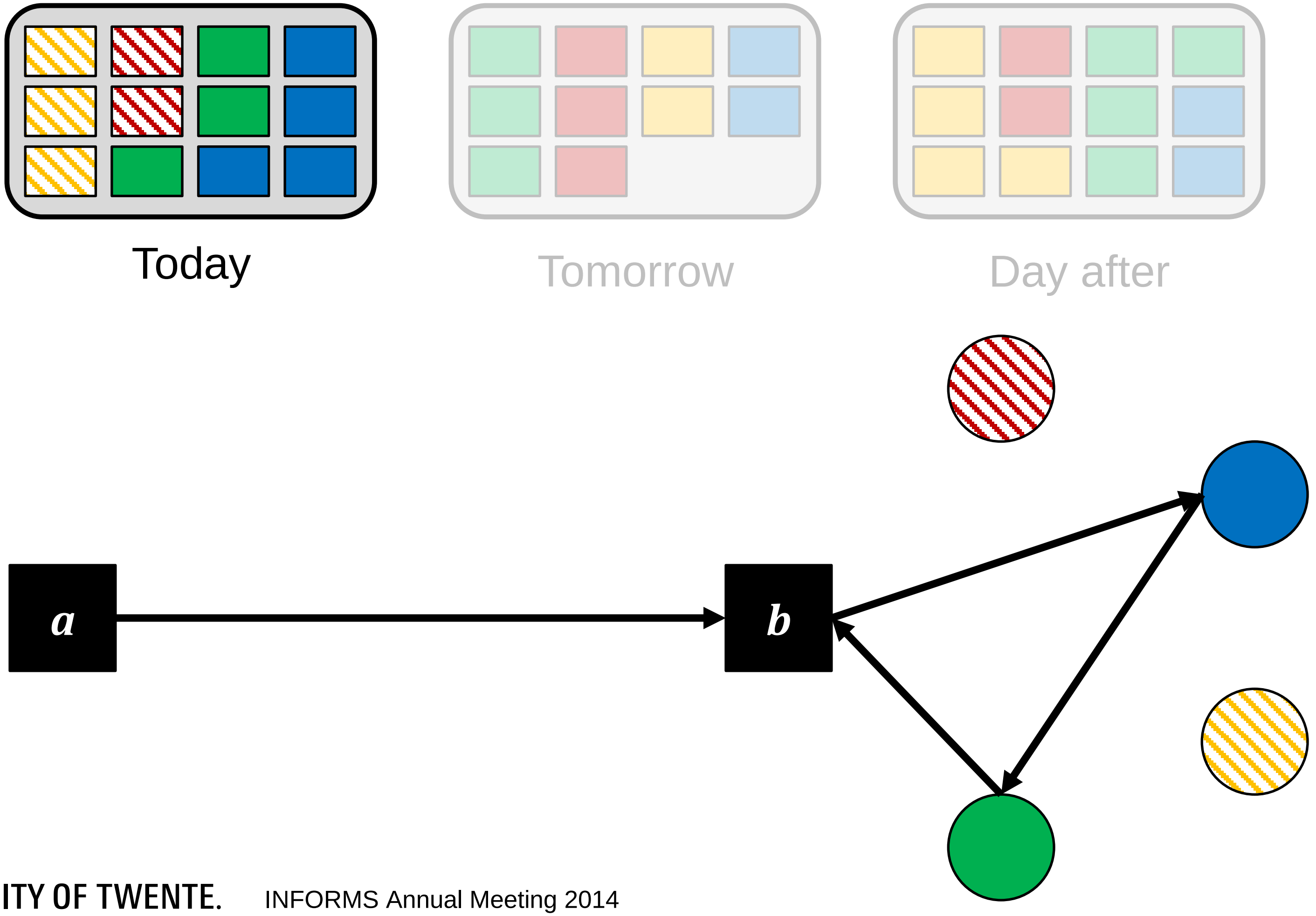

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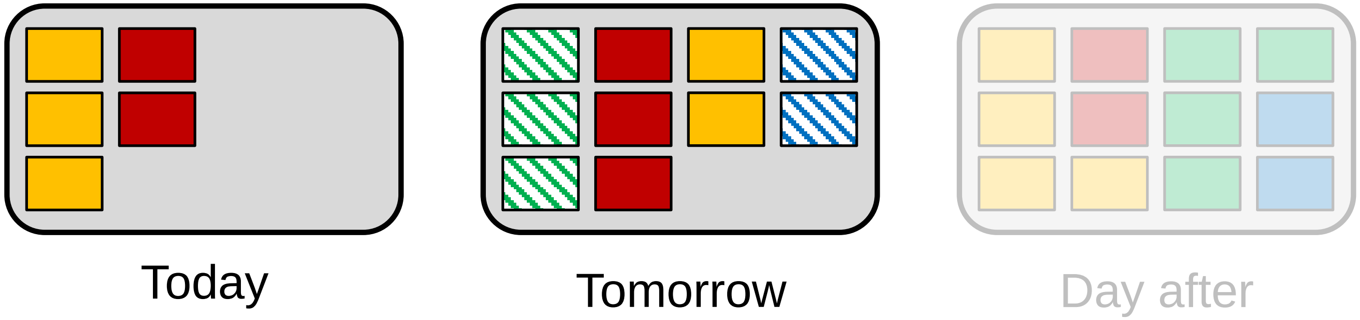

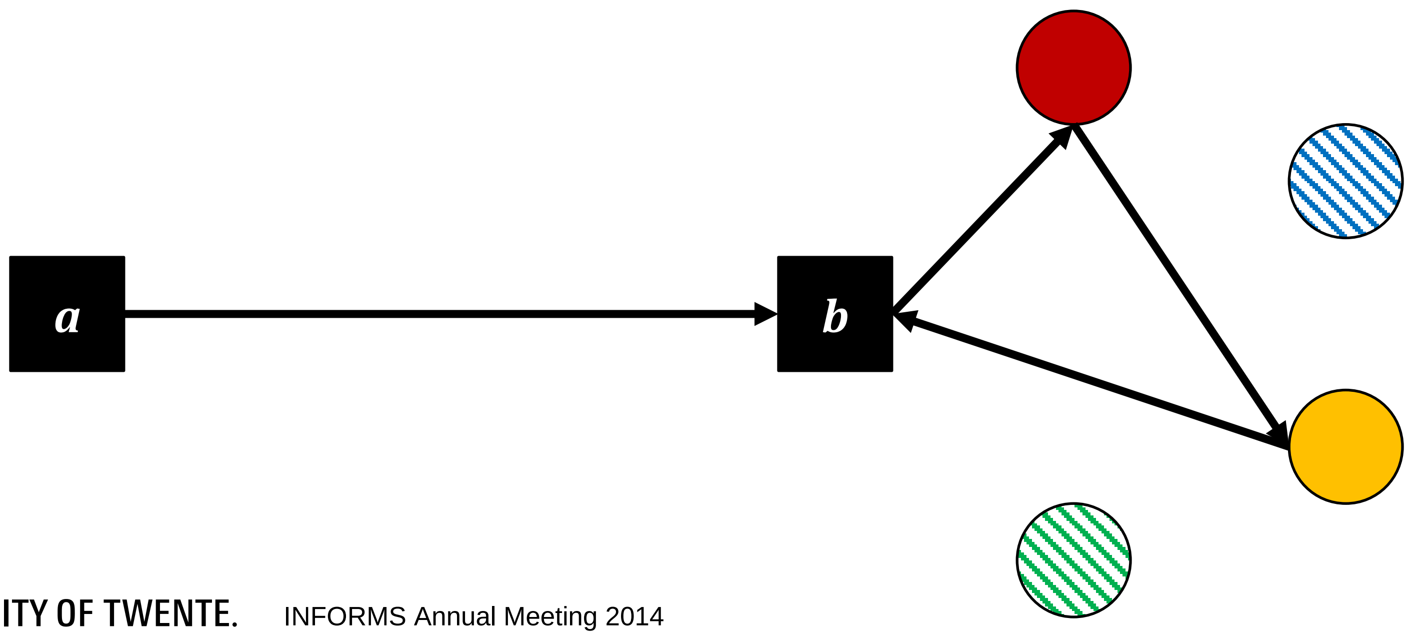

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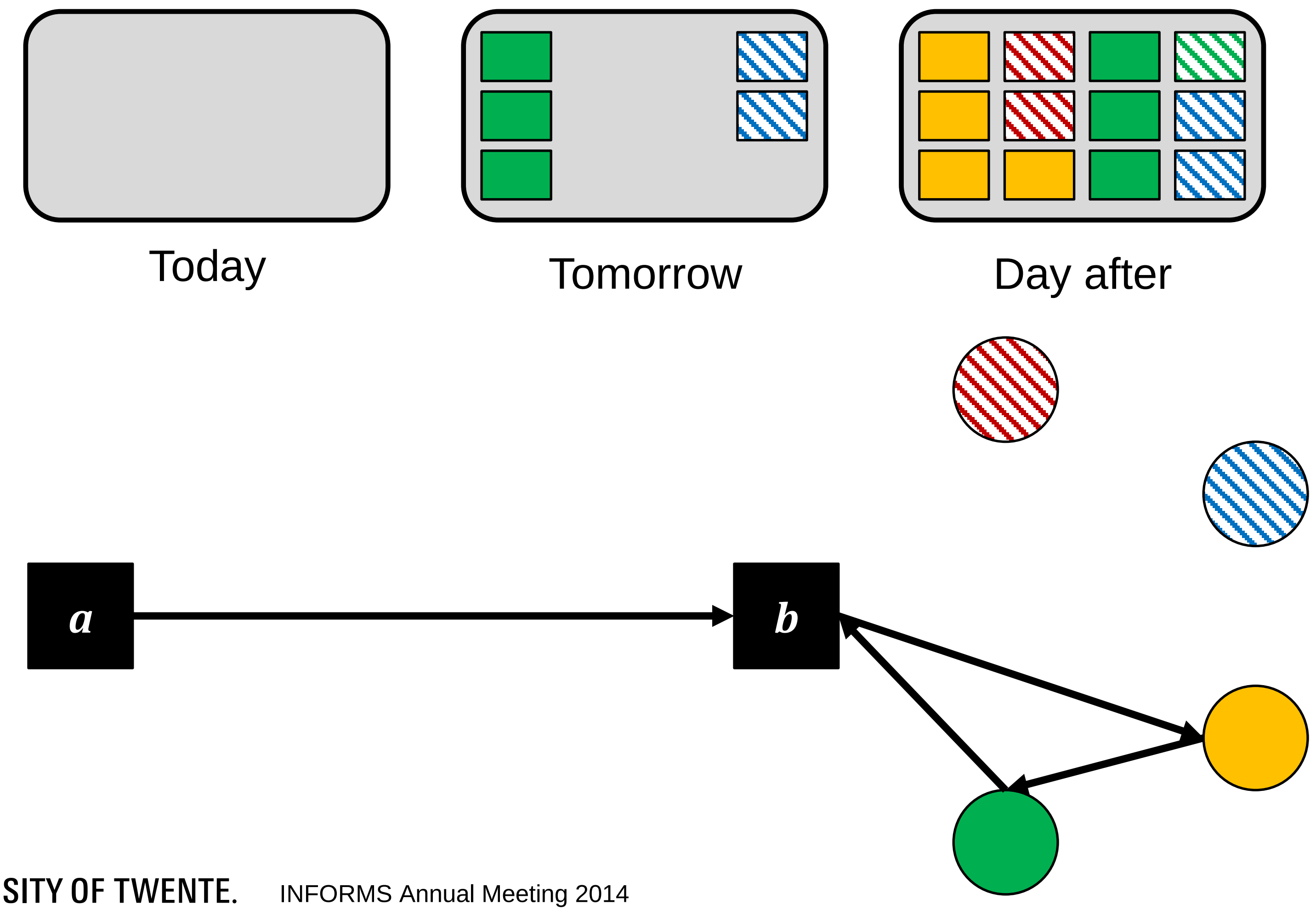

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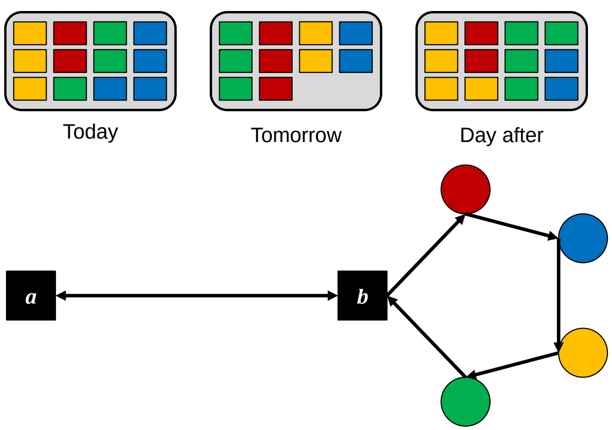
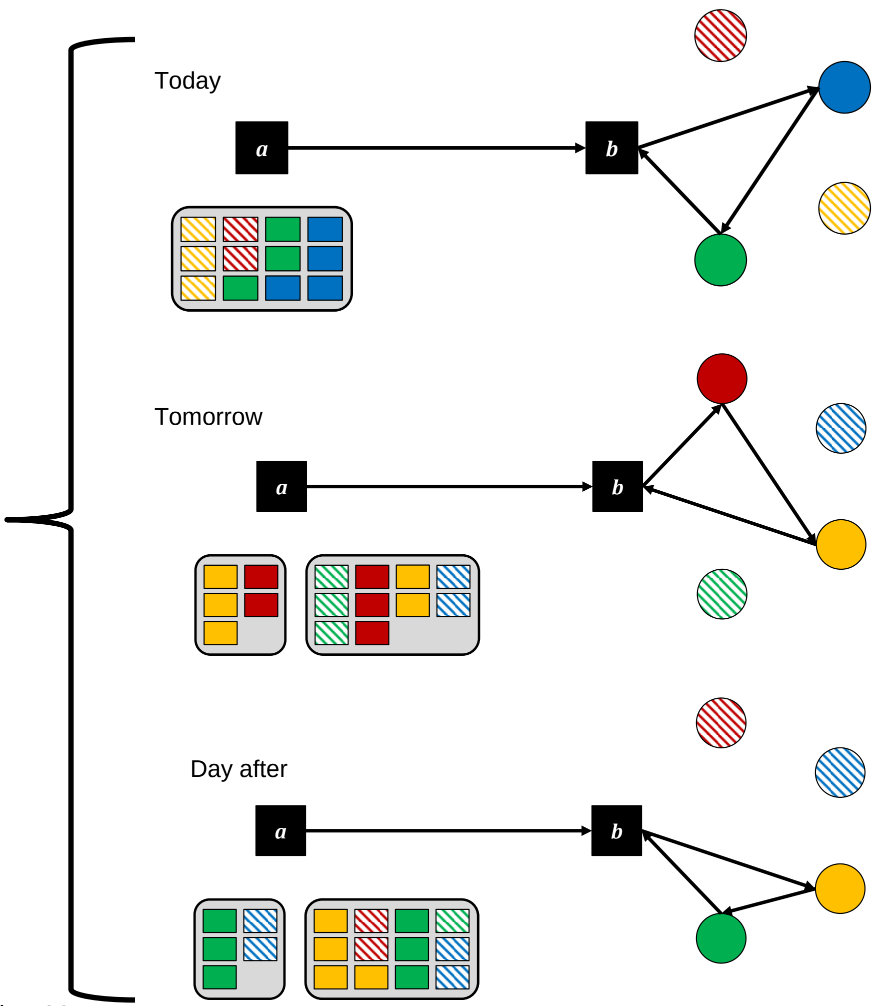




PROBLEM FORMULATION

What are our problem characteristics?

- Discrete and finite planning horizon $t \in \mathcal{T}$
- Set of freights $f \in \mathcal{F}$
  - Release-date $r \in \mathcal{R}$
  - Due-date $k \in \mathcal{K}$
  - Destination $d \in \mathcal{D}$
- Cost per subset of destinations via barge $C_{\mathcal{D}'} \in \mathbb{R}^{+}, \forall\, \mathcal{D}' \subseteq \mathcal{D}$
- Cost of direct transport via truck $B_d \in \mathbb{R}^{+}, \forall d \in \mathcal{D}$
- Capacity of the barge $Q \in \mathbb{N}$

PROBLEM FORMULATION

Assumptions and constraints:

- One barge sails per time unit (decision moment)
- Barge has a maximum capacity.
- Each freight consists of one unit (i.e., container).
- Each freight must be transported after its release-date and before its due-date.
- There is an unlimited number of trucks for the direct option.

MIXED-INTEGER LINEAR PROGRAMMING MODEL

$$\min Z$$

$$\text{s.t.}$$

$$Z = \sum_{t\in\mathcal{T}}\sum_{\mathcal{D}'\subseteq\mathcal{D}}\left(C_{\mathcal{D}'}\cdot\prod_{d'\in\mathcal{D}'} y_{d',t}\cdot\prod_{d''\in\mathcal{D}_t\setminus\mathcal{D}'}(1-y_{d'',t})\right)+\sum_{t\in\mathcal{T}}\sum_{f\in\mathcal{F}}\sum_{d\in\mathcal{D}}(B_d\cdot L_{f,d}\cdot v_{f,t}) \tag{1}$$

Non-linear!

$$\sum_{f\in\mathcal{F}} x_{f,t}\leq Q,\ \forall t\in\mathcal{T} \tag{2}$$

$$\sum_{t\in\mathcal{T}|t<R_f}(x_{f,t}+v_{f,t})=0,\ \forall f\in\mathcal{F} \tag{3}$$

$$\sum_{t\in\mathcal{T}|R_f\leq t\leq K_f}(x_{f,t}+v_{f,t})=1,\ \forall f\in\mathcal{F} \tag{4}$$

$$\sum_{f\in\mathcal{F}}(L_{f,d}\cdot x_{f,t})-M_d\cdot y_{d,t}\leq 0,\ \forall d\in\mathcal{D}_t,t\in\mathcal{T} \tag{5}$$

$$\mathcal{D}_t=\{d:L_{f,d}=1 \text{ and } R_f\leq t,\forall d\in\mathcal{D},f\in\mathcal{F}\},\ \forall t\in\mathcal{T} \tag{6}$$

Freight goes by barge → $x_{f,t}\in\{0,1\},\ \forall f\in\mathcal{F},t\in\mathcal{T}$ (7)

Destination is visited → $y_{d,t}\in\{0,1\},\ \forall d\in\mathcal{D}_t,t\in\mathcal{T}$ (8)

Freight goes by truck → $v_{f,t}\in\{0,1\},\ \forall f\in\mathcal{F},t\in\mathcal{T}$ (9)

MIXED-INTEGER LINEAR PROGRAMMING MODEL

- The objective can be linearized as follows:

$$Z = \sum_{t \in \mathcal{T}} \sum_{\mathcal{D}' \subseteq \mathcal{D}} \left(C_{\mathcal{D}'} \cdot w_{\mathcal{D}',t}\right) + \sum_{t \in \mathcal{T}} \sum_{f \in \mathcal{F}} \sum_{d \in \mathcal{D}} \left(B_d \cdot L_{f,d} \cdot v_{f,t}\right) \quad (10)$$

$$w_{\mathcal{D}',t} - y_{d',t} \leq 0,\ \forall \mathcal{D}' \subseteq \mathcal{D}_t, d' \in \mathcal{D}'_t, t \in \mathcal{T} \quad (11)$$

$$w_{\mathcal{D}',t} + y_{d',t} \leq 1,\ \forall \mathcal{D}' \subseteq \mathcal{D}_t, d' \in \mathcal{D}_t \setminus \mathcal{D}', t \in \mathcal{T} \quad (12)$$

$$w_{\mathcal{D}',t} + \left(\left|\mathcal{D}'\right| - 1\right) - \sum_{d' \in \mathcal{D}'} y_{d',t} + \sum_{d'' \in \mathcal{D}' \setminus \mathcal{D}_t} y_{d'',t} \geq 0,\ \forall \mathcal{D}' \subseteq \mathcal{D}_t, t \in \mathcal{T} \quad (13)$$

Subset of destinations is visited →

$$w_{\mathcal{D}',t} \in [0,1],\ \forall \mathcal{D}' \subseteq \mathcal{D}_t, t \in \mathcal{T} \quad (14)$$

All subsets of the set of destinations!

➢ ***MILP does not include uncertainty in arrival of freights!***

DYNAMIC PROGRAMMING MODEL

- One ***stage*** for each time period $t \in \mathcal{T}$.

Model's Uncertainty in arrivals between stages:

- Number of freights F : $P(\mathrm{F} = f),\ f \in \mathcal{F}$
- Release-day of each freight R : $P(\mathrm{R} = r),\ r \in \mathcal{R}$
- Due-day of each freight K : $P(\mathrm{K} = k),\ k \in \mathcal{K}$
- Destination of each freight D : $P(\mathrm{D} = d),\ d \in \mathcal{D}$

All random variables are captured in an ***exogenous information vector W_t*** :

$$\mathbf{W}_t = \left[\widetilde{F}_{t,d,r,k}\right]_{\forall d \in \mathcal{D}, r \in \mathcal{R}, k \in \mathcal{K}}, \ \forall t \in \mathcal{T}$$

DYNAMIC PROGRAMMING MODEL

Model's states and decisions:

- A ***state*** $\boldsymbol{S_t}$ is the collection of freights, and their characteristics, that are known at a given stage:

$$S_t = [F_{t,d,r,k}]_{\forall d \in \mathcal{D}, r \in \mathcal{R}, k \in \mathcal{K}}, \; \forall t \in \mathcal{T}.$$

- A ***decision*** $\boldsymbol{x_t}$ is the collection of freights, which have been released, that we are going to transport via barge at a given stage:

$$x_t = [x_{t,d,k}]_{\forall d \in \mathcal{D}, k \in \mathcal{K}}, \; \forall t \in \mathcal{T}$$

$$\text{s.t.}$$

$$0 \leq x_{t,d,k} \leq F_{t,d,0,k}, \; \forall t \in \mathcal{T}, d \in \mathcal{D}, k \in \mathcal{K}$$

$$\sum_{d \in \mathcal{D}} \sum_{k \in \mathcal{K}} x_{t,d,k} \leq Q, \; \forall t \in \mathcal{T}$$

DYNAMIC PROGRAMMING MODEL

Model's state transition between stages:

- A ***transition function S^M*** captures the evolution of the system over the stages as a result of the decisions and the stochastic arrivals.

$$S_t = S^M\left(S_{t-1}, x_{t-1}, W_t\right), \ \forall t \in \mathcal{T}$$

$$\text{s.t.}$$

$$F_{t,d,0,0} = F_{t-1,d,1,1} + \widetilde{F}_{t,d,0,0},$$
$$\forall t \in \mathcal{T}, d \in \mathcal{D}$$

$$F_{t,d,0,k} = F_{t-1,d,0,k+1} - x_{t-1,d,k+1} + F_{t-1,d,1,k+1} + \widetilde{F}_{t,d,0,k},$$
$$\forall t \in \mathcal{T}, d \in \mathcal{D}, k \in \mathcal{K} \setminus \{0, |\mathcal{K}|\}$$

$$F_{t,d,r,k} = F_{t-1,d,r+1,k+1} + \widetilde{F}_{t,d,r,k},$$
$$\forall t \in \mathcal{T}, d \in \mathcal{D}, r \in \mathcal{R} \setminus \{0\}, k \in \mathcal{K} \setminus \{0, |\mathcal{K}|\}$$

DYNAMIC PROGRAMMING MODEL

- A small example on how the ***transition function*** works:

$S_{t-1,d}$	$F_{t-1,d,0,0}$	$F_{t-1,d,0,1}$	$F_{t-1,d,0,2}$	$F_{t-1,d,1,2}$	$F_{t-1,d,1,3}$	$F_{t-1,d,2,3}$	$F_{t-1,d,3,4}$
	3	4	3	4	3	2	2

−

$x_{t-1,d}$	$F_{t-1,d,0,0}$	$F_{t-1,d,0,1}$	$F_{t-1,d,0,2}$
	3	2	0

=

$S^x_{t-1,d}$	$F_{t-1,d,0,0}$	$F_{t-1,d,0,1}$	$F_{t-1,d,0,2}$	$F_{t-1,d,1,2}$	$F_{t-1,d,1,3}$	$F_{t-1,d,2,3}$	$F_{t-1,d,2,4}$
	0	2	3	4	3	2	2

+

$W_{t,d}$	$F_{t,d,0,0}$	$F_{t,d,0,1}$	$F_{t,d,0,2}$	$F_{t,d,1,2}$	$F_{t,d,1,3}$	$F_{t,d,2,3}$	$F_{t,d,2,4}$
	0	0	0	1	2	0	1

=

$S_{t,d}$	$F_{t-1,d,0,0}$	$F_{t-1,d,0,1}$	$F_{t-1,d,0,2}$	$F_{t-1,d,1,2}$	$F_{t-1,d,1,3}$	$F_{t-1,d,2,3}$	$F_{t-1,d,2,4}$
	2	7	3	3	4	0	1

DYNAMIC PROGRAMMING MODEL

Model's costs and objective:

$$C\left(\boldsymbol{S}_t, \boldsymbol{x}_t\right) = \sum_{\mathcal{D}' \subseteq \mathcal{D}} \left(C_{\mathcal{D}'} \cdot \prod_{d' \in \mathcal{D}'} y_{d',t} \cdot \prod_{d'' \in \mathcal{D} \setminus \mathcal{D}'} \left(1 - y_{d'',t}\right) \right) + \sum_{d \in \mathcal{D}} \left(B_d \cdot \left(F_{t,d,0,0} - x_{t,d,0}\right)\right)$$

$$\text{s.t.}$$

$$y_{d,t} = \begin{cases} 1, & \text{if } \sum_{k \in \mathcal{K}} x_{t,d,k} > 0 \\ 0, & \text{otherwise} \end{cases}, \ \forall t \in \mathcal{T}, d \in \mathcal{D}$$

- The objective is to find a ***policy*** $\boldsymbol{\pi}$ that minimizes the expected costs over the planning horizon given an initial state.

$$\min_{\pi \in \Pi} \mathbb{E} \left\{ \sum_{t \in \mathcal{T}} C\left(\boldsymbol{S}_t, \boldsymbol{x}_t^{\pi}\right) | \boldsymbol{S}_0 \right\}$$

DYNAMIC PROGRAMMING MODEL

How to find this policy?

Using Bellman's principle of optimality and backward induction:

$$V_t\left(\boldsymbol{S}_t\right) = \min_{\boldsymbol{x}_t}\left(C\left(\boldsymbol{S}_t, \boldsymbol{x}_t\right) + \mathbb{E}\left\{V_t\left(S^M\left(\boldsymbol{S}_t, \boldsymbol{x}_t, \boldsymbol{W}_{t+1}\right)\right)\right\}\right)$$

$$V_t\left(\boldsymbol{S}_t\right) = \min_{\boldsymbol{x}_t}\left(C\left(\boldsymbol{S}_t, \boldsymbol{x}_t\right) + \sum_{\omega \in \Omega}\left(P(\boldsymbol{W}_{t+1} = \omega) \cdot V_t\left(S^M\left(\boldsymbol{S}_t, \boldsymbol{x}_t, \omega\right)\right)\right)\right)$$

All possible realizations of the random variables!

All possible decisions in a state!

All possible states!

$$\omega = \left[\acute{F}_{t,d,r,k}\right]_{\forall d \in \mathcal{D}, r \in \mathcal{R}, k \in \mathcal{K}}$$

$$P(\boldsymbol{W}_t = \omega) = \frac{\left(\sum_{d \in \mathcal{D}, r \in \mathcal{R}, k \in \mathcal{K}} \acute{F}_{t,d,r,k}\right)!}{\prod_{d \in \mathcal{D}, r \in \mathcal{R}, k \in \mathcal{K}}\left(\acute{F}_{t,d,r,k}!\right)} \cdot \prod_{d \in \mathcal{D}, r \in \mathcal{R}, k \in \mathcal{K}}\left(P(F = \sum_{d \in \mathcal{D}, r \in \mathcal{R}, k \in \mathcal{K}} \acute{F}_{t,d,r,k}) \cdot \left[P(D = d) \cdot P(R = r) \cdot P(K = k)\right]^{\acute{F}_{t,d,r,k}}\right)$$

APPROXIMATE DYNAMIC PROGRAMMING MODEL

Same cost and transition function as the DP model, however:

- A ***post-decision state*** $\boldsymbol{S}_t^x$ is used as a single estimator for all possible realization of the random variables.

$$\boldsymbol{S}_t^x = S^{M,x}\left(\boldsymbol{S}_{t-1}, \boldsymbol{x}_{t-1}\right)$$

- An ***approximated value function*** $V_t^x(\boldsymbol{S}_t^x)$ for the post-decision state to capture the future costs:

$$V_t\left(\boldsymbol{S}_t\right) = \min_{\boldsymbol{x}_t}\left(C\left(\boldsymbol{S}_t, \boldsymbol{x}_t\right) + \mathbb{E}\left\{V_t\left(S^M\left(\boldsymbol{S}_t, \boldsymbol{x}_t, \boldsymbol{W}_{t+1}\right)\right)\right\}\right)$$

$$V_t\left(\boldsymbol{S}_t\right) = \min_{\boldsymbol{x}_t}\left(C\left(\boldsymbol{S}_t, \boldsymbol{x}_t\right) + V_t^x\left(\boldsymbol{S}_t^x\right)\right)$$

APPROXIMATE DYNAMIC PROGRAMMING MODEL

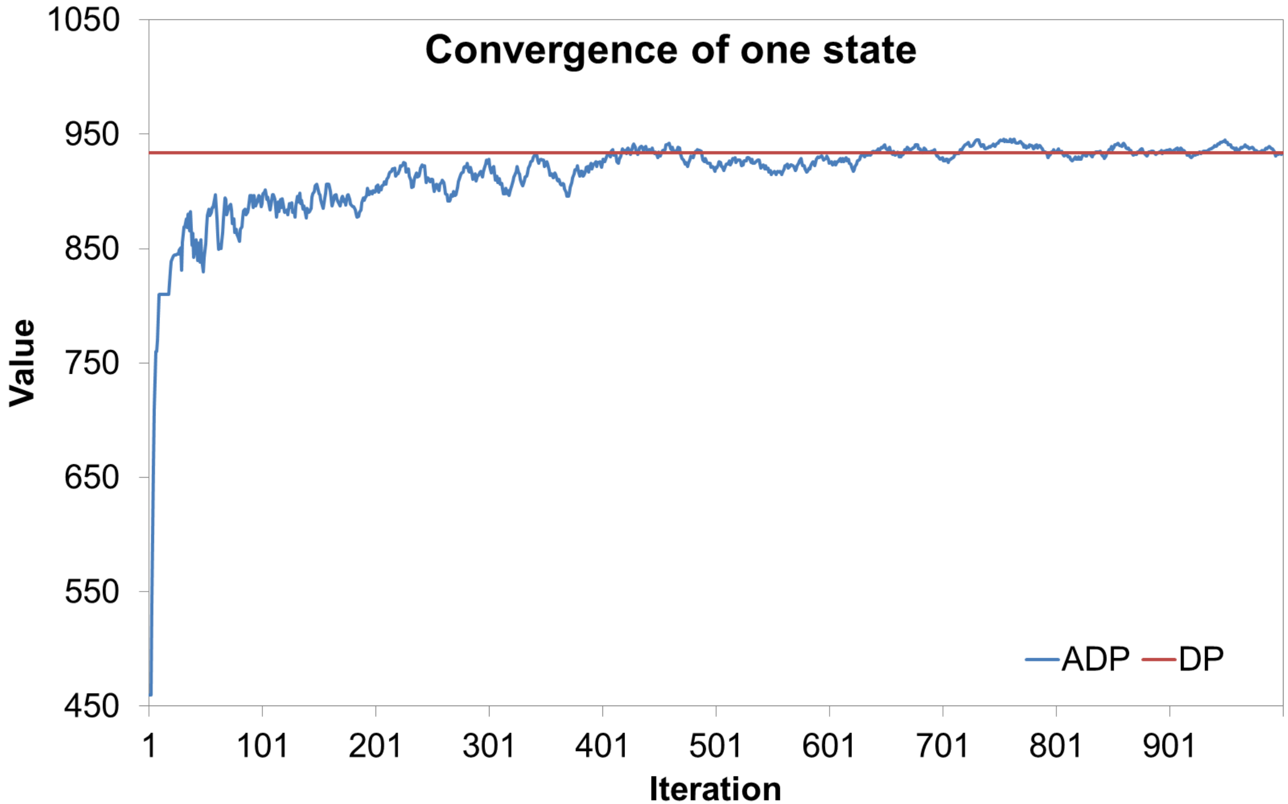
How to find the best decision for an initial state?[1]

- By stepping forward in time:
  1. Find best decision for current state with current estimated value function of post-decision states.
  2. Update the estimated value of the previous post-decision state.
  3. Sample all exogenous information (in a Monte Carlo fashion), and get the new state.
- Repeat for a number of iterations until convergence.

1. For the comprehensive algorithm see Powell (2010) Approximate Dynamic Programming.

APPROXIMATE DYNAMIC PROGRAMMING MODEL

- Comparison between the DP and ADP (with lookup tables) models, for a small example with 7k states.



In 6% of the states the ADP decisions differ from optimal.

OUR APPROACH

- Based on the ADP model with post-decision state approximation.

- Use ***basis functions*** for approximating the value of a state.

Basis functions are specific features of a state which have a significant impact on its value.

$$\overline{V}_t^n \left(S_t^x\right) = \sum_{f \in \mathcal{F}} \theta_f^n \phi_f \left(S_t^x\right), \qquad \forall t \in \mathcal{T}.$$

- Where θ_f^n is a weight for each feature $f \in F$, and $\phi_f(S_t^x)$ is the value of the particular feature given the post-decision state S_t^x.

OUR APPROACH

- With ***regression analysis*** we investigate which features have a significant impact on the value of a state.

- *In an example instance (with approx. 78k states) the following choice of basis functions explain a large part of the variance in the computed values with the DP model (R^2 = 0.94):*
  - **All state variables.**
  - **Number of different destinations of all freights that have the same release-day (for each release-day).**
  - **Sum of all freights that that have the same release-day (for each release-day).**

WHAT TO REMEMBER

- Selecting which freights to consolidate today while considering consolidation of freights in future days is important when costs depend on the combination of freights consolidated.
- The DP model can easily handle costs as a function of the combination of freights and uncertainty in the arrival of freights, but solving it means facing “the curses of dimensionality”.
- The ADP model overcomes the DP model dimensionality issues through the use of a post-decision state and basis functions.

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THANKS FOR YOUR ATTENTION!

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