Capacity Planning in Consolidation-based Transportation and Logistics
Planification de la capacité en logistique et transport avec consolidation

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Plan

- Consolidation-based transport and logistics (T&L)
- Planning the capacity
  - The classic approach – A carrier tactical planning illustration (SSND)
- Enhancing capacity representation – Integrating Bin Packing methodology
  - Shipper facility / corridor illustrations
- Perspectives

Bruni M.E., Crainic T.G., Perboli G. (2023), *Bin Packing Methodologies for Capacity Planning in Freight Transportation and Logistics*, In *Contributions to Combinatorial Optimization and Applications*, Crainic T.G., Frangioni A., Gendreau M. (Eds.), Springer (forthcoming)

Transportation & Logistics (T&L)

- Essential for human society
  - Economic, social, even political & historical points of view
  - Significant negative impacts
    - Environment, energy, resources, congestion, ...
- Complex systems, chains, networks
  - Multiple stakeholders & decision makers
  - Interrelated activities and conflicting objectives (internally and externally)
  - High-cost human & material (& financial) public & private resources
  - Regulation and taxation at all governmental levels
- A system made up of systems ...

Transportation & Logistics Science with Analytics

- Improving T&L systems and stakeholder efficiency and profitability, within their economic, social, and political environments, yielding significant social, environmental, and economic benefits
- Operations Research and T&L
  - Long and successful history
  - Methods to support analysis, planning, and management
    - All types of organizations
    - All geographical extensions
    - All planning levels, ...
  - Source and motivation for significant methodological advances
- Still many issues to address, models to build, algorithms to develop, decision-support methods & systems to transfer

Freight T&L – An Interplay of

Civil society & Facilitators

Shippers – Demand

Producers

Traders / Importers-Exporters / Distributors

Logistics service providers (Intermediaries)

Requests for
time and cost-efficient
transport (storage)

Carriers – Supply

Uni / Multi / Intermodal Freight Carriers

Modal / Intermodal / Storage Terminal Operators

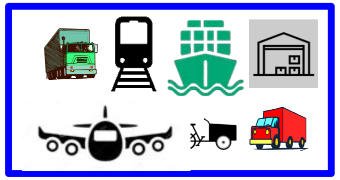
Logistics service providers (Intermediaries)

Service proposals/offers
(capacity, tariffs, times, ...)
to profitably answer demand

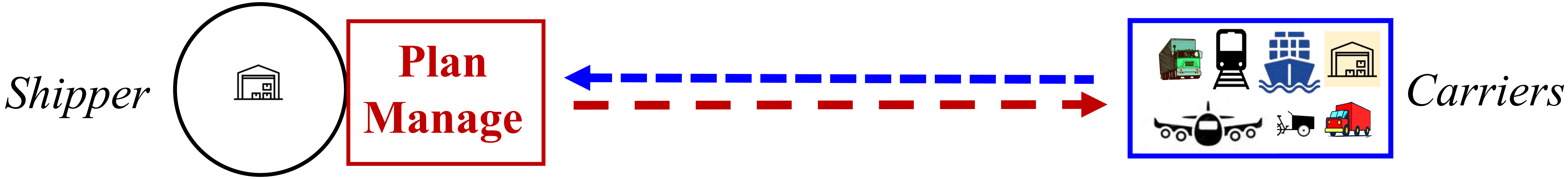
Governmental institutions

Economic and legal environment

Many diverse settings & organizations grouped into 3 major classes according to the scope of their main activities & planning



Many Carrier Offers to One *Shipper* Case (M1)



Decisions

Selection: carrier(s) & service(s) (scheduled)

Shipment: when & how = itinerary

Offer Capacity

Services (scheduled)

Individually / bundled

Tariffs, times, service types, ...

- Strategic: Assess & build/secure logistics network, supplier → end customer
  - Location & dimensioning of facilities & fleets
  - Secure transport / storage / “logistics” services & capacity from suppliers
- Tactic: Adjust long-term & secure medium-term capacity contracts
  - Allocate resources
  - Adjust plans for short-term activities

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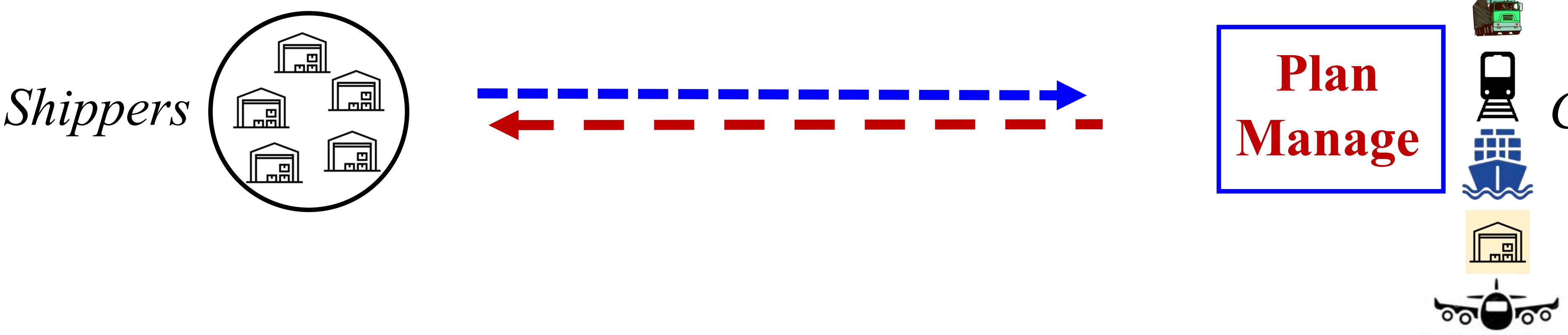
One *Carrier* to Many Shipper Requests Case (1M)



Requests:

Origin-Destination (OD)

volume, times, product & service types,

revenue, penalties, ...

Selection decisions: which (yes/no, when)

Service network (scheduled)

Resource management: resource-to-service assignment

Mobile resource & terminal utilization; Outsourcing

Shipment decisions: when, how = itinerary

- Strategic: Assess and build infrastructure (terminal) network
  - Material resources acquisition / securing
- Tactic: Service network design

Many Requests to One IDSP to Many Offers Case (M1M)

- ***Intermediary*** selecting requests and offers and managing assignments
  - 3/4/5PL and carrier acting as such
  - Arm-length platform for cooperating stakeholders

Shipper capacity requests
Origin-Destination (OD) demand
volume, times, product & service types,
revenue, penalties, …

Carrier capacity offers
Services (scheduled)
Individually / bundled
Tariffs, times, service types, …

Intelligent Decision-Support Platform

Decisions
Demand request selection and fulfillment
Carrier capacity-offer selection & utilization

Focus of this Talk

- The supply side of consolidation-based T&L
- Planning to efficiently and profitably (the O.R. ☺) secure or provide the required capacity and services for their regular operations over a short-medium-long time horizon
  - Facilities & space within, loading & transport units, transport services & slots, ...

Consolidation?

- According to the Merriam-Webster (https://www.merriam-webster.com/dictionary/consolidate. Accessed 7 Mar. 2023)
  - Join together into one whole (unite)
  - Make firm or secure (strengthen)
  - Form into a compact mass
  - From the Latin *consolidatus,* in "modern" vocabulary in 1512
- In transportation and logistics
  - Group "things" together for an economically and operationally efficient transportation (as well as storage)
  - At the core of efficient and profitable operations of most systems, firms, and organizations of all types

Consolidation

- Carrier operating consolidation-service type
  - The loads of several customers are grouped into an unique shipment and move together on the same vehicle (convoy, multimodal service)
- The carrier needs to set up an operation strategy toservice simultaneously & efficiently different customers with various characteristics and requirements
- ⇒ Customized service is impossible!
- ⇒ Offer (***plan*** & advertise) regular services (routes, frequencies, schedules) to answer multiple-customer regular demand over a period of time (e.g., season)
  - Based on forecast of regular demand (+ business environment)
- Plan the system (strategic) and service (tactic) networks

More Consolidation

- Shipper consolidation of loads ➞ joint request for service
- Carrier multi-level consolidation
  - Railroads: cars (loaded & empty) ➞ blocks ➞ trains
  - Less-than-truckload (LTL) motor carriers: loads ➞ trailers ➞ road-trains
- Intermodal carriers (shipping lines, railroads):
  containers ➞ ships / railcars / planes ...
- Postal & express couriers:
  items ➞ vehicles / containers ➞ vehicles & services
- Intermediaries multi-level consolidation
  Loads ➞ containers ➞ capacity secured from carriers
- …

Plan

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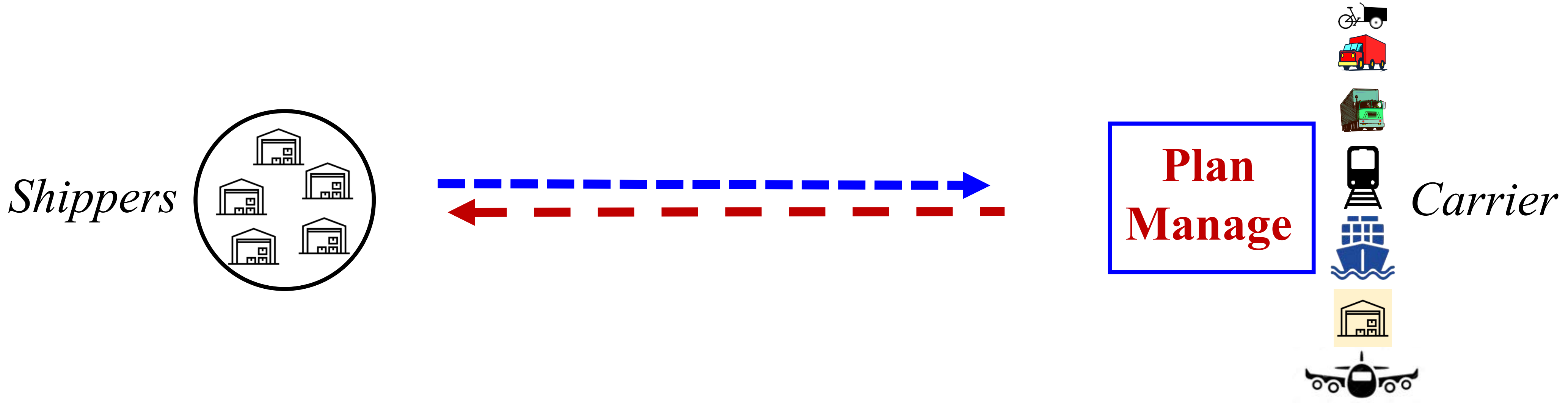
Classic Capacity Representation

- Capacity = Maximum volume of flow (similar measures) the facility / service may receive / transport during a given period of time
- The unit of transport / storage & its capacity are given
  - Commodity-specific capacities in some cases
  - In some (strategic) cases, one may select a capacity measure among a set
- In most cases, the capacity limit represented through "simple" knapsack constraints

$$total\ volume\ assigned\ \leq given\ capacity$$

- Illustrations: carrier and intermediary tactical planning

Carrier, Many-to-One Service Network Planning



Requests:

Origin-Destination (OD)
volume, times, product & service types,
revenue, penalties, ...

Selection decisions: which (yes/no, when)

Service network (scheduled)

Resource management: resource-to-service assignment

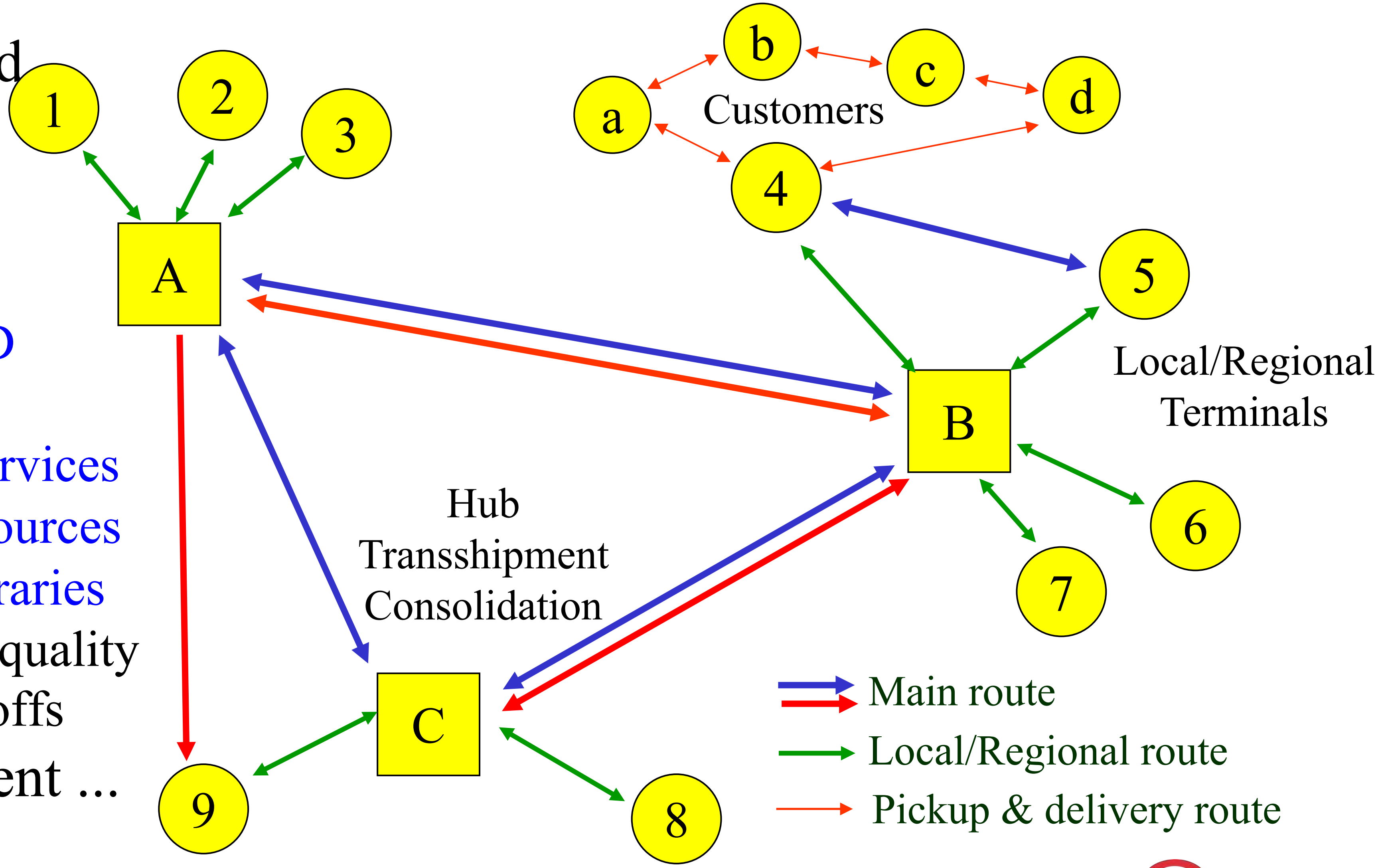
Mobile resource & terminal utilization; Outsourcing

Shipment decisions: when, how = itinerary

Tactic: Service network design

Carrier Service and Capacity Planning

- Consolidation-based single/multi-modal carrier
- Tactical planning
  - Given predicted OD demand
  - Select scheduled services
  - Assign/manage resources
  - Build demand itineraries
  - Cost, time, service-quality efficiency & trade offs
- Revenue management ...



Service Network Design

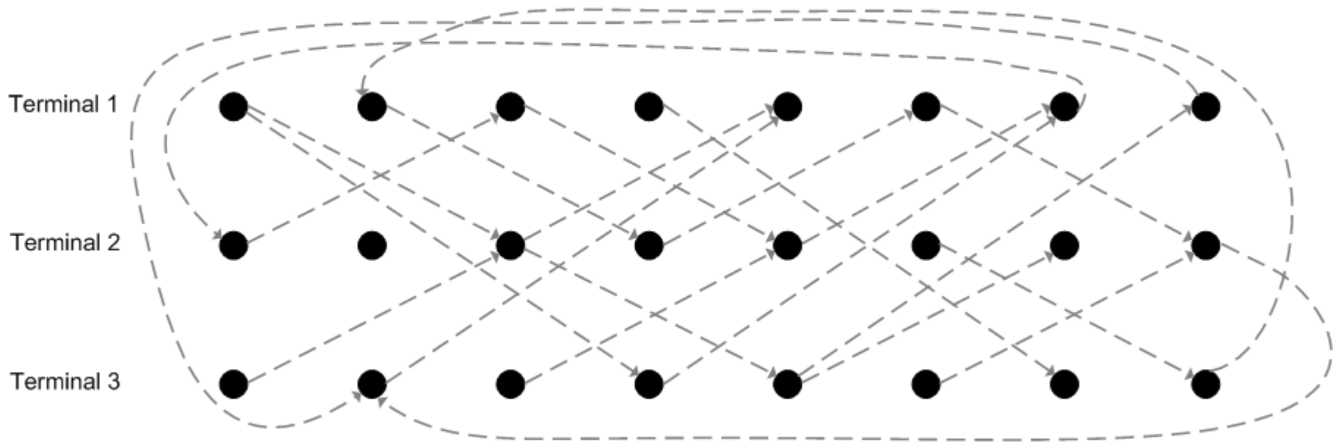
- Methodology of choice – quite an interesting body of contributions

  Crainic T.G., Hewitt M. (2021), Service Network Design, Chapter 12, *Network Design with Applications in Transportation and Logistics*, Crainic T.G., Gendreau M., Gendron B. (Eds.), 347-382, Springer

  - Service network defined on a physical network
  - Arc = Service or service leg (intermediary stops)
- Scheduled SND = Time dependency
  - Demand: O, D, availability at O, due-date at D, volume, ...
  - Service: O, D, schedule: departure from O, arrival at D, arrival & departure at intermediary stops
  - Time-space network: time discretization = periods (granularity? uniform?), node "copies" in time, holding arcs

Scheduled Service Network Design – SSND

- Cyclic time-space networks
- Schedule length discretized = periods Nodes = Terminals at "all" periods
- Arcs = Inter-period relations
  - Scheduled (time-specific) services = Movements
  - Holding at (successive in time) terminals (inventories)



- Decision variables
  - Select the scheduled service {0,1}
  - Commodity flows Continuous
- The objective function minimizes/maximizes the total cost/profit over the entire multi-period schedule length

SND

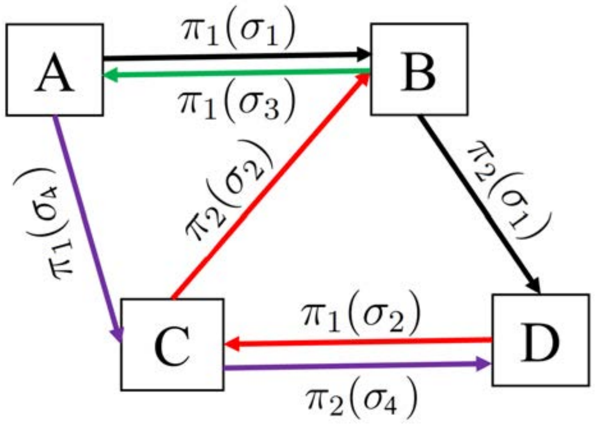
$$\text{Minimize} \sum_{\phi\in\Phi} f_\phi y_\phi + \sum_{k\in\mathscr{K}} \sum_{a\in\mathscr{A}} c_a^k x_a^k$$

$$\sum_{a\in\mathscr{A}_i^+} x_a^k - \sum_{a\in\mathscr{A}_i^-} x_a^k = \begin{cases} d^k, & \text{if } i = O(k), \\ -d^k, & \text{if } i = D(k), \\ 0, & \text{otherwise,} \end{cases} \quad \forall i \in \mathscr{N}, \forall k \in \mathscr{K},$$

$$\sum_{k\in\mathscr{K}} x_a^k \le u_a y_{\phi_a}, \quad \forall a \in \mathscr{A},$$

$$y_\phi \in \mathbb{Z}_+, \quad \forall \phi \in \Phi,$$

$$x_a^k \ge 0, \quad \forall a \in \mathscr{A}, \forall k \in \mathscr{K},$$



SSND

$$\text{Minimize} \sum_{\phi\in\Phi} f_\phi y_\phi + \sum_{k\in\mathscr{K}} \sum_{a\in\mathscr{A}} c_a^k x_a^k$$

$$\sum_{a\in\mathscr{A}^+_{(i,t_p^i)}} x_a^k - \sum_{a\in\mathscr{A}^-_{(i,t_p^i)}} x_a^k = \begin{cases} d^k, & \text{if } i = O(k), t_p^i = o(k), \\ -d^k, & \text{if } i = D(k), t_p^i = d(k) \\ 0, & \text{otherwise,} \end{cases}$$

$$\forall (i, t_p^i) \in \mathscr{N}, \forall k \in \mathscr{K},$$

$$\sum_{k\in\mathscr{K}} x_a^k \le u_a y_{\phi_a}, \ \forall a \in \mathscr{A},$$

$$y_\phi \in \mathbb{Z}_+, \ \forall \phi \in \Phi,$$

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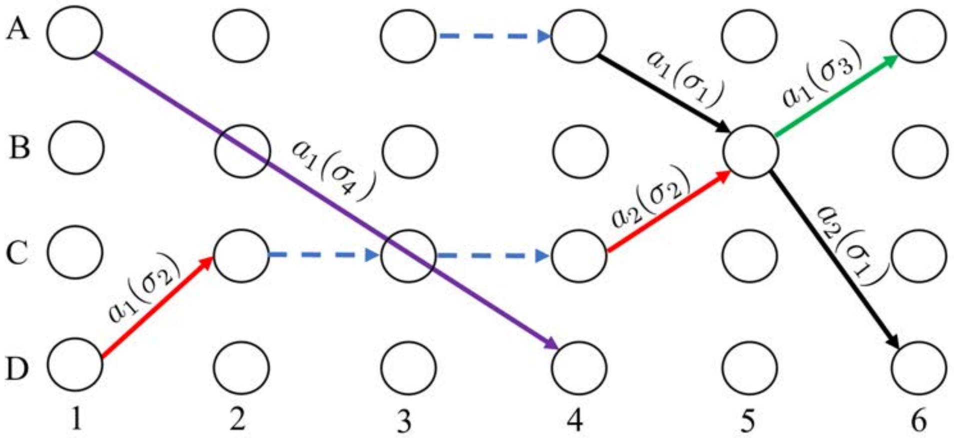
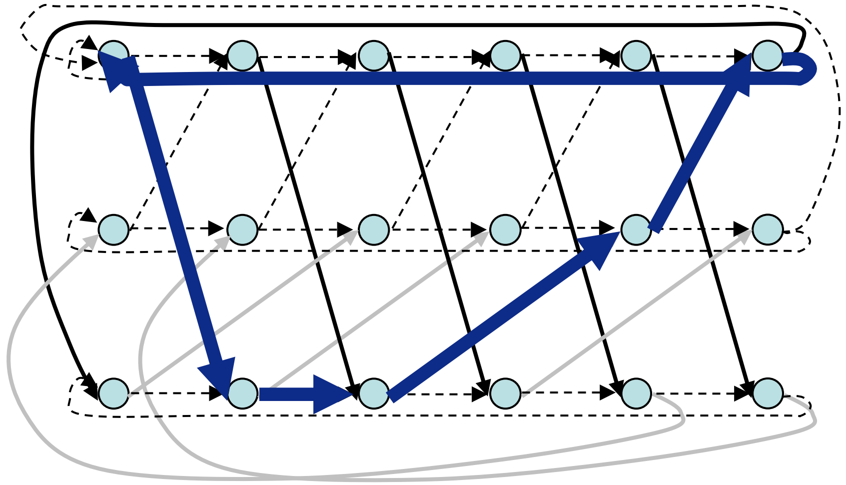


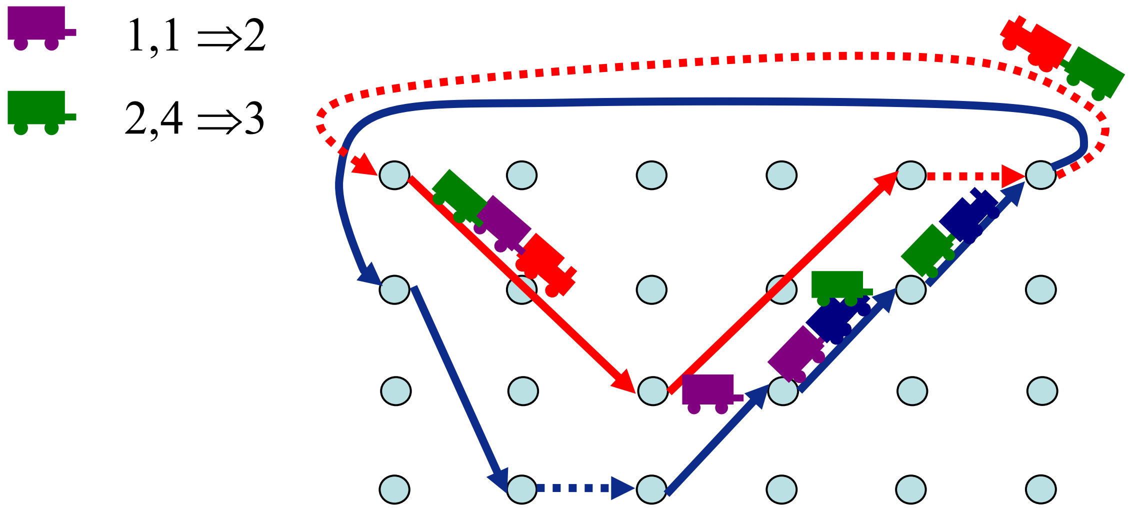
Services Need Resources to Operate

- Resources "operate" circular routes
  - "Return to base"
  - Balancing resources at terminals
- Single resource per service
  - Design-balancing constraints (arcs @ nodes)

$$\sum_{(i,j)\in\mathscr{A}_i^+} y_{ij} - \sum_{(j,i)\in\mathscr{A}_i^-} y_{ji} = 0, \ \forall i \in \mathscr{N}$$

- General
  - Balance resources
  - One set of constraints per type of resource





Arc versus Cycle-based Formulations

- Cycle-based formulations appear to dominate (Andersen et al. 2009, 2011a,b)
- Flexibility in modelling resource management rules
  - Length/duration
  - Availability at terminals
  - ...
- Must generate them ! ☺
  - Slope-scaling and matheuristic dynamic generation (Crainic et al. 2016)

Select and pay for services + cycles

$$\text{Minimize} \sum_{\phi \in \Phi} f_\phi y_\phi + \sum_{\theta \in \Theta} f_\theta y_\theta + \sum_{k \in \mathscr{K}} \sum_{a \in \mathscr{A}} c_a^k x_a^k$$

$$\sum_{a \in \mathscr{A}^+_{(i,t_p^i)}} x_a^k - \sum_{a \in \mathscr{A}^-_{(i,t_p^i)}} x_a^k = \begin{cases} d^k, & \text{if } i = O(k), t_p^i = o(k), \\ -d^k, & \text{if } i = D(k), t_p^i = d(k), \\ 0, & \text{otherwise}, \end{cases} \quad \forall (i, t_p^i) \in \mathscr{N}, \forall k \in \mathscr{K},$$

$$\sum_{k \in \mathscr{K}} x_a^k \le u_a y_{\phi_a}, \ \forall a \in \mathscr{A},$$

Services need resources $y_\phi \le \sum_{\theta \in \Theta} \delta_\theta^\phi y_\theta, \ \forall \phi \in \Phi,$

$$y_\phi \in \mathbb{Z}_+, \ \forall \phi \in \Phi, \quad y_\theta \in \{0,1\}, \ \forall \theta \in \Theta,$$

$$x_a^k \ge 0, \ \forall a \in \mathscr{A}, \forall k \in \mathscr{K},$$

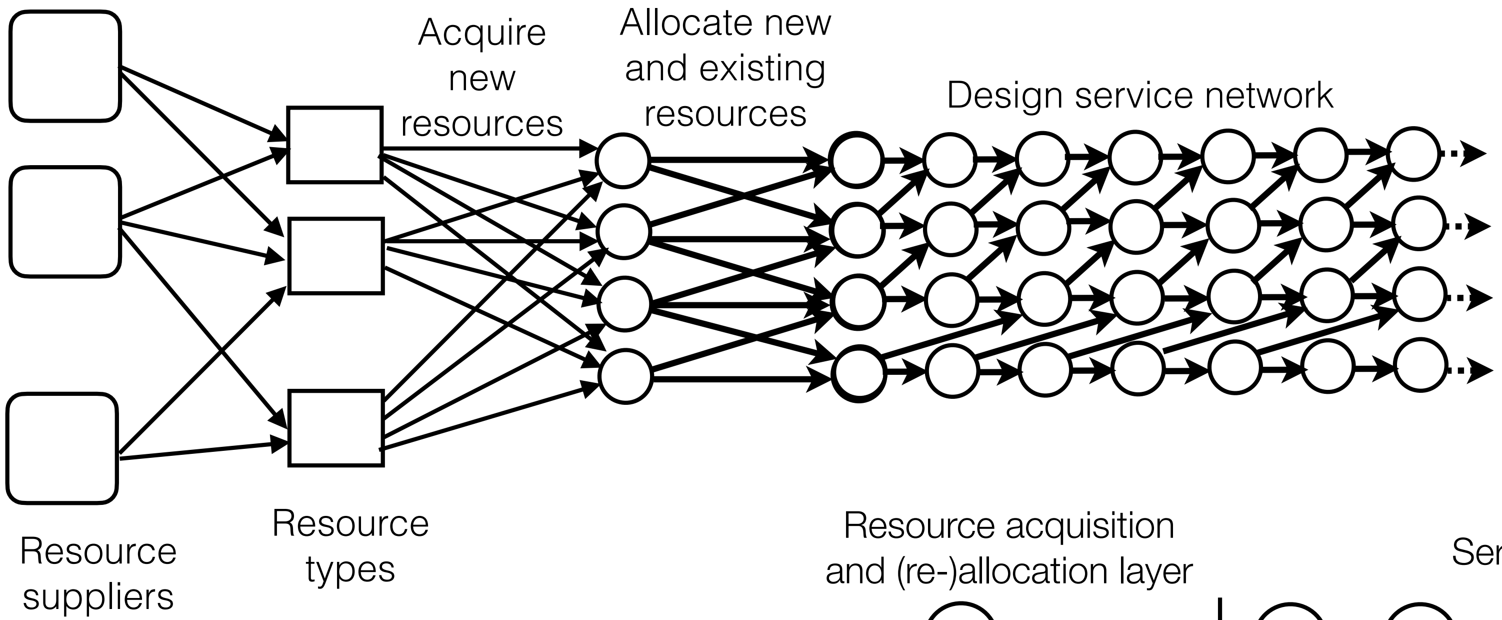
$$\mathscr{A}^+_{(i,t_p^i)} = \{((i', t_p^{i'}), (j, t_q^j)) \in \mathscr{A} : i' = i, t_p^{i'} = t_p^i\},$$

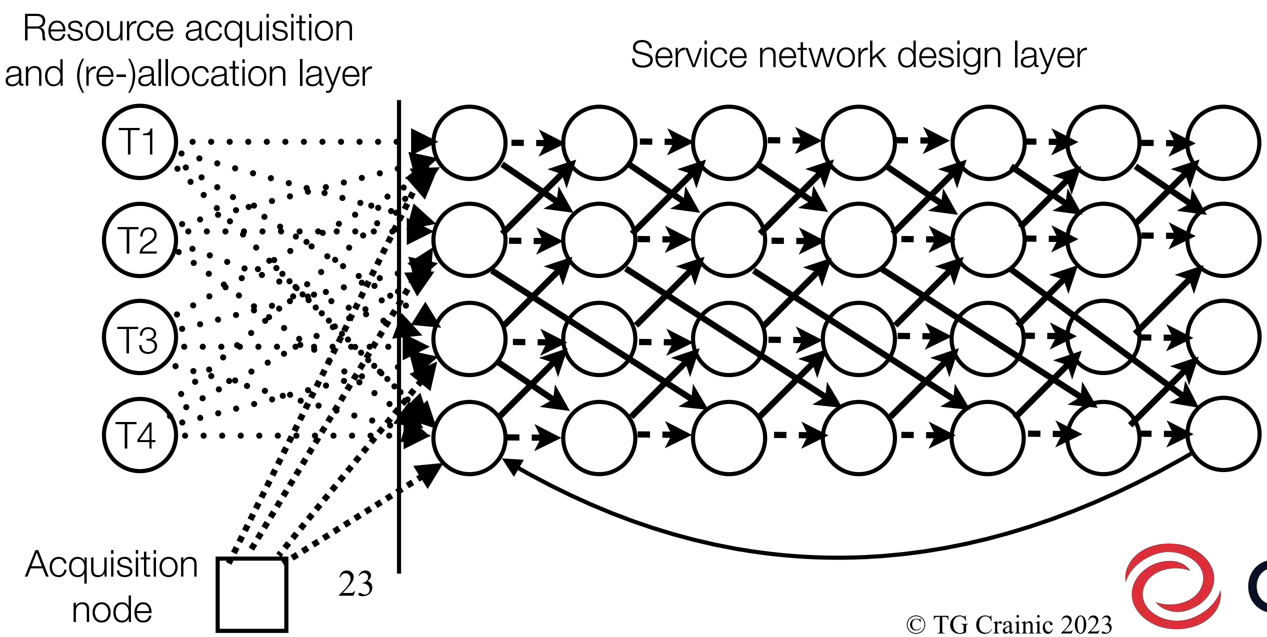
$$\mathscr{A}^-_{(i,t_p^i)} = \{((j, t_q^j), (i', t_p^{i'})) \in \mathscr{A} : i' = i, t_p^{i'} = t_p^i\}, \ \forall i, t_p^i) \in \mathscr{N}$$

Extending the Scope of SSND-RM

- SSND with Resource Acquisition and Management (Crainic et al. 2018)
  - Several resource types (combination rules still to come)
  - Longer-term resource management
  - Resource allocation & tactical planning
    - E.g., change of season & re-allocation
  - Resource allocation & strategic planning
    - Acquisition
    - Renting (for the system, for particular cycles, …)
    - Outsourcing certain services

SSND-RAM Problem and Time-Space Network





SSND-RAM Formulation

- Cycle definition extended to include acquisition and allocation
- Slope-scaling metaheuristics extended (Crainic et al. 2018)
  - Problem size limits?
- Demand uncertainty extension (Hewitt et al. 2019)
  - Two-stage stochastic model design then use + slightly adjust design
- Still, lot of ongoing work on SSND

Acquire + Reallocate

$$\text{Minimize} \sum_{r \in \mathcal{R}} \left(\sum_{i \in \mathcal{N}} h_i^r w_i^r + \sum_{i' \in \mathcal{N}} \sum_{j \in \mathcal{N}} h_{i'j}^r w_{i'j}^r \right) +$$

Select services operated with own resources

Outsourcing

$$+ \sum_{\phi \in \Phi} \left(f_\phi y_\phi + \sum_{r \in \mathcal{R}} f_\phi^r \sum_{\theta \in \Theta^r} \delta_\theta^\phi z_\theta^r \right) + \sum_{\phi \in \Phi} \sum_{r \in \mathcal{R}} F_\phi^r y_\phi^r$$

$$+ \sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{N}} f_i^r \sum_{\theta \in \Theta^r} z_\theta^r + \sum_{k \in \mathcal{K}} \sum_{a \in \mathcal{A}} c_a^k x_a^k$$

Select & use own resources

Initial allocation

$$\sum_{i' \in \mathcal{N}'} w_{i'j}^r = I_i^r, \ \forall r \in \mathcal{R}, \forall (j, t_1^j) \in \mathcal{N},$$

Resources @ terminals

$$\sum_{\theta \in \Theta_{i'}^r} z_\theta^r \leq \sum_{(j, t_1^j) \in \mathcal{N}} h_{i'j}^r, \ \forall r \in \mathcal{R}, \forall i' \in \mathcal{N}',$$

$$\sum_{a \in \mathcal{A}^+_{(i,t_p^i)}} x_a^k - \sum_{a \in \mathcal{A}^-_{(i,t_p^i)}} x_a^k = d^k, \ \forall (i, t_p^i) \in \mathcal{N}, \forall k \in \mathcal{K},$$

$$\sum_{k \in \mathcal{K}} x_a^k \leq \sum_{r \in \mathcal{R}} u(\phi, r) \left(\sum_{\theta \in \Theta^r} \delta_\theta^\phi z_\theta^r + y_\phi^r \right), \ \forall a \in \mathcal{A},$$

$$y_\phi \leq \sum_{r \in \mathcal{R}} \sum_{\theta \in \Theta^r} \delta_\theta^\phi z_\theta^r, \ \forall \phi \in \Phi,$$

Select services at most once

$$y_\phi + y_\phi^r \leq 1, \ \forall \phi \in \Phi,$$

Intermediary Many-to-One-to-Many Network Planning

- ***Intermediary*** selecting requests and offers and managing assignments
  - 3/4/5PL and carrier acting as such
  - Arm-length platform for cooperating stakeholders

Shipper capacity requests

Origin-Destination (OD) demand

volume, times, product & service types,
revenue, penalties, …

Carrier capacity offers

Services (scheduled)

Individually / bundled

Tariffs, times, service types, …

Intelligent Decision-Support Platform

Decisions

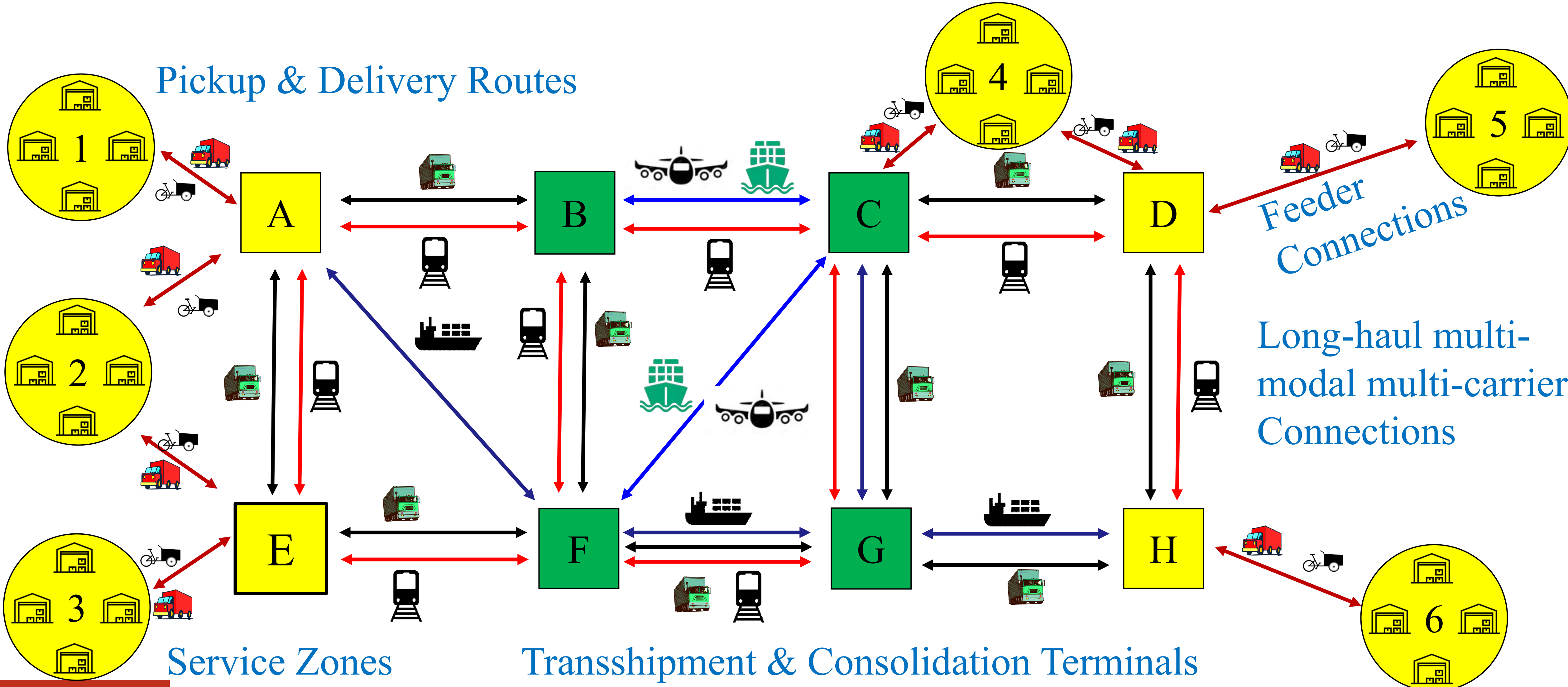
Demand request selection and fulfillment

Carrier capacity-offer selection & utilization

Integrated Multi-stakeholder/partner M1M Systems

- IDSP = intermediary & integrator
  - “Automated” optimized planning and management of operations
  - To profitably & simultaneously satisfy the needs of stakeholders
- Receives time-dependent requests and offers
- Optimizes in time & space
  - Selection of requests and offers
  - Request-to-offer assignments
  - ⇒ Consolidated carrier loads
  - ⇒ Request itineraries
- Earns & pays, monitors = gathers information, evaluates = learns

The Physical Network



M1M Tactical Planning

- A few particular features (Taherkhani et al. 2022)
- Service and fare differentiation (Revenue Management Bilegan et al. 2022)
- Individual and bundled-service offers
- Regular, known or expected, shipper requests and carrier offers
    - Point forecast currently
  - Contract, need to *fully* satisfy or not
    - Not for carriers in the current implementation
  - Non-contract to *fully* or partially satisfy if selected

M1M Tactical Planning – Demand and Supply (2)

- Shippers and shipper-request attributes
- Identity: Origin, destination, volume
    - No-split pickup and delivery
- Type: Contract or no-contract
- Service-quality (fare) category = time-based service-quality differentiation: Standard or rapid
- Time: Availability and delivery time intervals
  No acceptance interval
- Economic
    - Fare = revenue for the IDSP
    - Penalties for early/late pickup and delivery

M1M Tactical Planning – Demand and Supply (3)

- Carrier and carrier-offer attributes
- Identity: Origin, destination, capacity, route, schedule
- Offered individually or within a bundle
- Type of service
  - Regular and fast
  - Temporary-storage services at terminals (some services only)
- Time: Scheduled services only currently
- Economic: Cost for the IDSP
  - Fixed, discounted when in a bundle
  - Variable
- ⇒ Service network of the IDSP

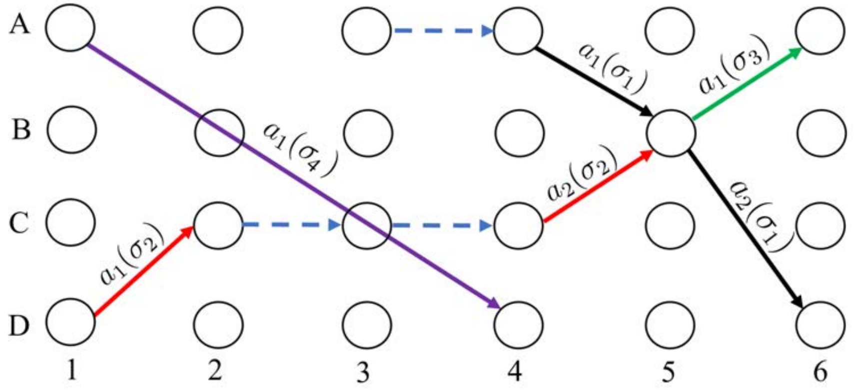
M1M Tactical Planning – Decisions & Goals

- Select profit-generating non-contract shipper requests
- Satisfy the demand – build shipper-request itineraries through the selected carrier-offer network – of contract and selected non-contract shipper requests
- Select individual and bundled-service carrier offers
- Identify the terminals where loads are to be stored temporarily
- Maximize profit
- Scheduled Service Network Design with Revenue Management – SSND-RM (Taherkhani et al. 2022)
  - Resource management only through service and terminal capacity enforcement = the IDSP does not own/manage the fleets (yet)

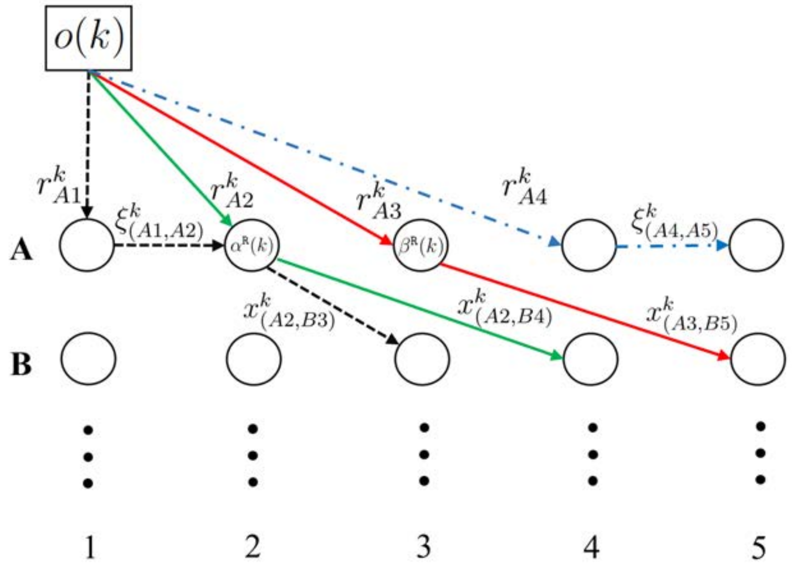
SSND-RM Decision Variables

- $z_k = 1$, if shipper-demand request $k \in \mathcal{K}$ is accepted, 0 otherwise;
- $r^k_{(o(k),t)} = 1$, if shipper-demand request $k \in \mathcal{K}$ is picked up from its origin $o(k)$ at time $t \in \mathcal{T}$, 0 otherwise.
- $x^k_a = 1$, if shipper-demand request $k \in \mathcal{K}$ is traveling on arc $a \in \mathcal{A}^{\mathtt{E}}$, 0 otherwise, with $x^k_{a_l(\sigma)} = x^k_a$, for $a = a_l(\sigma)$, $a_l(\sigma) \in \mathcal{L}(\sigma)$, $\sigma \in \Sigma$.
- $\xi^k_a = 1$, if shipper-demand request $k \in \mathcal{K}$ is held on holding arc $a \in \mathcal{A}^{\mathtt{H}}$, 0 otherwise.
- $r^k_{(d(k),t)} = 1$, if shipper-demand request $k \in \mathcal{K}$ is delivered at its destination $d(k)$ at time $t \in \mathcal{T}$, 0 otherwise. This is an auxiliary variable dependent on $r^k_{(o(k),t)}$, x^k_a, and ξ^k_a which corresponds to the delivery time of shipper-demand request $k \in \mathcal{K}$.
- $y_\sigma = 1$, if service $\sigma \in \Sigma$ is selected, 0 otherwise.
- $\gamma_b = 1$, if bundle $b \in \mathcal{B}$ is selected, 0 otherwise.
- $\lambda_n = 1$, if the warehousing space of terminal $n \in \mathcal{N}^{\mathtt{P}}$ is used, 0 otherwise.

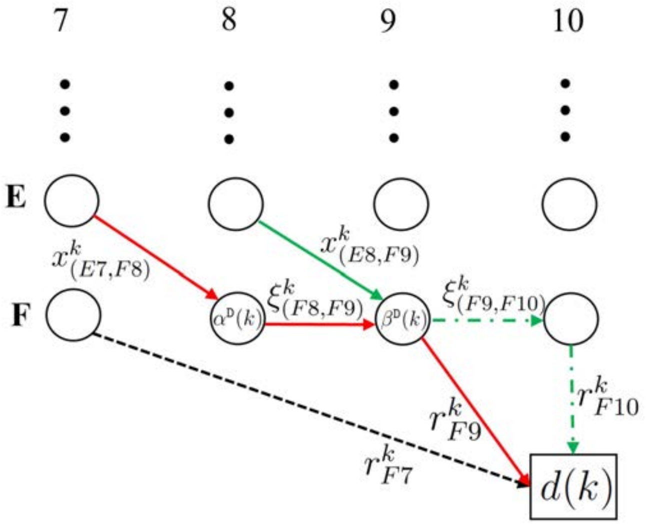
Time-Space Network



Services (single and multi-leg)



Demand at origin



Demand at destination

SSND-RM Formulation

Max profit = revenue – (penalties + transport + hold) shipments – select single and bundle services – warehousing costs

$$\sum_{k\in\mathcal{K}} w_k \Big[\rho_k z_k - \sum_{t\in\mathcal{T}} \psi^k_{(o(k),t)} r^k_{(o(k),t)} - \sum_{t\in\mathcal{T}} \psi^k_{(d(k),t)} r^k_{(d(k),t)} - \sum_{a\in\mathcal{A}^{\mathtt{E}}} c^k_a x^k_a - \sum_{a\in\mathcal{A}^{\mathtt{H}}} \bar{c}^k_a \xi^k_a \Big] - \sum_{\sigma\in\Sigma} f_\sigma y_\sigma - \sum_{b\in\mathcal{B}} f_b \gamma_b - \sum_{n\in\mathcal{N}^{\mathtt{P}}} f_n \lambda_n$$

No-split pickup & delivery

$$\text{s.t.} \quad z_k = \sum_{t\in\mathcal{T}} r^k_{(o(k),t)} \qquad k\in\mathcal{K}$$

$$z_k = \sum_{t\in\mathcal{T}} r^k_{(d(k),t)} \qquad k\in\mathcal{K}$$

Shipper-request flow conservation

$$r^k_{(o(k),t)} + \sum_{a\in\mathcal{A}^{\mathtt{E}(-)}(o(k),t)} x^k_a + \xi^k_{((o(k),t-1),(o(k),t))} = \sum_{a\in\mathcal{A}^{\mathtt{E}(+)}(o(k),t)} x^k_a + \xi^k_{((o(k),t),(o(k),t+1))} \qquad k\in\mathcal{K}, (o(k),t)\in\mathcal{N}$$

$$r^k_{(d(k),t)} + \sum_{a\in\mathcal{A}^{\mathtt{E}(+)}(d(k),t)} x^k_a + \xi^k_{((d(k),t),(d(k),t+1))} = \sum_{a\in\mathcal{A}^{\mathtt{E}(-)}(d(k),t)} x^k_a + \xi^k_{((d(k),t-1),(d(k),t))} \qquad k\in\mathcal{K}, (d(k),t)\in\mathcal{N}$$

$$\sum_{a\in\mathcal{A}^{\mathtt{E}(-)}(n,t)} x^k_a + \xi^k_{((n,t-1),(n,t))} = \sum_{a\in\mathcal{A}^{\mathtt{E}(+)}(n,t)} x^k_a + \xi^k_{((n,t),(n,t+1))} \qquad k\in\mathcal{K}, (n,t)\in\mathcal{N} : n\neq o(k), n\neq d(k)$$

SSND-RM Formulation (2)

Services selected at most once	$\sum_{b \in \mathcal{B}: \sigma \in \Sigma(b)} \gamma_b \leq 1 - y_\sigma$	$\sigma \in \Sigma$
Segment linking/capacity	$\sum_{k \in \mathcal{K}} w_k x^k_{a_l(\sigma)} \leq u_{a_l(\sigma)} (y_{a_l(\sigma)} + \sum_{b \in \mathcal{B}: \sigma \in \Sigma(b)} \gamma_b)$	$a \in \mathcal{A}^E$
Terminal handling capacity	$\sum_{k \in \mathcal{K}} w_k [\sum_{a \in \mathcal{A}^{\mathtt{E}(-)}(n,t)} x^k_a] \leq u^{\mathtt{MH}}_{(n,t)}$	$(n,t) \in \mathcal{N}$
Terminal storage capacity	$\sum_{k \in \mathcal{K}} w_k \xi^k_{((n,t-1),(n,t))} \leq u^{\mathtt{W}}_n \lambda_n$	$(n,t) \in \mathcal{N}$
Shipper contracts serviced	$z_k = 1$	$k \in \mathcal{K}^{\mathtt{C}}$

$z_k \in \{0,1\}$	$k \in \mathcal{K}^{\mathtt{NC}}$
$r^k_{(o(k),t)} \in \{0,1\}$	$k \in \mathcal{K}, (o(k),t) \in \mathcal{N}$
$r^k_{(d(k),t)} \in \{0,1\}$	$k \in \mathcal{K}, (d(k),t) \in \mathcal{N}$
$x^k_a \in \{0,1\}$	$k \in \mathcal{K}, a \in \mathcal{A}^{\mathtt{E}}$
$\xi^k_a \in \{0,1\}$	$k \in \mathcal{K}, a \in \mathcal{A}^{\mathtt{H}}$
$y_\sigma \in \{0,1\}$	$\sigma \in \Sigma$
$\gamma_b \in \{0,1\}$	$b \in \mathcal{B}$
$\lambda_n \in \{0,1\}$	$n \in \mathcal{N}^{\mathtt{P}}$.

Plan

- Consolidation-based transport and logistics (T&L)
- Planning the capacity
  - The classic approach – A carrier tactical planning illustration (SSND)
- Enhancing capacity representation – Integrating Bin Packing methodology
  - Shipper facility / corridor illustrations
- Perspectives

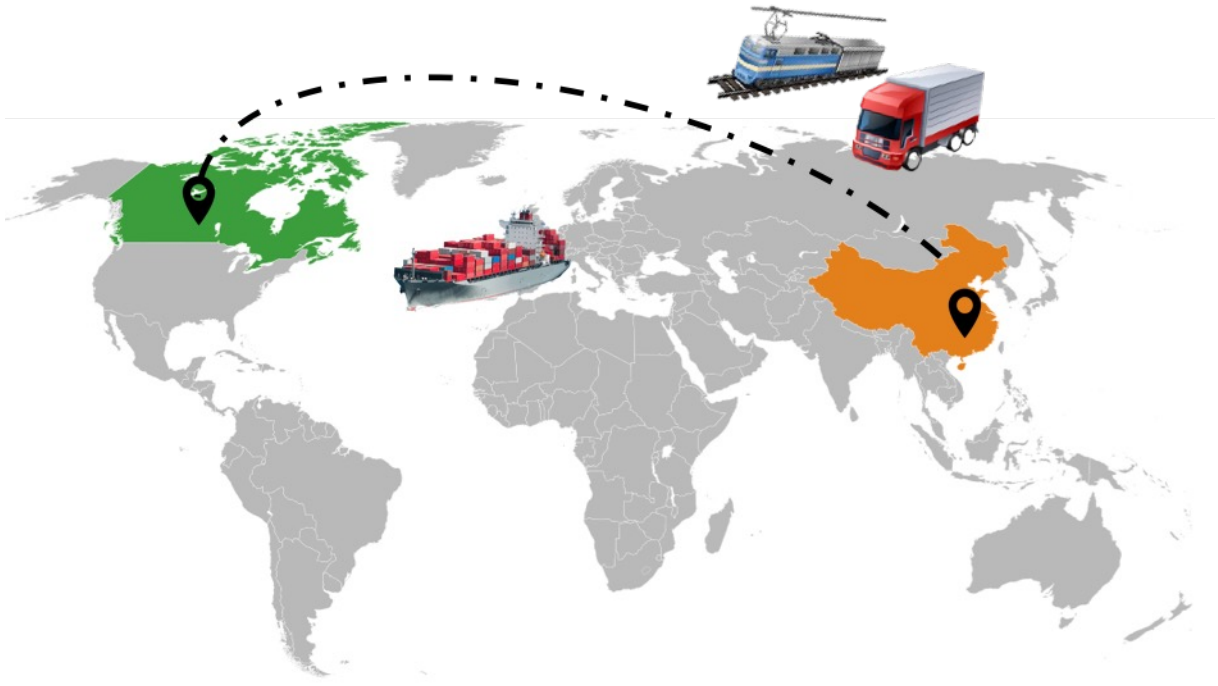
Enhancing Capacity Representation

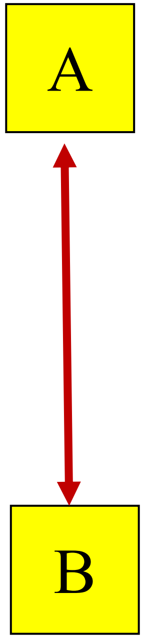
- Classic approach ignores most attributes of capacity units and demand flows in terms of loading/packing and utilization
  - Dimensions, types, selection issues, ...
- Integrating Bin Packing methodologies appears as a very interesting approach
- Not much research yet !

	Single node		Network	
	Strategic	**Tactic**	**Strategic**	**Tactic**
Shipper	Crainic et al., 2023 Crainic et al., 2016 Crainic et al., 2014a	Crainic et al., 2021a Crainic et al., 2016 Crainic et al., 2014a	None	None
Carrier	Bruni et al., 2023b	Bruni et al., 2023a Perboli et al., 2021a Baldi et al., 2019 Perboli et al., 2012 Baldi et al., 2012a	None	Hewitt and Lehuédé, 2023 Côté et al., 2017

- Illustration on shipper planning for a facility / corridor

Shipper Capacity Planning on (“simple”) Corridor





Service zone
Shenzhen (China) or
Montreal city & region

Long-haul
multi-modal, multi-carrier

Service zone
Vancouver (Canada) or
Toronto city & region

Shipper Capacity Planning

- Secure now (plan for) sufficient capacity from multiple offers (from $M \geq 1$ carriers) to use repeatedly over the next tactical planning horizon to store or move loads
  - Load units = "items", various attributes, e.g., size
  - Capacity units = "bins", various attributes, e.g., (fixed) cost & size
- Modelling = Variable Size and Cost Bin Packing
  - Variants, bounds, heuristics, meta-heuristics … (early 2010s')
  - Based on a point forecast of future demand and, thus, no need to worry for future (ad hoc) supply availability … !

Shipper Capacity Planning (2)

- Shipper decision maker – accounting for uncertainty
- Sources of uncertainty
  - Demand: Item characteristics (e.g., size)
  - Ad hoc (spot market) future capacity when needed:
    Bin cost & availability (by type)
  - Availability of contracted capacity:
    (no/partial show, capacity loss due to damage, unloaded items, ...)
    Number, cost, available capacity
- Accounting for such uncertainty into tactical-planning methodology =
  Stochastic Variable Size and Cost Bin Packing with Capacity Loss
  (Crainic et al. 2016, 2020, 2021)

Shipper Stochastic VSCBP with Capacity Loss (3)

- Two-stage SP model with recourse
- First stage: Tactical decisions
  - *A priori* capacity (bin) selection
- Second stage: Operational plan-adjustment / Recourse actions once realized capacity & spot market observed
  - Acquire ad hoc capacity on spot market
  - Re-optimize capacity utilization = item-to-bin assignment
- Progressive Hedging-based meta-heuristic (Rockafellar and Wets 1991; Crainic et al. 2016)
  - Considering uncertainty is valuable !
  - Behavior-analysis tool

Capacity selection + Expected recourse cost

$$\min_{y} \sum_{t\in T}\sum_{j\in\mathcal{J}^t} f^t y_j^t + E_\xi\left[Q\left(y,\xi(\omega)\right)\right]$$

$$\text{s.t.}\quad y_j^t \ge y_{j+1}^t, \quad \forall t\in T, j = 1,\dots,|\mathcal{J}^t|-1,$$

$$y_j^t \in \{0,1\}, \quad \forall t\in T, j\in\mathcal{J}^t.$$

Break bin selection symmetry

where

$$Q(y,\xi(\omega)) = \min_{z(\omega),x(\omega)} \sum_{\tau\in\mathcal{T}}\sum_{k\in\mathcal{K}^\tau(\omega)} g^\tau(\omega) z_k^\tau(\omega) + \sum_{t\in T}\sum_{j\in\mathcal{J}^t} c^t(V^t - \mathcal{V}_j^t(\omega))y_j^t$$

Extra capacity selection + Capacity loss cost

$$\text{s.t.}\quad \sum_{j\in\mathcal{J}} x_{ij}(\omega) + \sum_{k\in\mathcal{K}(\omega)} x_{ik}(\omega) = 1, \quad \forall i\in\mathcal{I}(\omega),$$

$$\sum_{i\in\mathcal{I}(\omega)} v_i(\omega)x_{ij}(\omega) \le \mathcal{V}_j^t(\omega)y_j^t, \quad \forall\, t\in T, j\in\mathcal{J}^t,$$

$$\sum_{i\in\mathcal{I}(\omega)} v_i(\omega)x_{ik}(\omega) \le V^\tau z_k^\tau(\omega), \quad \forall\,\tau\in\mathcal{T}, k\in\mathcal{K}^\tau(\omega),$$

$$x_{ij}(\omega)\in\{0,1\}, \quad \forall\, i\in\mathcal{I}(\omega), j\in\mathcal{J},$$

$$x_{ik}(\omega)\in\{0,1\}, \quad \forall\, i\in\mathcal{I}(\omega), k\in\mathcal{K}(\omega),$$

$$z_k^\tau(\omega)\in\{0,1\}, \quad \forall\,\tau\in\mathcal{T}, k\in\mathcal{K}^\tau(\omega).$$

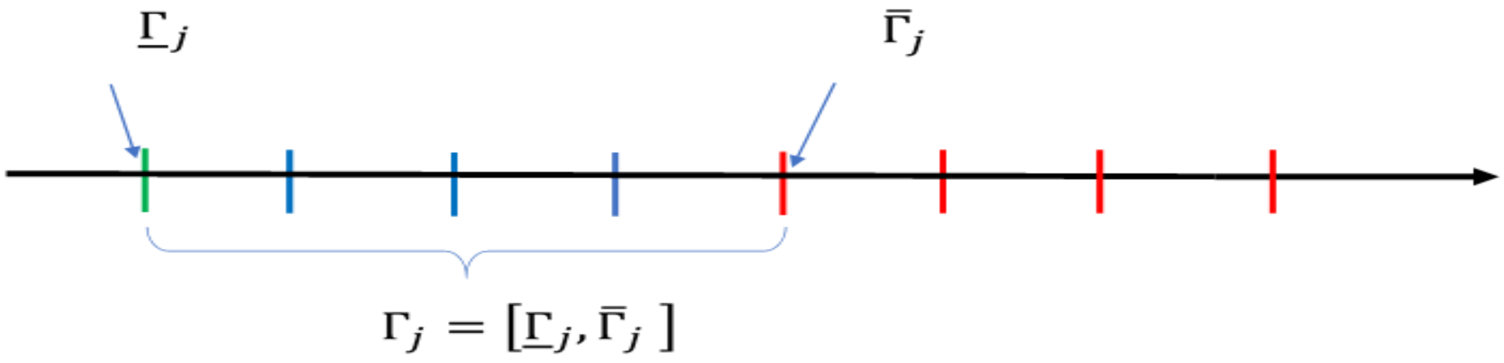
Assign & Pack

Time-Sensitive VSCBP with Assignment Costs

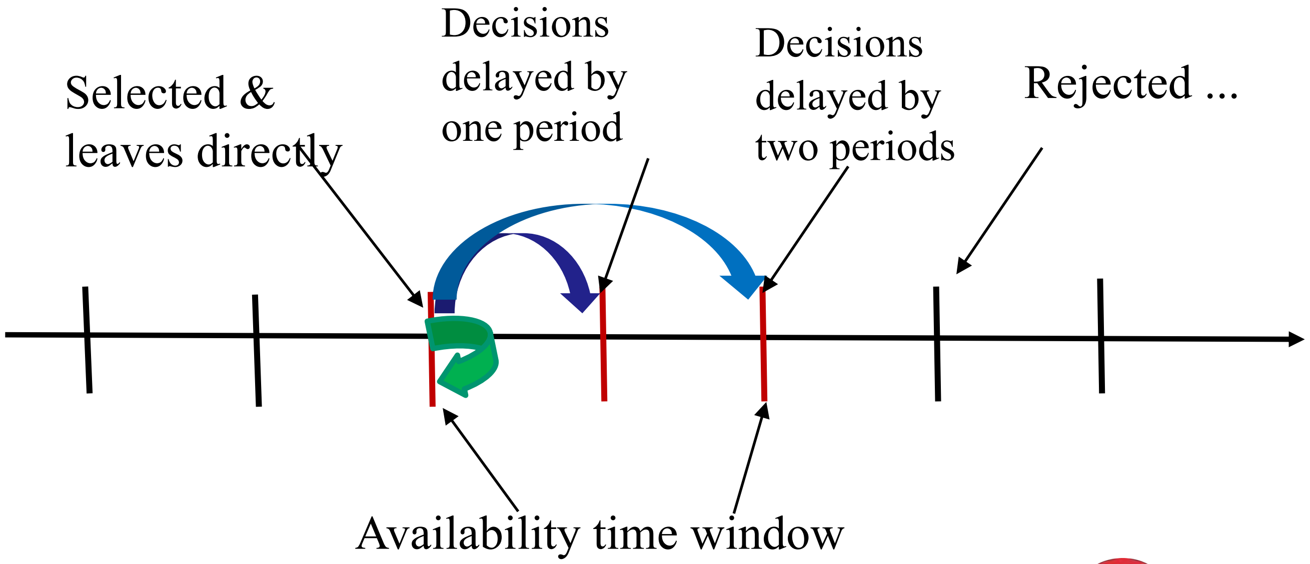
- Time characteristics for shipments (items) and capacity offers (bins) (Fomeni et al. 2021)
  - When available and when picked up?
  - When it can leave and when it will leave?
  - How long it may be delayed?
- Take advantage of time to increase the consolidation opportunities & play the delay-penalty game to find the best total cost solution
- Bin packing (VSCBP) formulations may be extended

Time-Sensitive VSCBP with Assignment Costs (2)

- Supply (Bins)
  - Fixed cost (and type)
  - Capacity
  - Availability time window for departure
  - Duration (travel time)

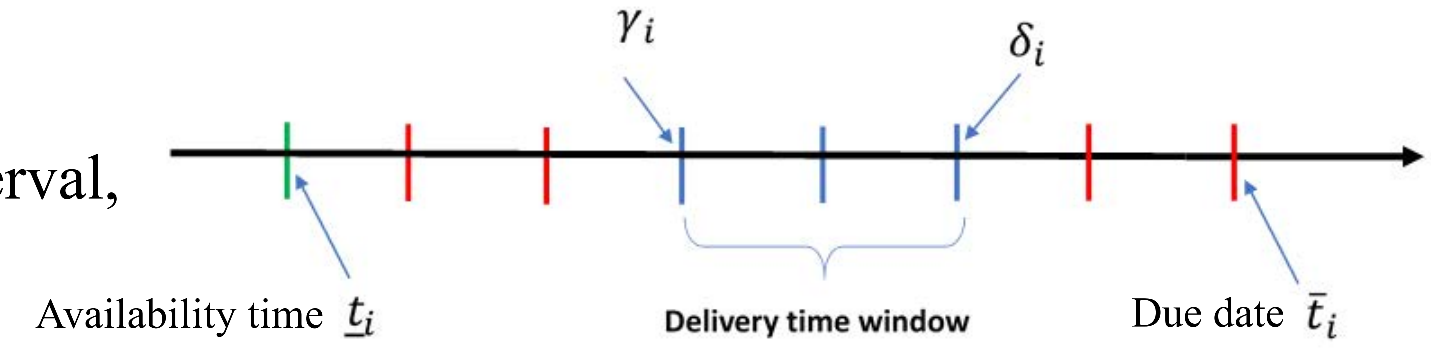


- Selection and departure (delayed) decisions

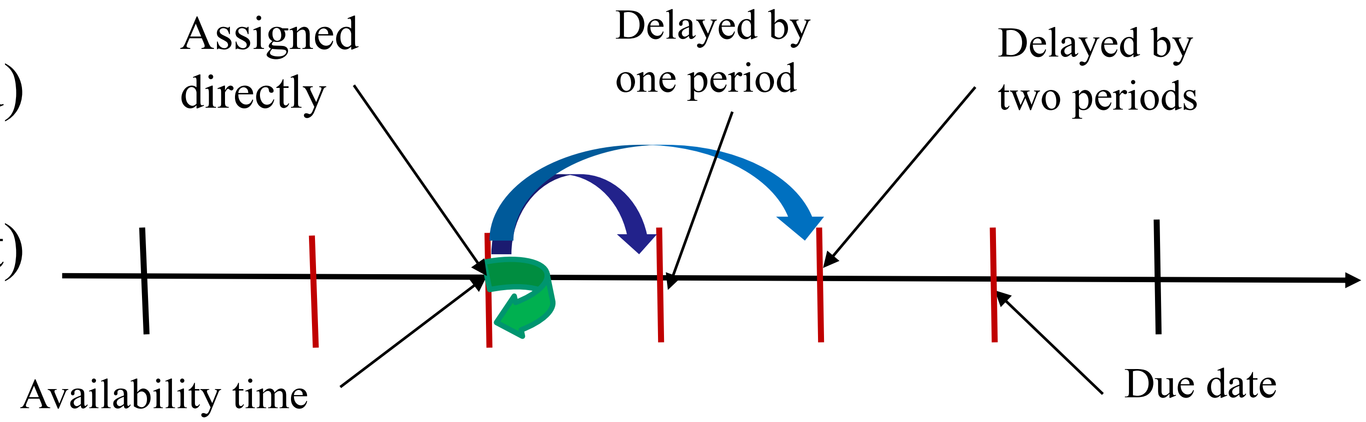


Time-Sensitive VSCBP with Assignment Costs (3)

- Demand (Items)
  - Volume (weight, ...)
  - Availability period, due-date interval, maximum late delivery



  - Assignment to selected bin (delayed) decisions
  - Selection of ad hoc bin (spot market) when needed



Multi-period VSCBP with Assignment Costs (4)

$$y_j^t = \begin{cases} 1 & \text{if bin } j \in \mathcal{J} \text{ is selected at time period } t \in \Gamma_j, \\ 0 & \text{otherwise;} \end{cases}$$

$$x_{ij}^t = \begin{cases} 1 & \text{if item } i \in \mathcal{I} \text{ is assigned to bin } j \in \mathcal{J} \text{ at time period } t \in \mathcal{T}_{ij}, \\ 0 & \text{otherwise;} \end{cases}$$

$$u_i^t = \begin{cases} 1 & \text{if item } i \in \mathcal{I} \text{ is assigned to a spot-market bin at time period } t \in \mathcal{T}_i, \\ 0 & \text{otherwise.} \end{cases}$$

$$\min_{y,x,u} \sum_{j\in\mathcal{J}} \sum_{t\in\Gamma_j} f_j y_j^t + \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} \sum_{t\in\mathcal{T}_{ij}} a_{ij}^t x_{ij}^t + \sum_{i\in\mathcal{I}} \sum_{t\in\mathcal{T}_i} p_i^t u_i^t$$

Select bins + assign items to bins + select ad-hoc bins

$$s.t. \quad \sum_{i\in\mathcal{I}} v_i x_{ij}^t \le V_j y_j^t, \qquad \forall j \in \mathcal{J}, t \in \Gamma_j,$$

Linking / capacity

$$\sum_{j\in\mathcal{J}} \sum_{t\in\mathcal{T}_{ij}} x_{ij}^t + \sum_{t\in\mathcal{T}_i} u_i^t = 1, \qquad \forall i \in \mathcal{I},$$

Load all items

$$\sum_{t\in\Gamma_j} y_j^t \le 1, \qquad \forall j \in \mathcal{J},$$

Select bins at most once

$$y_j^t \in \{0,1\}, \qquad \forall j \in \mathcal{J}, t \in \mathcal{T}_j,$$

$$x_{ij}^t \in \{0,1\}, \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, t \in \mathcal{T}_{ij},$$

$$u_i^t \in \{0,1\}, \qquad \forall i \in \mathcal{I}, t \in \mathcal{T}_i.$$

Time-Sensitive VSCBP with Assignment Costs (5)

- General multi-period (time-dependent) model
  - Single-period model with no anticipation
- Constructive heuristics based on classical best/first-fit-decreasing ideas
  - Several item or bin criteria
  - Time-based decomposition
  - Very fast – may be applied together;
  - Very good (particularly when dimensions grow)
- Uncertainty – work in progress

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Research Perspectives

- Integration of packing considerations/constraints in network capacity planning
  - SND & SSND
    - Split demand-flows → What / how many items to pack?
    - Single or several bins on each service leg (node)
    - Conservation of flows on bins
  - SSND with resource management, i.e., selecting and managing “bins”
    - Selecting the bin combination for each service leg (node)
    - Circulation of multi-type bin flows

Research Perspectives (2)

- Integration of packing considerations/constraints in network capacity planning
- SND & SSND & SSND+RRM & SSND-M1M & SSND-VRP & SSND+Hubs
  - Higher-dimension packing considerations (not only physical)
  - Selection of suppliers (with reliability scores) & customers
  - Adding layers of design decisions – nice models, challenging to address
  - Uncertainty
    - Demand, time, costs, ...
    - Reliability, resilience (beyond "business-as-usual")
    - Expert estimations (poor theoretical/experimental distributions)
- Solution methods

Research Perspectives (3)

- Generalization / extension of packing problems
  - Higher dimensions (not only physical)
    - Multiple attributes, e.g., costs, profits, quality, time ...
  - Item differentiation & selection
  - Selection of suppliers (with reliability scores)
  - Integrating Revenue Management
  - Uncertainty
    - Demand, time, costs, ...
    - Reliability, resilience (beyond "business-as-usual")
    - Expert estimations (poor theoretical/experimental distributions)
  - Solution methods

Research Perspectives (4)

- Richer environments (problem settings)
  - Multi-stakeholders
    - Integrated decision-making, sharing networks & resources
    - “New” stakeholders, e.g., policy makers & institutional entities
  - Regional/national/larger spaces analysis & planning
- Modelling time and time-dependent/sensitive events
  - Combining discreet and continuous representations
  - Synchronizing decisions and flows
- Non-linear formulations – congestion, penalties, etc.
  - Flexibility in capacity modelling at medium & long-term planning levels
  - Regularity in meeting quality targets

Merci beaucoup !
Thank you very much !