Operations Research & City Logistics Planning

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Urban Freight Transport & Logistics

- "Derived" but essential to most economic and social activities
  - No transportation = No society as we know it
  - No logistics = No modern economy
- *Cities cannot survive without freight transportation*
  - Bring in what is needed to live, work & play
  - Take out what is produced: goods & refuse
  - Internal movements of goods for people, stores, firms, institutions, …

The City and Freight Transportation
Vital but Many Drawbacks

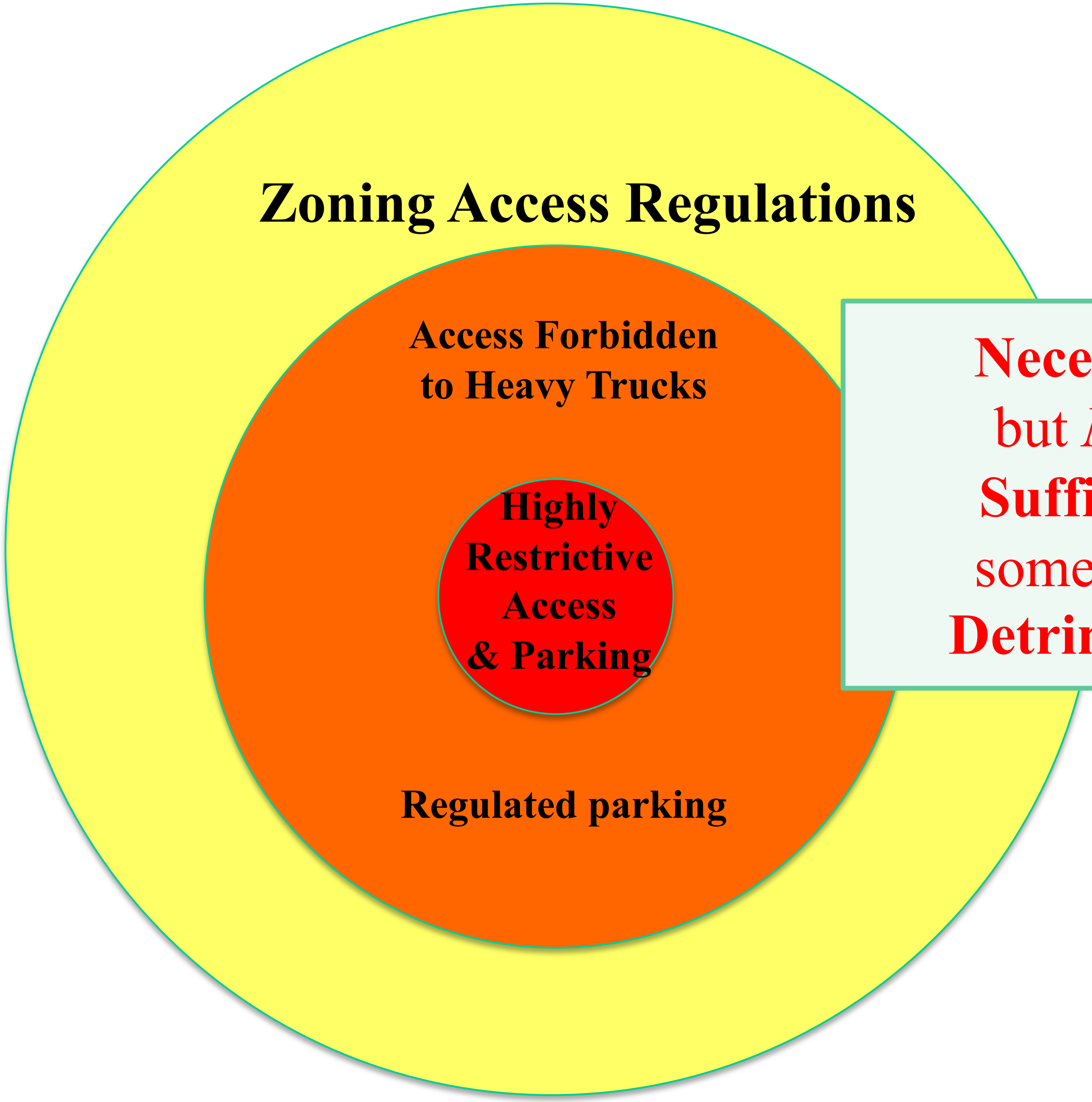
Issues & Challenges

- Transportation systems & logistics chains are
- Efficient
  - Freight flows around the globe supplying people, industry, institutions
  - On time, low cost, making a profit …
- Inefficient
  - System perspective: congestion, competing with people, land use, safety, ...
  - Costs for society, individuals, firms & organizations: environment, energy consumption, time & money lost, ...
  - Resource – infrastructure, vehicles, facilities - utilization
- The current model for the development and management of (urban) freight transportation is **not** sustainable

Issues & Challenges (2)

- Heavy trend toward world-wide urbanization
  An urban planet of continuously growing cities
- Accelerating factors
  - People (and organizations) behaviour & requirements
    E-business, Express delivery, JIT/door-to-door, ...
  - Reverse/green logistics, …
- Freight volumes, number of vehicles & impacts are continuously growing
- Better engines **but** more vehicles ⇒
  Pollution due to freight transport is raising

What Can We Do? Regulate! Well …



Necessary
but ***NOT***
Sufficient
sometimes
Detrimental

Serious Freight Traffic Issues in Cities: Nothing New 😇

- Roma: Imperial city and center of the world (as Rome was claiming ...)
- Streets shared by people on foot, on horseback, in sedan chairs + chariots and wagons with iron-clad wheels + vendor stalls + …
  - ⇒ Congestion, incidents, accidents …
- Cesar, 45 a.c., bans cattle-drawn wagons during daylight (except Vestals, Priests & empties leaving the city)
  - ⇒ Great noise in the night and unhappy citizens
- Hadrian,117-138, limits freight traffic during the night as well …
  - ⇒ Human (slave)-powered distribution ...
- ... Larger and larger cities, more and more intensive trade and transport, ... more and more troubles & regulation with so-and-so results ...

What Can We Do? Innovate!

- Change the way things are perceived, planned, and performed
- "New" organizational (and business) strategies/models
  - Foster efficient & sustainable transportation & logistics systems
    - Address externalities
    - Without penalizing the economic development
    - Rally stakeholders and reconcile their requirements
- Become part of mainstream urban design and planning
- Go beyond "urban freight transport" to City Logistics

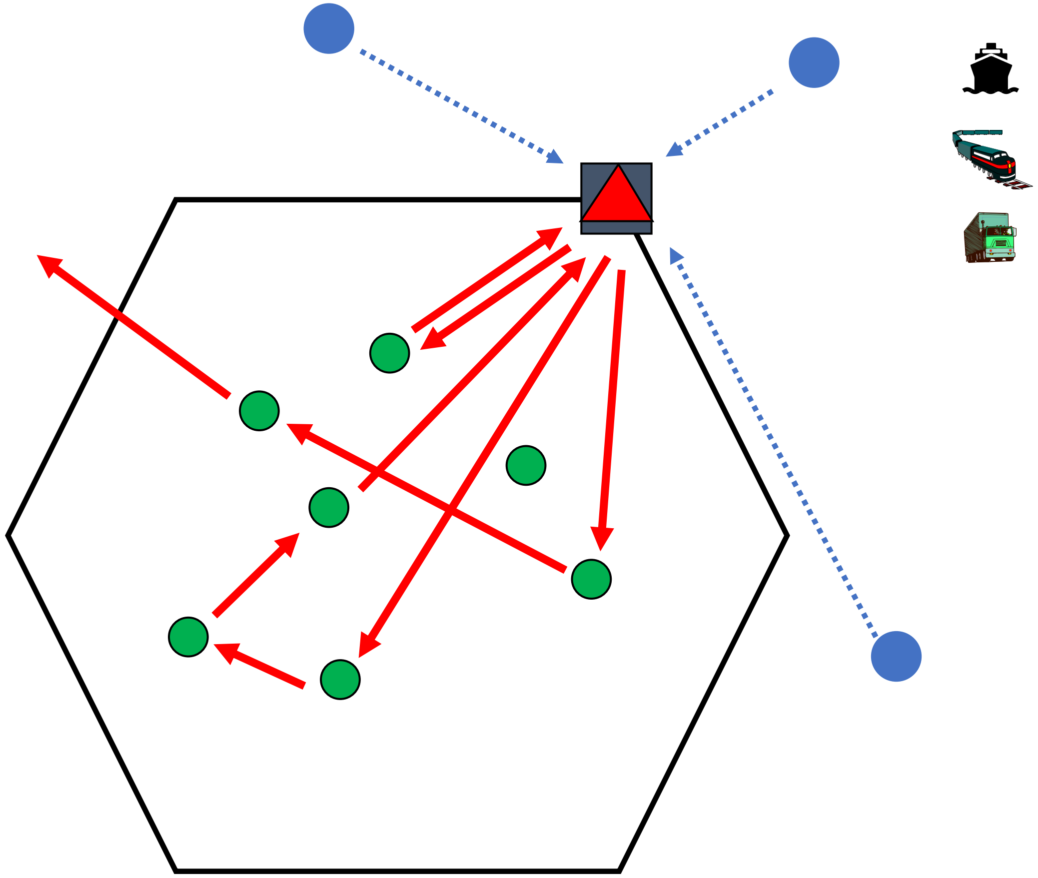
City Logistics

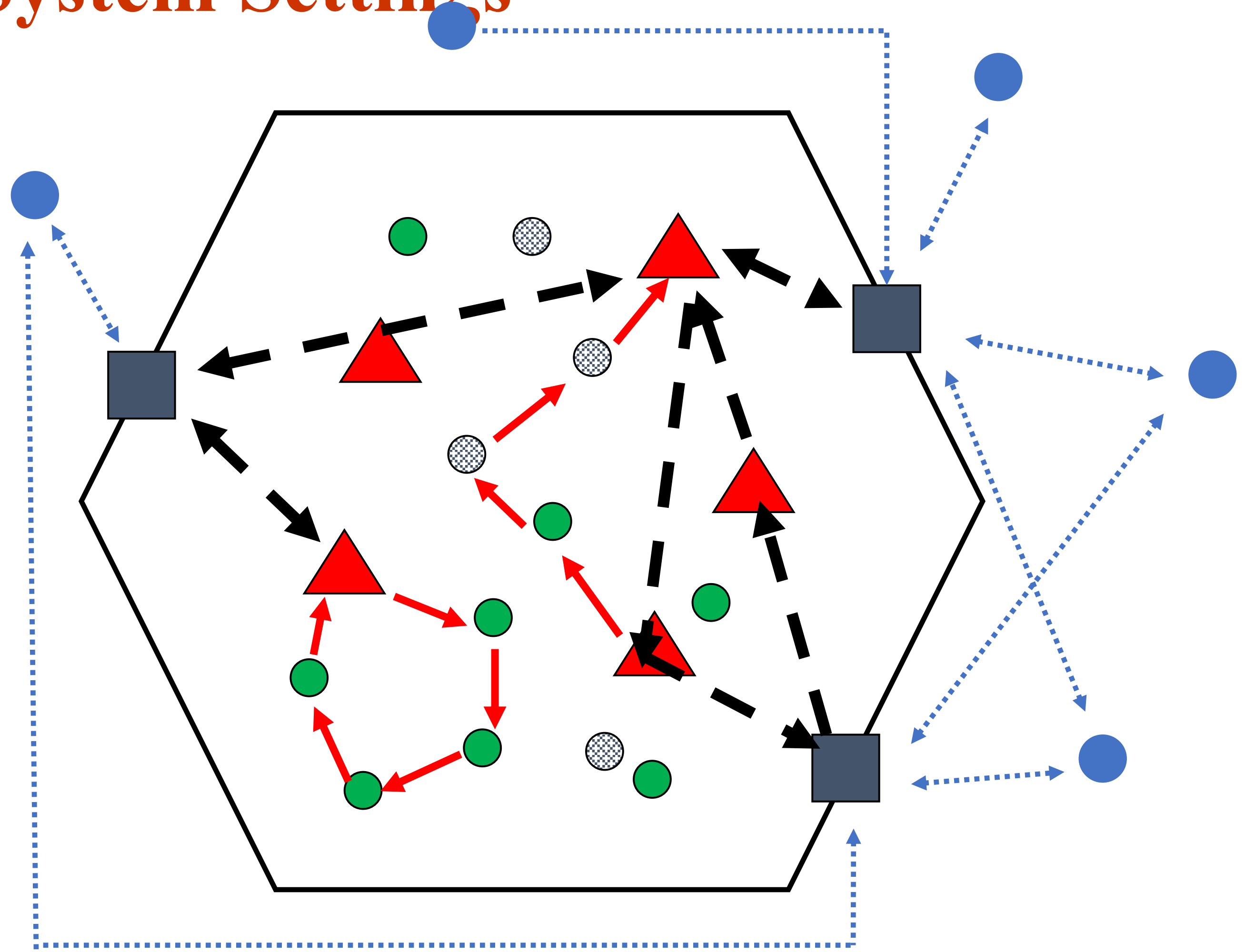
- Reduce & control freight-vehicle types, flows & impacts
  - Vehicles (eco-friendly) & infrastructure appropriate for each city zone/neighbourhood and activity type
  - Higher capacity utilization, less empty vehicle-km
- Move from truck-based to a multi/intermodal system
- To reduce the environmental footprint & impact on congestion & quality of life (“interference” with people)

City Logistics (2)

- Continuous developments and challenges
  - Many projects, ideas, pilot studies, implementations (some) …
  - For individual organizations or a set of stakeholders
    - Many concepts taken up by industry
- Addressing the demand and the supply sides
  - Move the freight out of the way in space or time
  - “Optimized” (integrated) logistics system
    - Collaboration & sharing (resources, data, & decision making)
    - Consolidation
    - Multi-tier systems
- Obviously, new technology, new problem settings & decisions
- ⇒ Challenges for Operations Research & Transportation Science

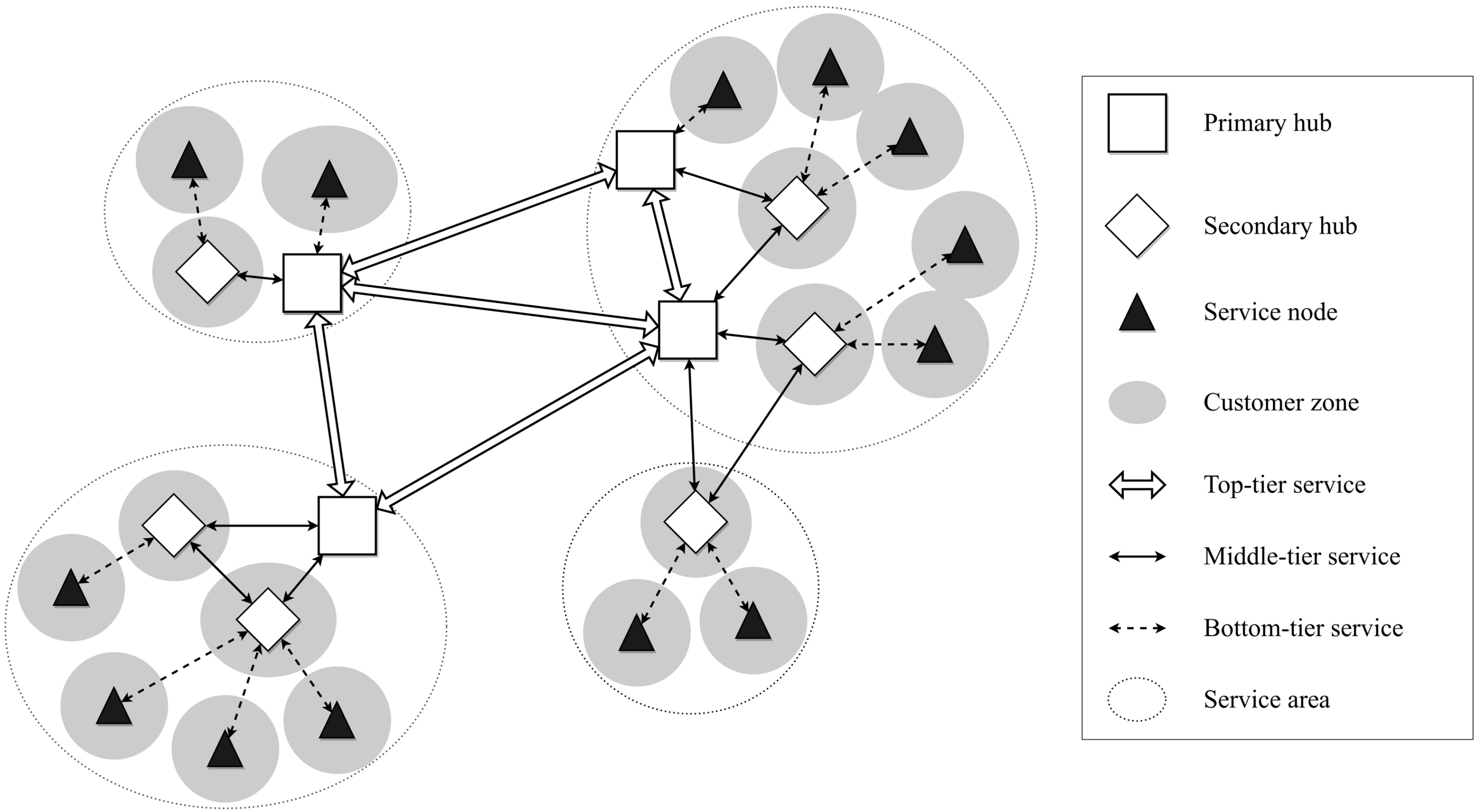
Single/Last and Two-Tier CL System Settings





External customer zone
Inbound   Outbound   customer
CDC
Satellite
Urban-vehicle route
City-freighter route

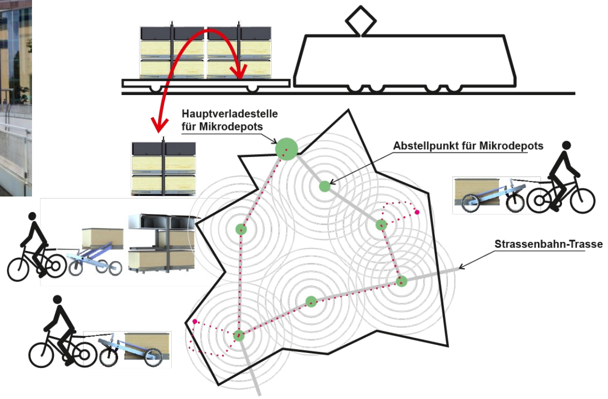
Multi-tier Settings



CDC

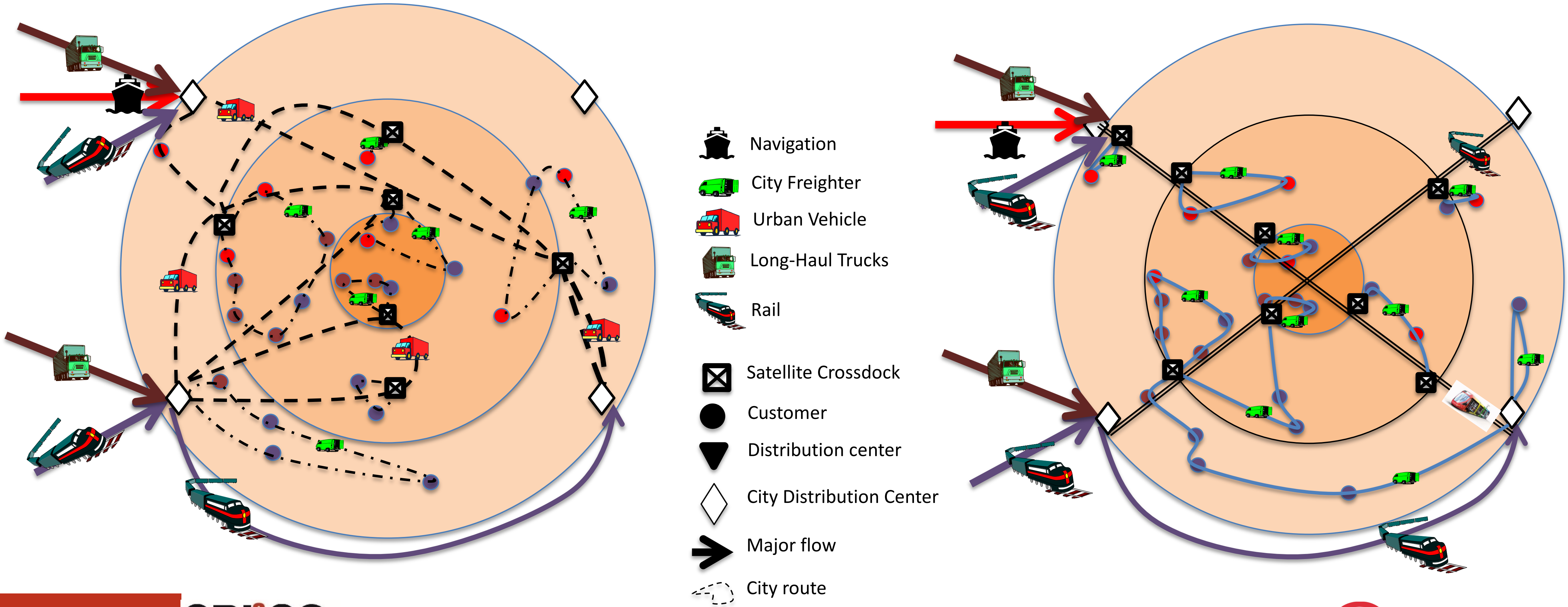
Satellites
(mini hubs, etc.)

Tier-Appropriate Ecofriendly Vehicles



Frankfurt logistiktram.de - © Herbert Riemann

Multi-tier CL "Classical" vs. Rail (Private) & Transit (Public)



Scope of Talk

- 30+ years of City Logistics
- ~25 years of Operations Research methodology to plan and manage CL
- Recall (some) main contributions to planning the *supply* side of CL
  - Design the system
  - Design the service
- With a few thoughts on challenges and perspectives

Recent Relevant Reviews

- Marcucci E, Gatta V, Le Pira M (Eds.), *Handbook on City Logistics and Urban Freight,* Edward Elgar, 2022 forthcoming
  - Crainic, T.G., J. Gonzalez-Feliu, N. Ricciardi, F. Semet, T. Van Woensel, Operations Research for Planning and Managing City Logistics System*s* (long version: CIRRELT-2021-45)
- Crainic, T.G., G. Perboli, N. Ricciardi, City Logistics, *Network Design with Applications in Transportation and Logistics*, T.G. Crainic, M. Gendreau, B. Gendron, (Eds.), Springer, 507–537, 2021

30 – 25 Years + ...

- Historically, sporadic interest but for regulation and taxation
- Brief & intense activity beginning of 70's: Heavy-vehicle traffic regulation
- EU and Japan projects in the 90's
  - Data surveys → Demand models ...
    This field continues to develop
  - Heavily financed, no real CL business models for long-term activities
    - "new" handling activities + extra time & cost need to compensated for (OR!)
  - Many (single tier) implementations with little fundamental research
    Most failed and closed once public money stopped
  - No ITS, no OR (or so little ...)
  - Monaco introduces the CDC-consolidation-based system

30 – 25 Years + ... (2)

- OR-based R&D targeting the supply side initiated "with" the millennium
  - 1999 First CL Conference (Institute for City Logistics, Kyoto U.)
  - Taniguchi at al. 1999
    - First strategic design (location) paper
  - Crainic, Ricciardi, Storchi 2004
    - The Two-Tier CL system; locating satellites
  - Crainic, Ricciardi, Storchi 2009
    - Tactical-operational planning 2T-CL
    - Time-dependent demand and operations
    - Scheduled Service Network Design + multi-period OD-demand VRPTW
    - Two-echelon multi-period OD-demand VRPTW

30 – 25 Years + ... (3)

- The ~25 of OR-based R&D for CL
  - A few contributions only for the initial 10 years
  - The pace increases significantly from 2010 on
  - Continuously increasing flow of contributions
    - Problem settings and new challenges
    - Modelling
    - Algorithmic development
    - Implementations

Planning for City Logistics (Supply)

- Consolidation-based
- Many and varied stakeholders
- Single decision maker, platform (at arm-length)
- Not to be neglected
  - Demand planning
  - Business models
  - Cooperation understandings
  - Politics, public policies
  - Urban & regional planning
  - Social & work relations
  - Taxes & incentives, …

Decisions & Problem Settings	*Models & Algorithms*
Long-term Planning - ***Strategic*** *Organizational, business-model, physical, …* ***System design and deployment, evaluation, …***	Location Location-routing Location-design
Plans & Guidelines ↓ ↑ Measures & Evaluations	
Medium-to-Short-term Planning ***Tactical*** (medium = "season", 4-6 months) ***Service design and resource managemen**t* Service and route selection, demand journeys, synchronization Plans & Guidelines ↓ ↑ Measures & Evaluations ***Operational*** (short = "the day before") Tactical-plan adjustment and disaggregated planning	Service Network Design & Routing First/Last-mile Routing Pickup & Delivery Multi-tier Routing
Plans & Guidelines ↓ ↑ Measures & Evaluations	
Execution ***Dynamically in real-time*** *Re-organization/optimization of activities on new information*	Sets of routes / itineraries Individual route Trip (Path) computation

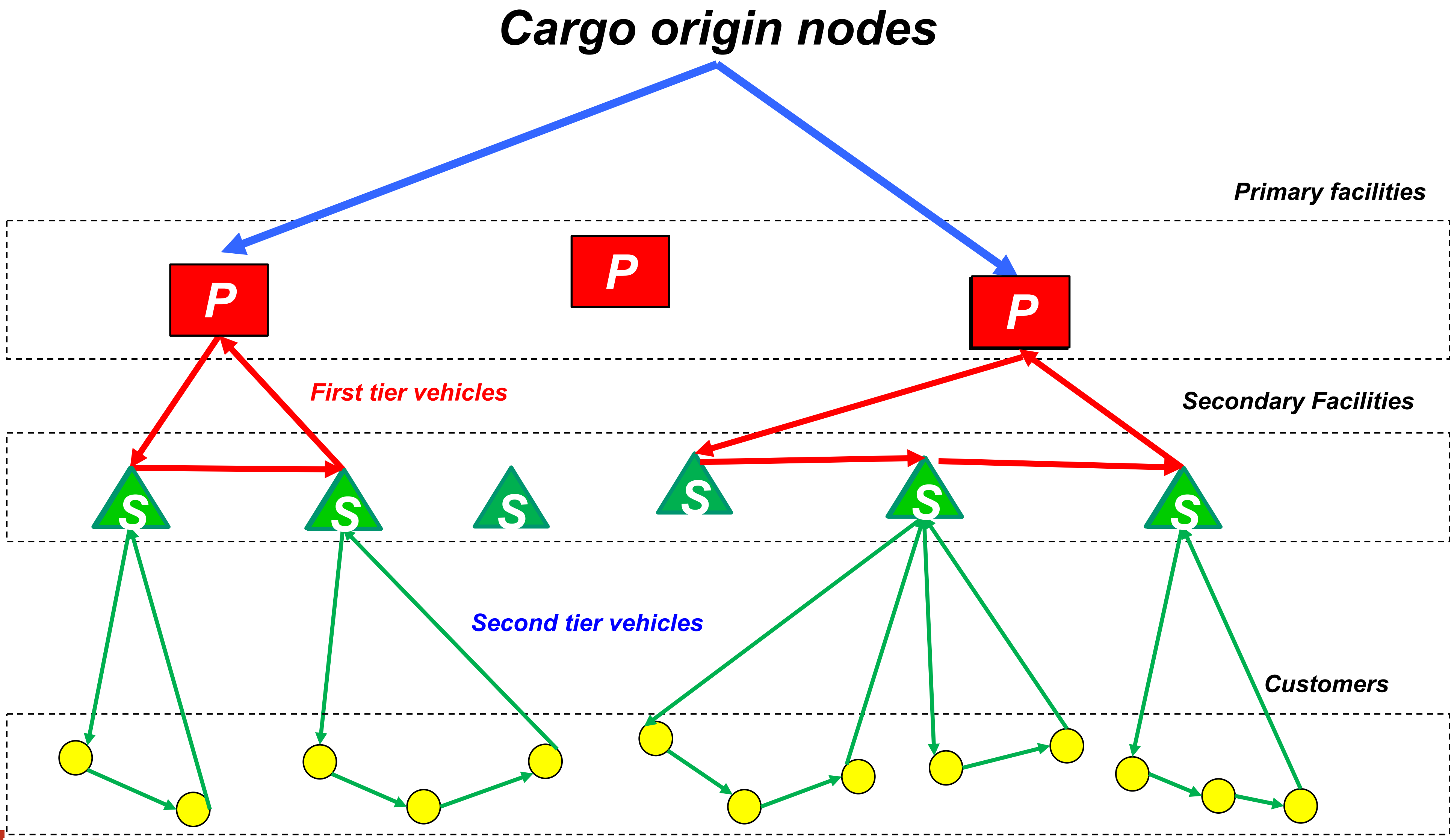
System Representation for Multi-tier City Logistics Planning

- Need a system network representation to optimize the system (strategic) and the service (tactical-operational), particularly for multi-tier *nT-CL*, $n \gg 2$ (most current literature: $n = 2$)
- Two approaches (not very far, yet …)
- Routing nE-VRP and variants (echelon = tier)
  - A routing problem on each tier
- Service network design + routing
  - Scheduled Service Network Design (SSND) on upper (1st, currently) tiers
  - Vehicle Routing Problem(s) (VRP+ or approximations) on lower tiers
- Rich, CL-particular, and complementRY problem settings

System Representation - City Logistics Routing

- Multi-commodity with Origin-to-Destination (OD) demand
- Time-dependent demand (availability @ origins & due-date @ destination)
  ⇒ Scheduled routes ⇒ Synchronization at satellites on multiple tiers
- Multiple types of demand / traffic
  - Inbound (classic; the most addressed)
  - Outbound & local ⇒ Pickup & Delivery
- Multi-tour (fleet management) routing / P&D
- Multi-modal
  - Line-based: light & heavy rail, buses & trolleybuses, barges
  - No-line: trucks, cargobikes, drones, robots, on foot, ..., barges
  - nE-VRP appears less appropriate for line-based modes

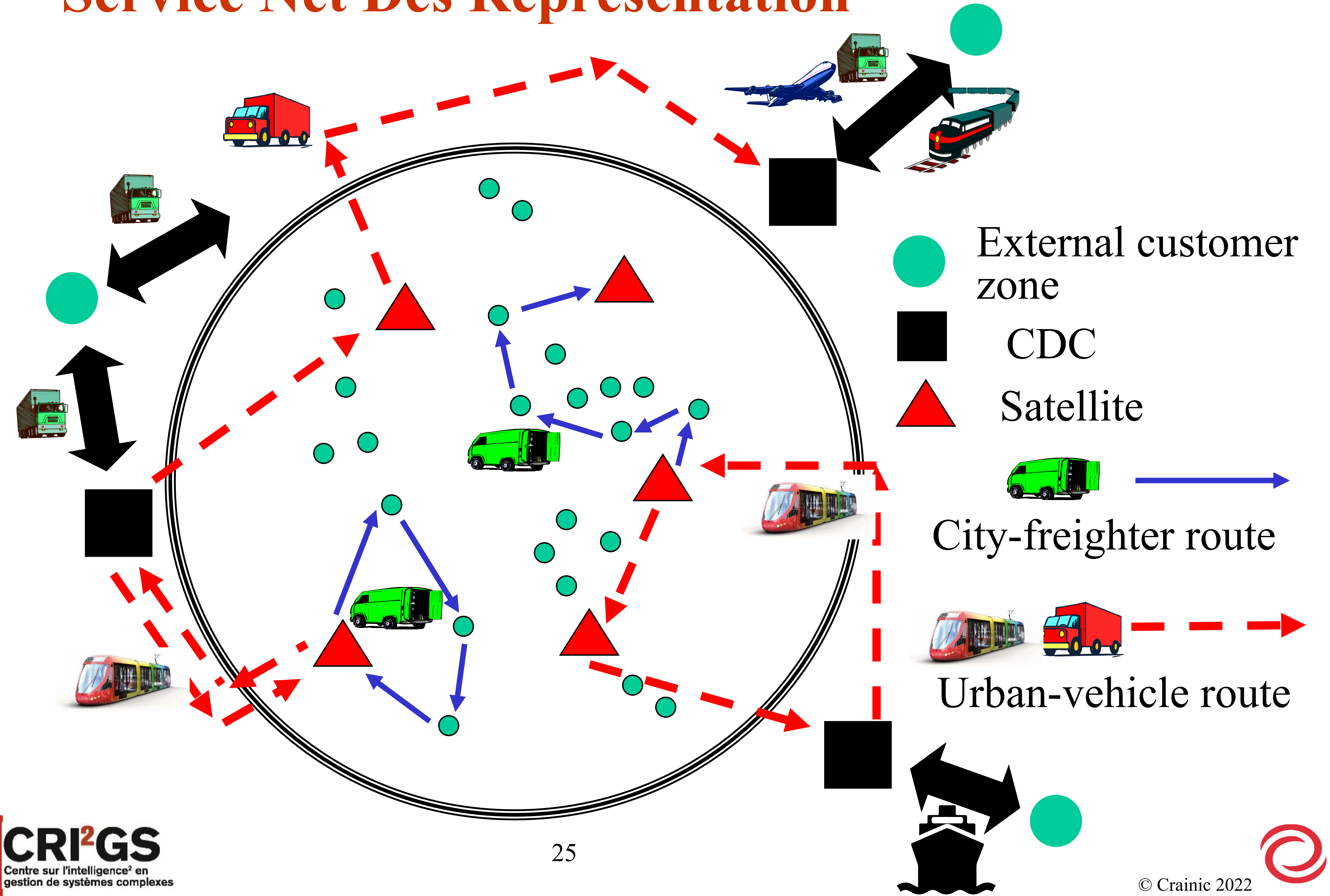
2T-CL – Routing Representation (inbound)



System Representation - City Logistics Service Network Design

- Time-dependent demand ⇒ Scheduled service routes
- Synchronization at satellites (multiple tiers)
  - Vehicles of scheduled services and flows
- Multi-modal: scheduled services on line-based and no-line modes
  - Coexistence – "simultaneous" operation – with people service
- "Large" vehicles, potentially compartmented (e.g., multi-door light rail)
- Multiple types of demand / traffic
  - Inbound (classic; the most addressed), outbound & local
- Fleet management: resource-to-service assignment
- Lower tiers require routing approaches

2T-CL – Service Net Des Representation



Long-term Planning - ***Strategic***

Organizational, business-model, physical, ...

System design and deployment, evaluation, ...

Location

Location-routing

Location-design

Optimize the City Logistics System Design

- Select among potential facilities on one or several tiers
  - Select interconnection network, e.g., street sub-networks for particular fleets
  - Fleet dimensioning
- Determine usage by services, routes, & demand flows
- Min. Generalized cost of the system = selection + usage + impact on the city
- Satisfy demand & enforce physical & operational system attributes & rules
- Methodological approaches
  - Location (allocation)
  - Location-routing
  - Location – service design
- Few contributions yet, mostly single-tier location & based on routing

Facility Location (on a single tier)

- OD (multicommodity) demand matrix
- Binary selection decision variable for each potential site
  - Fixed (generalized) cost & capacity
- Continuous flow (utilization) decision variables on each arc of the network
  - Unit (generalized) transportation cost for each commodity on each arc
  - Arc capacity (global and, possibly, by commodity)
- Minimize total generalized cost of the system, while movind the demand within the system limits

$$\text{Min} \ \sum_j f_j y_j + \sum_j \sum_i c_{ji} x_{ji}$$

$$\text{s.a.} \quad x_{ji} \leq d_i y_j \quad \text{for all } j, i$$

$$x_{ji} \leq u_j y_j \quad \text{for all } j, i$$

$$\sum_i x_{ji} \leq u_j y_j \quad \text{for all } j$$

$$\sum_j x_{ji} = d_i \quad \text{for all } i$$

$$y_j = \{0,1\}$$

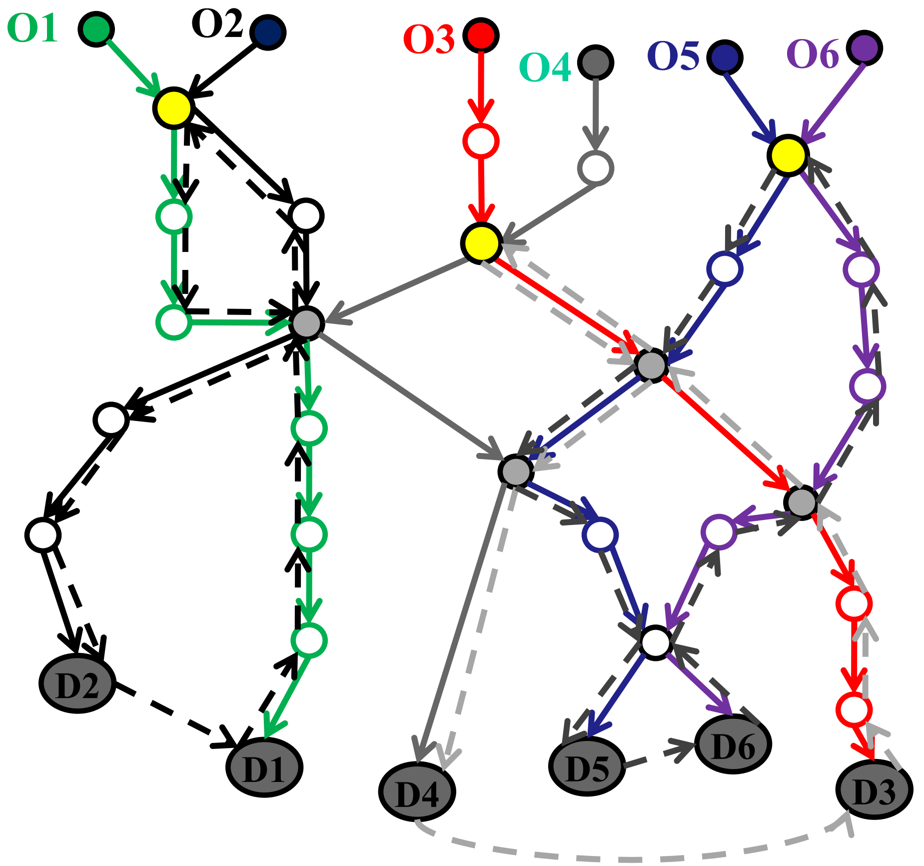
$$x_{ji} \geq 0$$

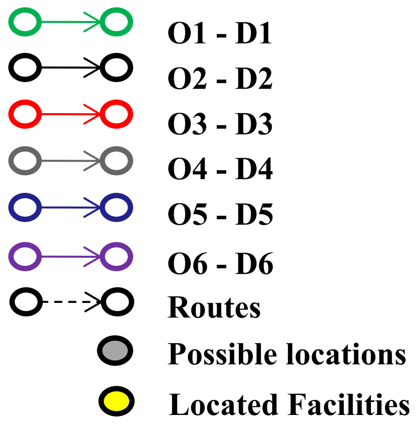
Facility Location (on a single tier)

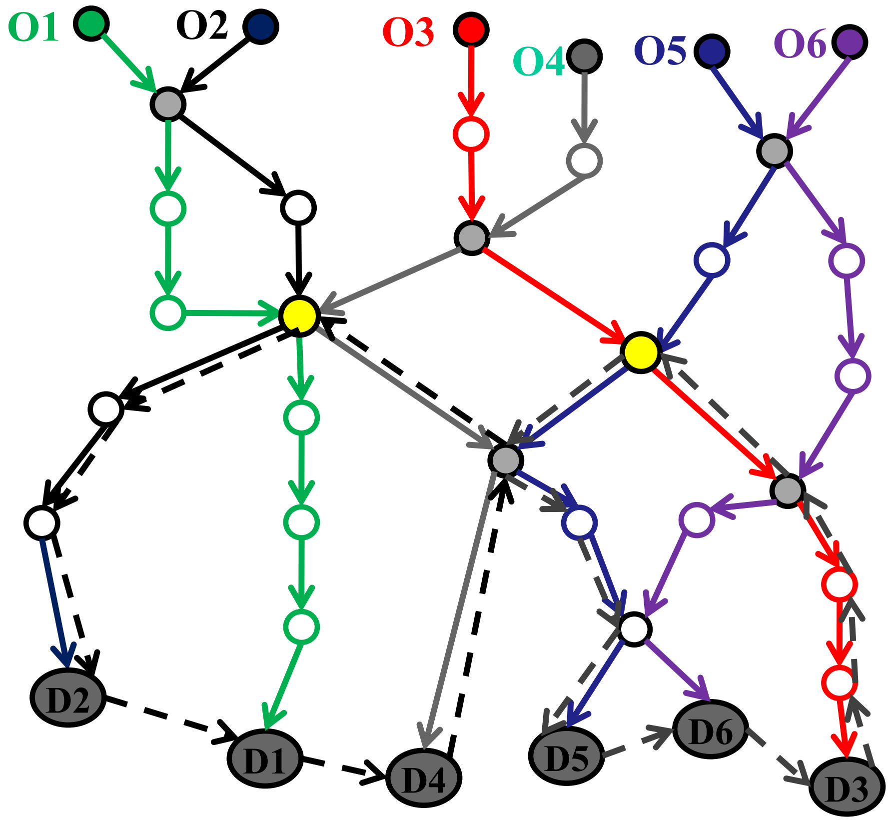
- Combinatorial optimization formulation – "Location-allocation"
  - Need to schematize journeys & approximate routing costs
- Taniguchi et al. (1999)
  - Single-tier, generalized system cost - pollution
  - Bi-level idea: authorities locate, truckers decide usage
  - Two linked models
- Crainic, Ricciardi, Storchi (2004)
  - Two-tier, satellite location only
  - Generalized system cost
    - Undesirability factor on nodes (sites) and arcs (streets)
    - Arc costs = min-cost path within street network

Location-Routing (LRP)

- Utilization = represent explicitly the network and the routing of vehicles carrying freight out of / into selected facilities
- Guyon et al. (2012) first CL LRP model
  - Single tier, fleet, inbound demand
  - Generalized cost: environment and social impact
- Most contributions: Locate on a single tier (multi-tier settings), inbound
  - Gianessi et al. (2016): Locate facilities & a high-capacity ring + routing
  - Boccia et al. (2018): Flow-intercepting LRP
    - Take advantage of actual urban network and flow patterns
    - Locate satelites to intercept the currently-known paths
    - Many questions open !!







Flows intercepted by 3 facilities as near as possible to the origin

→Low travel cost to reach the facilities

→High travel cost to reach the destinations

→High routing costs

Flows intercepted by 2 facilities further towards destinations

Increased travel cost to reach the facilities

→Reduced travel cost to reach the destinations

→Reduced routing costs

Facility Location on Multi-tier Systems

- Locate on several tiers simultaneously: significantly more challenging
  - Increased combinatorial nature (number of selection variables and linking/feasibility constraints)
  - More complex transportation issues
- Easiest way: Multi-tier location-allocation with approximated inter-facility and facility ↔ customer transportation costs
  - Still difficult (linking decisions on several tiers)
  - Applications in logistics network (supply chain) design
- More precise and challenging: Multi-tier location-routing

Multi-tier Location-Routing (nE-LRP)

- Boccia et al. (2010, 2011)
  - Locate on two tiers
  - Inbound single-commodity flow; no time – static setting
  - Formulations:

    3 (the most detailed) and 2 (somewhat easier to address) index arc models

    1 (the one for “optimal” solutions via column generation) path model

- Most contributions focus on meta- and matheuristics for this “basic” variant

Illustration: A three-index Formulation

Platform set: $p \in P$
Location Cost: H_p
Capacity: K_p
Location variable: $y_p = \{0,1\}$

First echelon vehicles: $g \in G$
Vehicle Capacity: UG
Vehicle Cost: TCG
Vehicle variable: $t^g = \{0.1\}$

Routing cost: CT_{ij}
Flow Variable: f_{ps}
Routing variables: $r_{ij}^g = \{0,1\}$

Satellite set: $s \in S$
Location Cost: H_s
Capacity: K_s
Location variable: $y_s = \{0,1\}$

Customer Set: $z \in Z$
Customer Demand: d_z
Allocation variable: w_{sz}

Second echelon vehicles: $v \in V$
Vehicle Capacity: UV
Vehicle Cost: TCV
Vehicle variable: $t^v = \{0,1\}$

Routing cost: CT_{ij}
Routing variables: $x_{ij}^v = \{0,1\}$

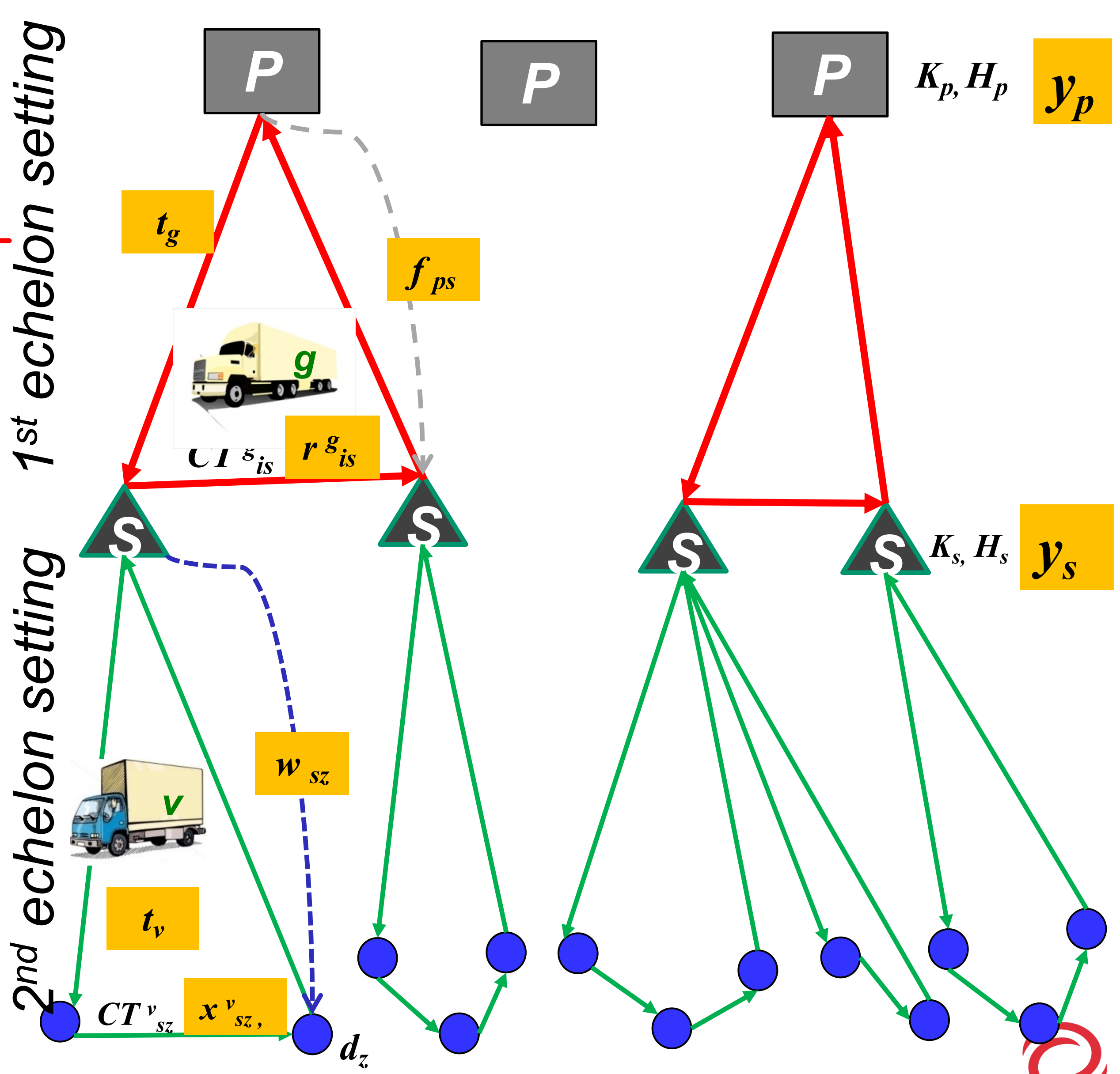
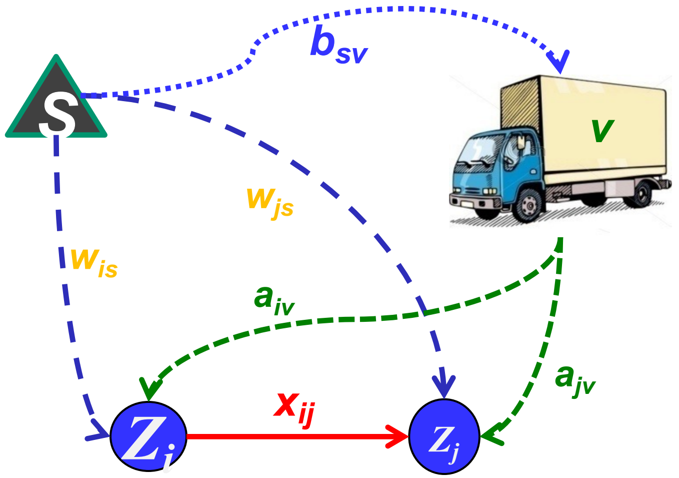


Illustration: A two-index Formulation

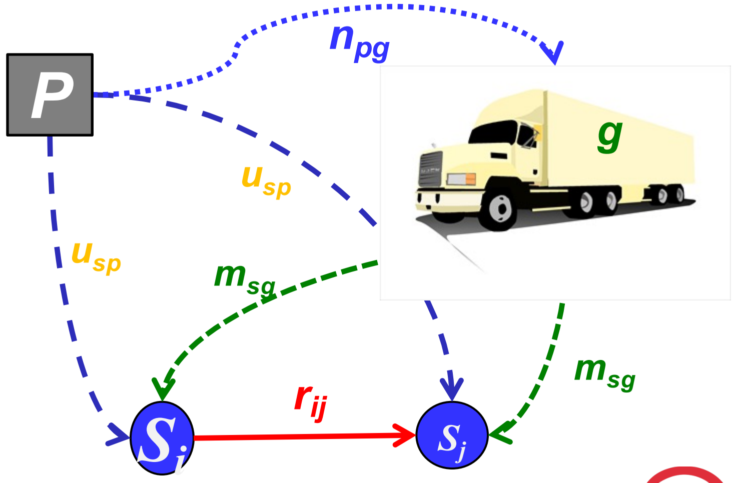
Second Echelon:

$a_{zv} = \{0, 1\}$ → Assign vehicle ***v*** to customer ***z***
$b_{sv} = \{0, 1\}$ → Assign vehicle ***v*** to satellite ***s***
$w_{zs} = \{0, 1\}$ → Assign customer ***z*** to satellite ***s***
$x_{ij} = \{0, 1\}$ → Denote that customer ***i*** is visited before customer ***j*** ($i < j$).



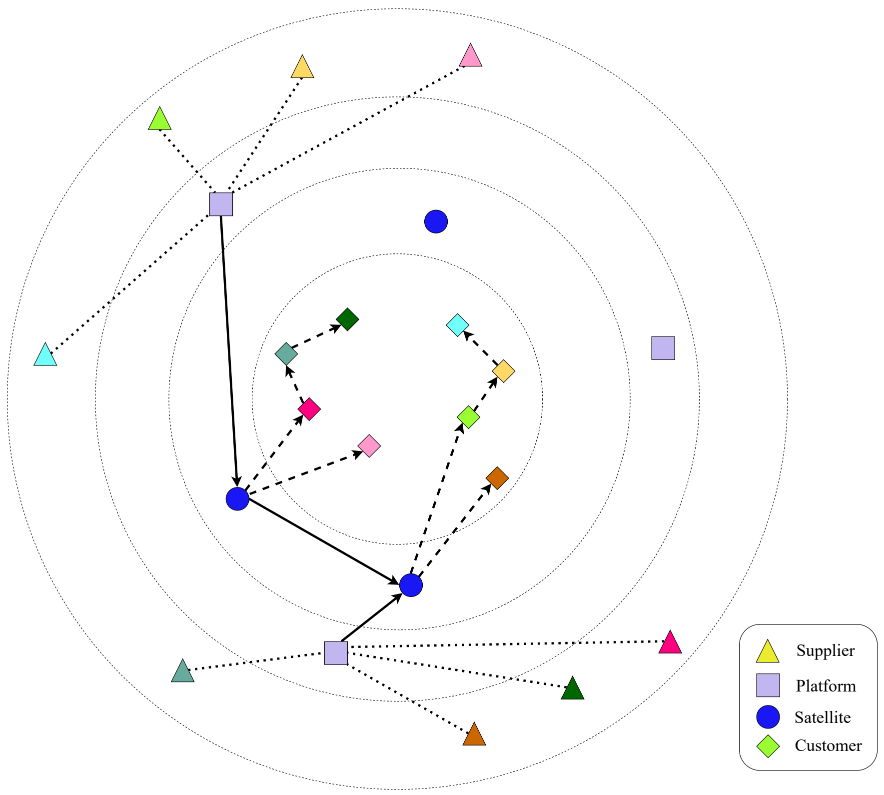
First Echelon:

$m_{sg} = \{0, 1\}$ → Assign vehicle ***g*** to satellite ***s***
$n_{pg} = \{0, 1\}$ → Assign vehicle ***g*** to platform ***p***
$u_{sp} = \{0, 1\}$ → Assign satellite ***s*** to platform ***p***
$r_{ij} = \{0, 1\}$ → Denote that satellite ***i*** is visited before satellite ***j*** ($i < j$).

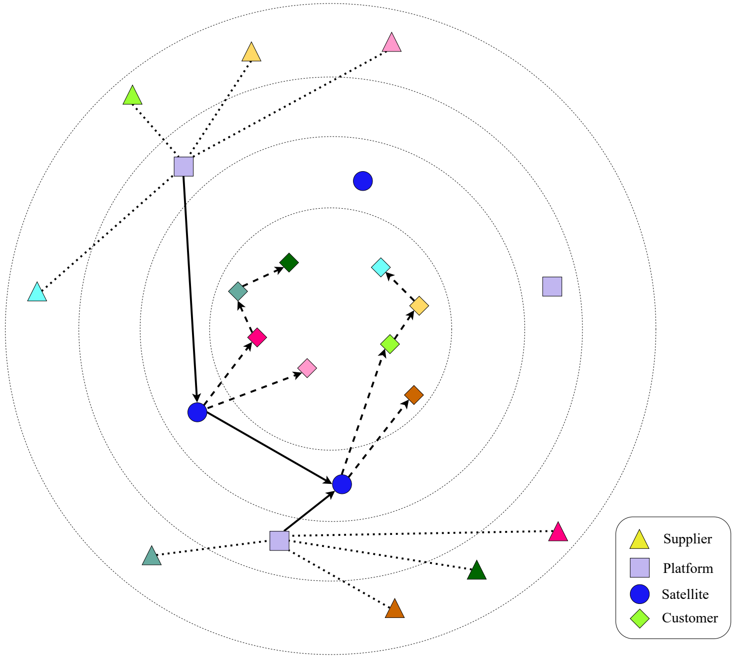


Multi-tier Location-Routing (2)

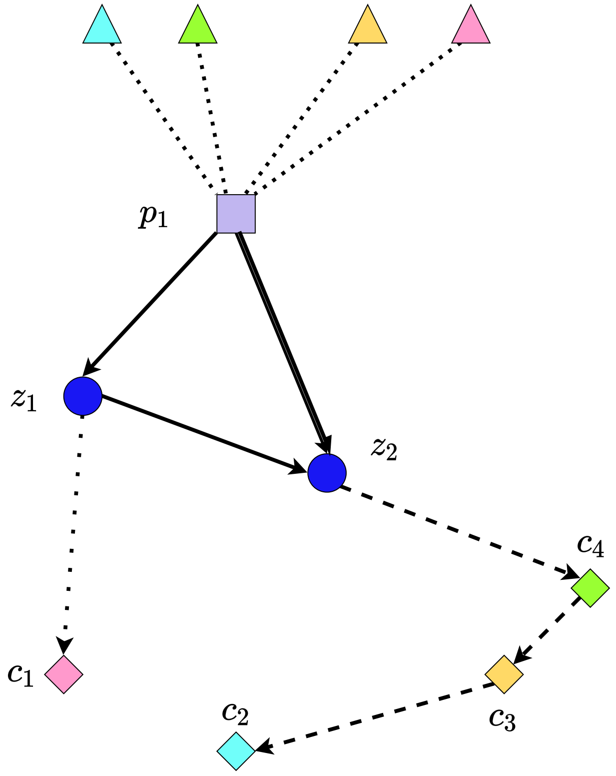
- Current work on multi-attribute 2E-LRP with synchronization (2E-MLRPS)
  - Escobar-Vargas (PhD student finishing)
- Time-dependent OD demand
  Availability (@ O) & due-date hard TW (@D)
  → time dependency of routes (schedules)
- Synchronize capacitated, tier-specific fleets at (capacitated) satellites
- Hybrid, discreet & continuous, time-space network formulation
- Dynamic Discretization Discovery methodology



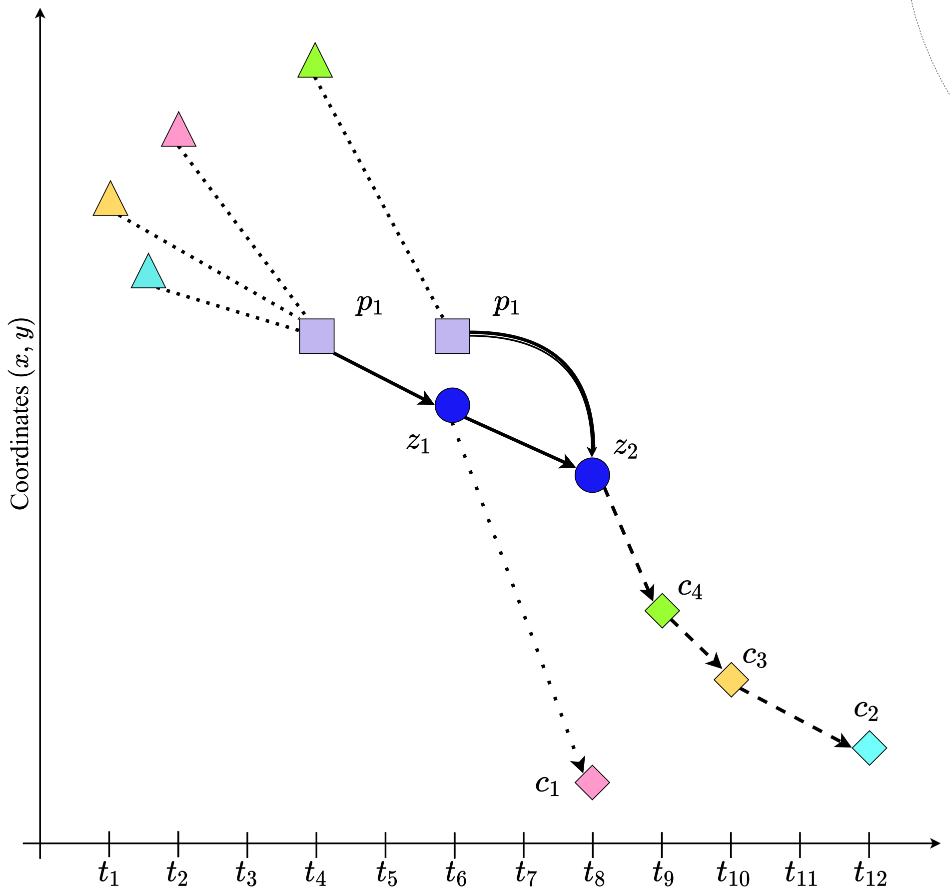
Multi-Attribute 2E-LRP



Static view



Time-sensitive view



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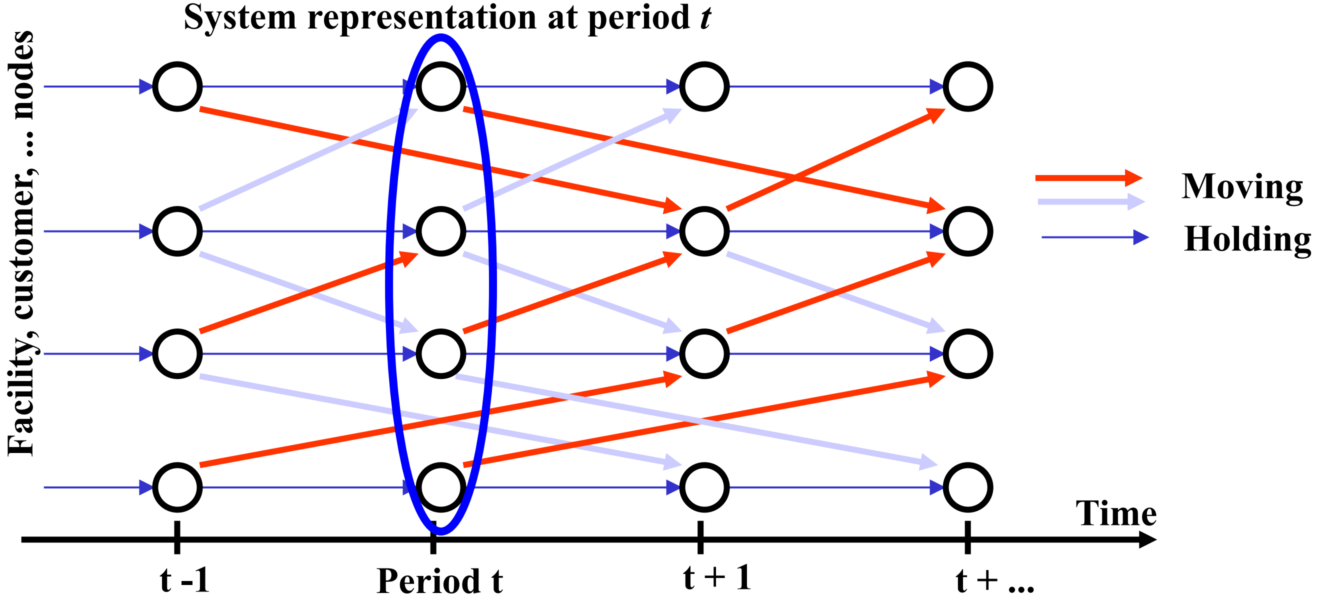
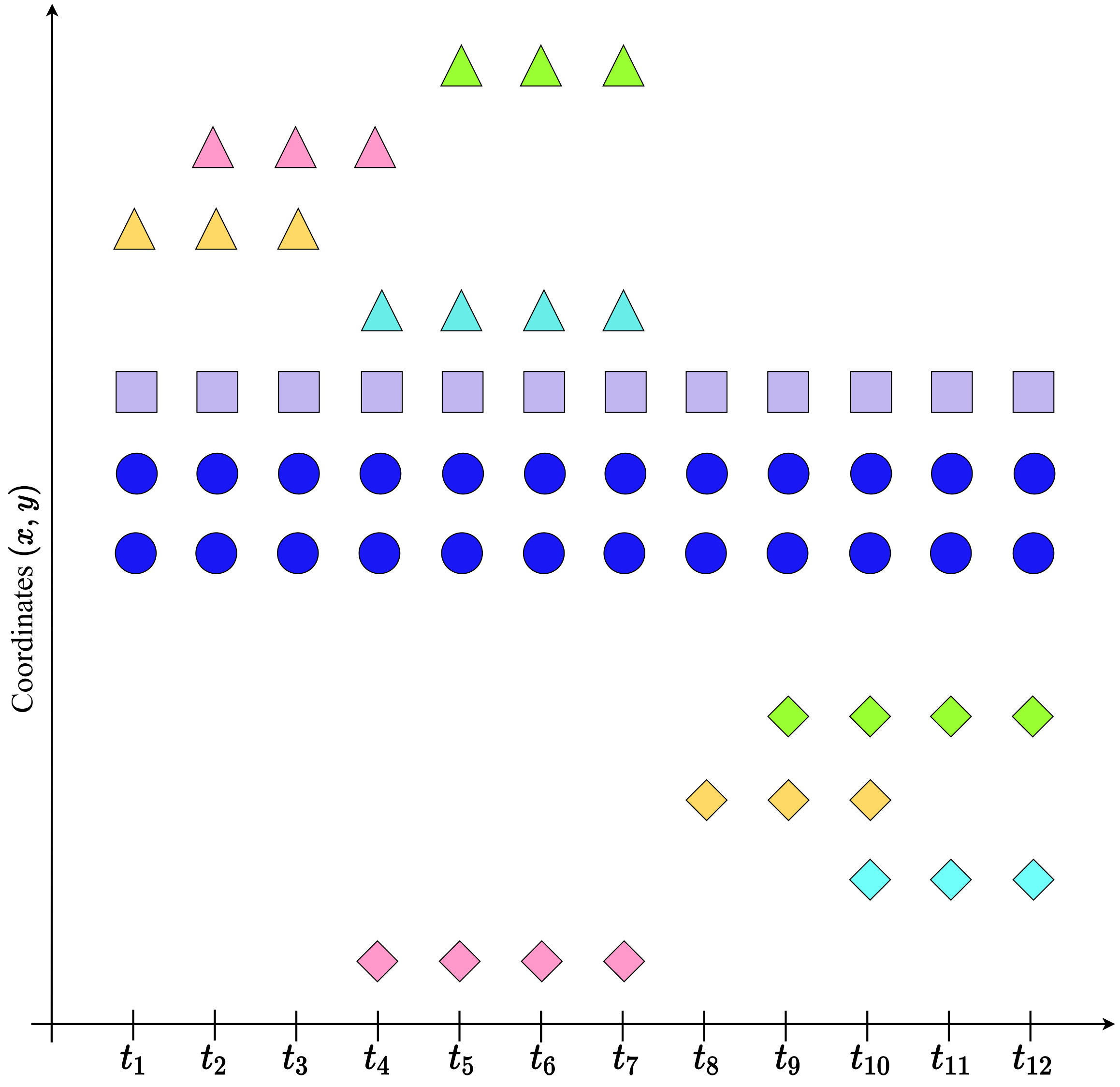
Time-Space Networks

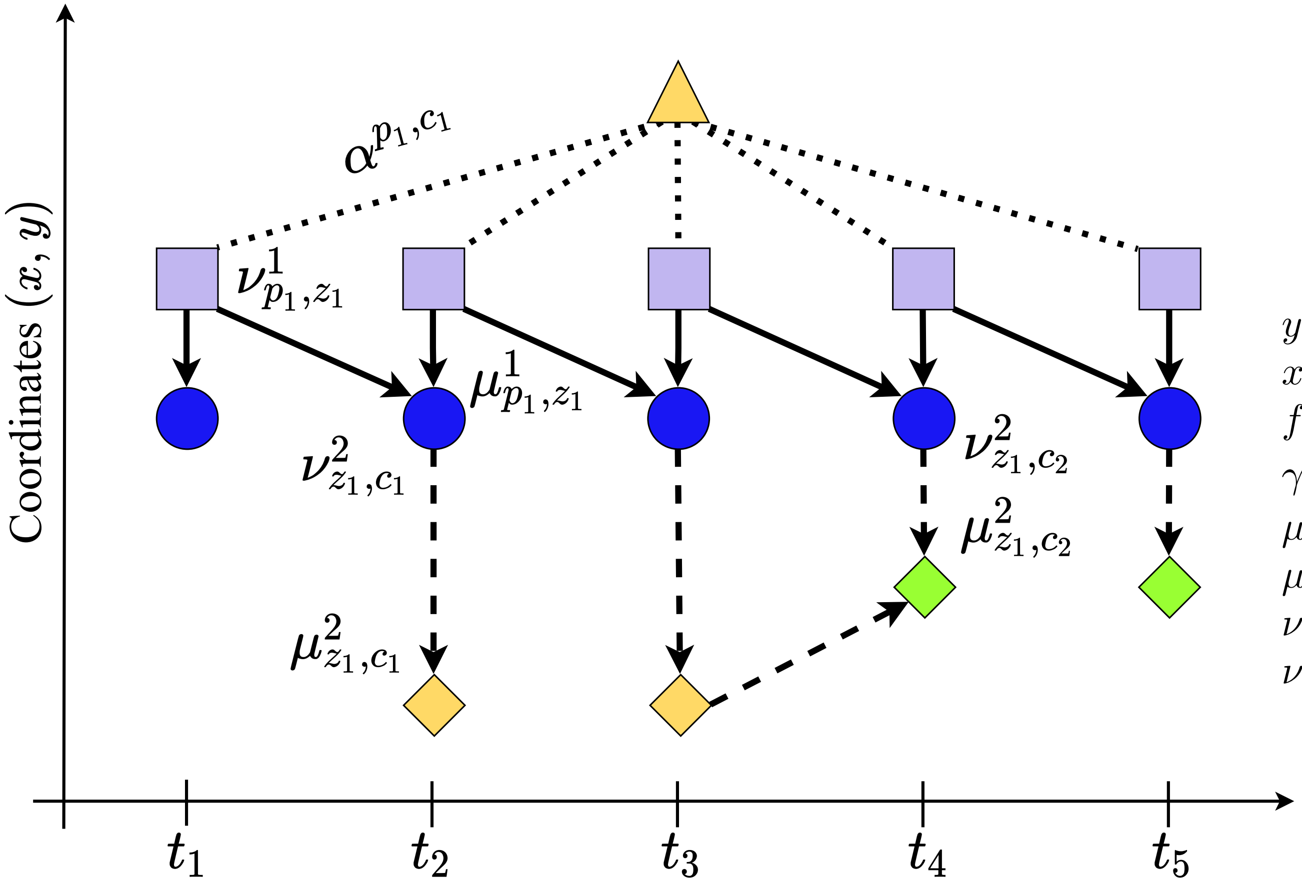
"Classic" = all nodes @ all periods



Nodes @ *relevant* periods



Hybrid Time-Space Modelling



$y_i = 1$, if facility i is open, 0 otherwise (location);
$x_{ij} = 1$ if arc (i, j) is selected, 0 otherwise (vehicle routing);
$f^k_{ijh} = 1$, if commodity k goes through arc (i, j) with vehicle h, 0 otherwi
$\gamma^k_{ij} = 1$, if commodity k goes through the arc (i, j), 0 otherwise;
μ^1_{ih}: Arrival time of first-echelon vehicle h at vertex i;
μ^2_{ik}: Arrival time of commodity k at vertex i;
ν^1_{ih}: Departure time of first-echelon vehicle h from vertex i;
ν^2_{ik}: Departure time of commodity k from vertex i .

Formulation

$$\min \sum_{i\in\mathcal{P}^{ph}} F_i y_i + \sum_{i\in\mathcal{Z}^{ph}} F_i y_i + \sum_{(i,j)\in\mathcal{A}^1} \zeta_{ij} x_{ij} + \sum_{(i,j)\in\mathcal{A}^2} \zeta_{ij} x_{ij}$$

Select facilities + route vehicles

$$\sum_{j\in\mathcal{C}_c} \sum_{i\in((\mathcal{C}\setminus\mathcal{C}_c)\cup\mathcal{Z})} x_{ij} = 1 \quad \forall c \in \mathcal{C}$$

Single customer visit

$$\sum_{j\in\mathcal{C}_c} \sum_{i\in((\mathcal{C}\setminus\mathcal{C}_j)\cup\mathcal{Z})} x_{ij} = \sum_{j\in\mathcal{C}_c} \sum_{i\in((\mathcal{C}\setminus\mathcal{C}_j)\cup\mathcal{E}^2)} x_{ji} \quad \forall c \in \mathcal{C}^{ph}$$

Vehicle flow conservation at customers (2nd tier)

$$\sum_{i\in((\mathcal{C}\setminus j)\cup\mathcal{Z})} x_{ij} \geq \sum_{h\in\mathcal{C}_j} \sum_{i\in((\mathcal{C}\setminus\mathcal{C}_j)\cup\mathcal{E}^2)} x_{hi} \quad \forall j \in \mathcal{C}$$

Don't leave a customer before ending service

$$\sum_{i\in\mathcal{E}^2} x_{ij} \leq \sum_{i\in\mathcal{C}} x_{ji} \quad \forall j \in \mathcal{Z}$$

An inbound 2-tier vehicle @ satellite for an outbound vehicle to customers

$$\sum_{j\in\mathcal{Z}_z} \sum_{i\in\mathcal{E}^2} x_{ij} = \sum_{j\in\mathcal{Z}_z} \sum_{i\in\mathcal{C}} x_{ji} \quad \forall z \in \mathcal{Z}^{ph}$$

Vehicle flow conservation at satellites

$$\sum_{i\in((\mathcal{Z}\setminus\mathcal{Z}_j)\cup\mathcal{P})} x_{ijh} \leq y_j \quad \forall j \in \mathcal{Z}$$

Visits at open satellites only

$$\sum_{i\in((\mathcal{Z}\setminus\mathcal{Z}_z)\cup\mathcal{P})} x_{ijh} \leq \sum_{i\in((\mathcal{Z}\setminus\mathcal{Z}_j)\cup\mathcal{E}^1)} x_{jih} \quad \forall j \in \mathcal{Z}, h \in H$$

An inbound 1-tier vehicle @ satellite for an outbound to satellite/garage

$$\sum_{i\in\mathcal{E}^1} x_{ijh} = \sum_{i\in\mathcal{Z}} x_{jih} \quad \forall j \in \mathcal{P}, h \in H$$

Vehicle flow conservation on 1st tier

$$\sum_{h\in H} \sum_{j\in\mathcal{Z}} x_{ijh} \leq |K^1| y_i \quad \forall i \in \mathcal{P}$$

Fleet size @ platforms

$$\sum_{h\in H}\sum_{i\in P_0(k)} f^k_{ijh} = 1 \quad \forall k \in \mathcal{K}, j \in \mathcal{Z} \tag{42}$$

Unsplit demand

$$\sum_{h\in H}\sum_{i\in\mathcal{P}_p}\sum_{j\in\mathcal{Z}} f^k_{ijh} \le y_p \quad \forall k \in \mathcal{K}, p \in \mathcal{P}^{ph} \tag{43}$$

Leave from selected platform

$$\sum_{i\in((\mathcal{C}\setminus\mathcal{C}_j)\cup\mathcal{Z})}\sum_{j\in\mathcal{C}_j}\gamma^k_{ij} - \sum_{i\in((\mathcal{C}\setminus\mathcal{C}_j)\cup\mathcal{E}^2)}\sum_{j\in\mathcal{C}_j}\gamma^k_{ji} = 0 \quad \forall j \in \mathcal{C}^{ph}, k\in\mathcal{K}, j \neq d_k \tag{44}$$

$$\sum_{j\in\mathcal{C}_j}\gamma^k_{ij} - \sum_{j\in\mathcal{C}_j}\gamma^k_{ji} \le 1 - \sum_{j\in\mathcal{C}_j} x_{ji} \quad \forall j\in\mathcal{C}^{ph}, k\in\mathcal{K}, j\neq d_k \tag{45}$$

Commodity flow conservation @ customers

$$\sum_{i\in((\mathcal{C}\setminus\mathcal{C}_j)\cup\mathcal{Z})}\sum_{j\in\mathcal{C}_j}\gamma^k_{ij} - \sum_{i\in((\mathcal{C}\setminus\mathcal{C}_j)\cup\mathcal{E}^2)}\sum_{j\in\mathcal{C}_j}\gamma^k_{ji} = \sum_{i\in((\mathcal{C}\setminus\mathcal{C}_j)\cup\mathcal{Z})}\sum_{j\in\mathcal{C}_j} x_{ijh}$$
$$\forall j\in\mathcal{C}^{ph}, k\in\mathcal{K}, j = d_k \tag{46}$$

Commodity flow conservation @ destination

$$\sum_{h\in H}\sum_{j\in\mathcal{Z}_z}\sum_{i\in((\mathcal{Z}\setminus\mathcal{Z}_j)\cup\mathcal{P})} f^k_{ijh} = \sum_{h\in H}\sum_{j\in\mathcal{Z}_z}\sum_{h\in((\mathcal{Z}\setminus\mathcal{Z}_j)\cup\mathcal{E}^1)} f^k_{jh} + \sum_{j\in\mathcal{Z}_z}\sum_{l\in(\mathcal{C})}\gamma^k_{jl} \quad \forall z\in\mathcal{Z}^{ph}, k\in\mathcal{K} \tag{47}$$

Commodity flow conservation @ satellites

$$\sum_{h\in H}\sum_{i\in((\mathcal{Z}\setminus\mathcal{Z}_j)\cup\mathcal{P})} f^k_{ijh} \le \sum_{h\in H}\sum_{h\in((\mathcal{Z}\setminus\mathcal{Z}_j)\cup\mathcal{E}^1)} f^k_{jdh} + \sum_{l\in(\mathcal{C})}\gamma^k_{jl} \quad \forall j\in\mathcal{Z}, k\in\mathcal{K} \tag{48}$$

Vehicle synchronization (space & time) @ satellites

$$\sum_{k\in\mathcal{K}} w^k \sum_{i\in((\mathcal{Z}\setminus\mathcal{Z}_j)\cup\mathcal{P})} f^k_{ijh} \le cap_1 \quad \forall j\in\mathcal{Z}, h\in H \tag{49}$$

$$\sum_{k\in\mathcal{K}} w^k \sum_{i\in\mathcal{Z}}\gamma^k_{ij} \le cap_2 \quad \forall j\in\mathcal{C}, \tag{50}$$

Vehicle capacity @ each tier

$$\sum_{k\in\mathcal{K}} w^k \sum_{h\in H}\sum_{j\in(\mathcal{Z}\setminus\mathcal{Z}_j)} f^k_{ijh} \le \Theta_p y_i \quad \forall i\in\mathcal{P} \tag{51}$$

Vehicle flow conservation on 1st tier

$$\sum_{h\in H} f^k_{ijh} \le x_{ijh} \quad \forall k\in\mathcal{K}, h\in H, (i,j)\in\mathcal{A}^1 \tag{52}$$

$$\gamma^k_{ij} \le x_{ij} \quad \forall k\in\mathcal{K}, (i,j)\in\mathcal{A}^2 \tag{53}$$

Link commodity and vehicle flows

Formulation (3)

$$\nu^1_{ih} \geq \sum_{j \in \mathcal{Z}} \alpha^{ik} f^k_{ijh} \quad \forall h \in \mathcal{H}^1, k \in \mathcal{K}, i \in \mathcal{P}$$

Departure from platform once commodity is available

$$\nu^2_{jk} \geq \mu^1_{jh} - (2 - \gamma^k_{jd(k)} - \sum_{i \in (\mathcal{Z} \cup \mathcal{P}), i \neq j} f^k_{ijh})M \quad \forall k \in \mathcal{K}, h \in \mathcal{H}^1, j \in \mathcal{Z}$$

$$\nu^1_{jh} \geq \mu^2_{jk} - (2 - \gamma^k_{jd(k)} - \sum_{i \in (\mathcal{Z} \cup \mathcal{P}), i \neq j} f^k_{ijh})M \quad \forall k \in \mathcal{K}, h \in \mathcal{H}^1, j \in \mathcal{Z}$$

Arrival 1st and 2nd tier vehicles @ satellite for synchronization

$$\mu^1_{ih} + \tau_{ij} - \mu^1_{jh} \leq (1 - f^k_{ijh})M \quad \forall k \in \mathcal{K}, h \in \mathcal{H}^1, (i,j) \in \mathcal{A}^1$$

$$\nu^1_{ih} + \tau_{ij} - \mu^1_{jh} \leq (1 - f^k_{ijh})M \quad \forall h \in \mathcal{H}^1, k \in \mathcal{K}, (i,j) \in \mathcal{A}^1$$

Arrival & departure times 1st tier vehicles

$$\mu^2_{ik} + \tau_{ij} - \mu^2_{jk} \leq (1 - \gamma^k_{ij})M \quad \forall k \in \mathcal{K}, (i,j) \in \mathcal{A}^2$$

$$\nu^2_{ik} + \tau_{ij} - \mu^2_{jk} \leq (1 - f^k_{ijh})M \quad \forall k \in \mathcal{K}, h \in \mathcal{H}^2, (i,j) \in \mathcal{A}^2$$

Arrival & departure times 2nd tier vehicles

$$\nu^1_{ih} - \mu^1_{ih} \leq W^2_{max} \quad \forall h \in \mathcal{H}^1, i \in \mathcal{Z}$$

$$\nu^2_{ik} - \mu^2_{ik} \leq W^2_{max} \quad \forall k \in \mathcal{K}, i \in \mathcal{Z}$$

Waiting time limitation @ satellites

$$a_i \leq \mu^2_{ik} \leq b_i \quad \forall i \in \mathcal{C}^{ph}, k \in D(k)$$

Customers visited within their time windows

Dynamic Discretization Discovery (DDD) Solution Method

- The precision of time-space models & the computational challenges of addressing them grows as granularity (number of periods) grows !
- DDD idea (Boland et al. 2017)
  - Start with coarse granularity (sparse time-space network)
  - Iteratively refine the granularity (add nodes and links)
    - Compute bounds by solving the formulation on the restricted network
- Applied quite successfully to "standard" Service Network Design
- Work underway to generalize
- Multi-attribute location-routing quite challenging but appears successful

Medium-to-Short-term Planning

Tactical (medium = "season", 4-6 months)

Service design and resource management

Service and route selection, demand journeys, synchronization

Plans & Guidelines ↓ ↑ Measures & Evaluations

Operational (short = "the day before")

Tactical-plan adjustment and disaggregated planning

Service Network Design & Routing

First/Last-mile Routing

Pickup & Delivery

Multi-tier Routing

Tactic-Operational City Logistics Planning

- Medium-to-short term planning = Plan regular operations, based on a (point) forecast, for efficient resource allocation & utilization, customer satisfaction, profitable operations for stakeholders, citizens, the city
- Select services, routes (tours), and schedules + terminal activities at all tiers
- Select OD demand itineraries through the service network
- Manage and synchronize resources, facilities & fleets, at all tiers
- Minimize total (generalized) cost of the system
- Satisfy the demand within the agreed time restrictions
- Physical & operational requirements and limits
- Plan for a schedule length, repeatedly applied over the planning horizon, or for the next operation period ("tomorrow")

Tactic-Operational City Logistics Planning (2)

- One must account for Demand & Supply knowledge / forecast confidence
  - How large variations? How regular? How reliable? ⇒
- From no-plan (high variance + no confidence): Not in CL literature
  - Dynamic fleet management
- To confident plan (low variance or high confidence)
  - Deterministic formulations
  - Most contributions
- Through various formulations, e.g., Stochastic, accounting for uncertainty
    - Plan main resources & services (1st stage)
    - On-the-day routing adjustments/recourses (2nd stage)
    - (Crainic et al. 2016)
  - Not much, yet!

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CIRRELT

Routing & Tactic-Operational CL Planning

- Single-tier systems & last-mile delivery (first-mile pickup)
  - CVRP/VRPTW variants for a few CL attributes, e.g., returns to satellites for reloading, crowdsourcing, ...
  - Many new hardware (vehicles, lockers, ...) technologies
  - Evolving people behaviour and requirements
    ⇒ e-commerce clash with CL sustainability goals
  - Challenge of integrating into CL framework & goals
- Multi-tour pickup & delivery on given tier with multiple demand types and multiple visits to satellites to load/unload/exchange loads (synchronize)
  ➞ the pseudo-backhaul policy
  (Crainic et al. 2012, Nguyen et al. 2013, 2016, Bettinelli et al. 2019)

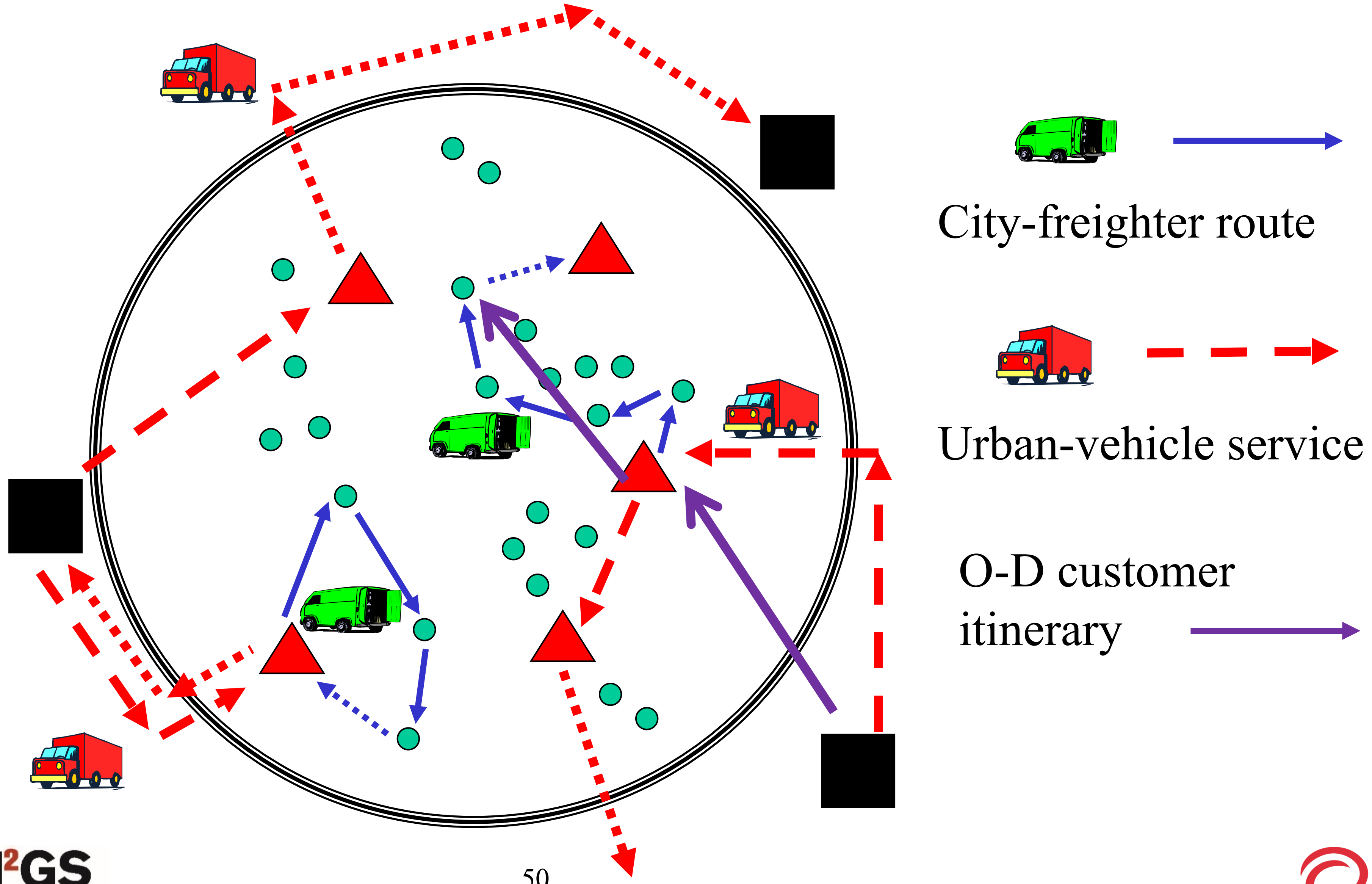
Routing & Tactic-Operational CL Planning (2)

- nE-VRP for CL not much work yet ...
- 2E-VRP formally defined as extension of CVRP (Perboli et al. 2011): single CDC & inbound (single) commodity
  - Much algorithmic work on the basic setting
  - Few (if any) CL attributes
- Arc and path models for multi-attribute 2E-VRPTW with time-dependent OD demand, scheduled routes (1st tier), multi-tours (2nd tier), and synchronization (Crainic et al. 2009)
  - Algorithmic work addressing groups of attributes
  - Currently: OD demand (multi-commodity) and TW (Dellaert et al. 2021)

SSND & Tactic-Operational CL Planning

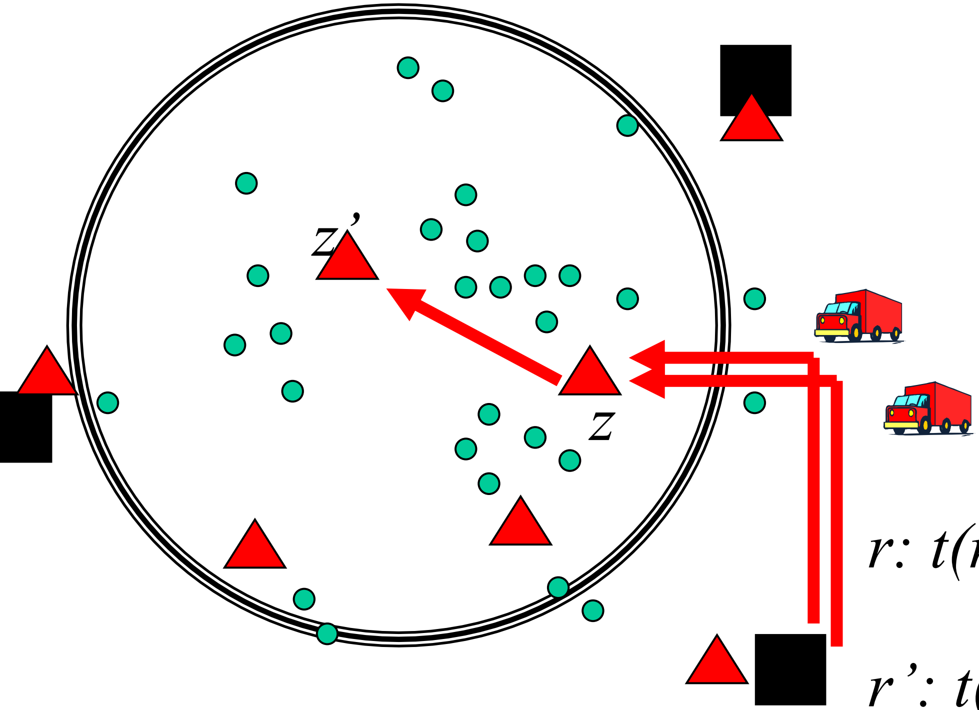
- Multi-period, time-space network formulations
- Time-dependent inbound, outbound, internal OD demand
- SSND (-RM) +VRP(TW) (Crainic et al. 2009)
  - Scheduled service network design with resource management
    - No-line and line-based scheduled potential services on top tiers (currently 1st tier)
  - nE-VRP / P&D on lower tiers
    - multiple-tour P&D vehicle routes
  - Synchronization (at satellites)
- SSND (1st tier) + approximate routing costs (Fontaine et al. 2020)
  - Customers linked to satellites with approximated routing costs
  - Distribution of demand: select OD itinerary = assignment to (service, compartment, satellite) combination, implicitly selects the CDC as well

Select Services, Routes, Itineraries in Time



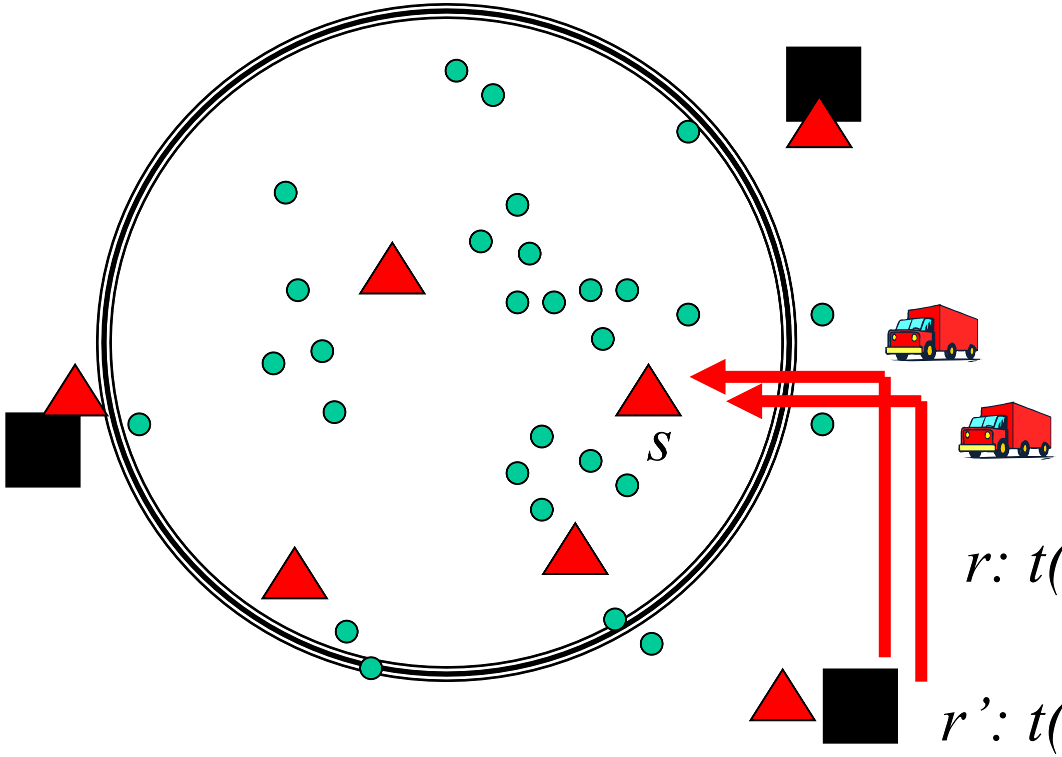
Scheduled Urban-Vehicle Services

Which service to run, when? $\rho(r) \in \{1,0\}$



r: $t(r)=t$; $\sigma(r) = \{z,z'\}$

r': $t(r')=t$; $\sigma(r)=\{z\}$

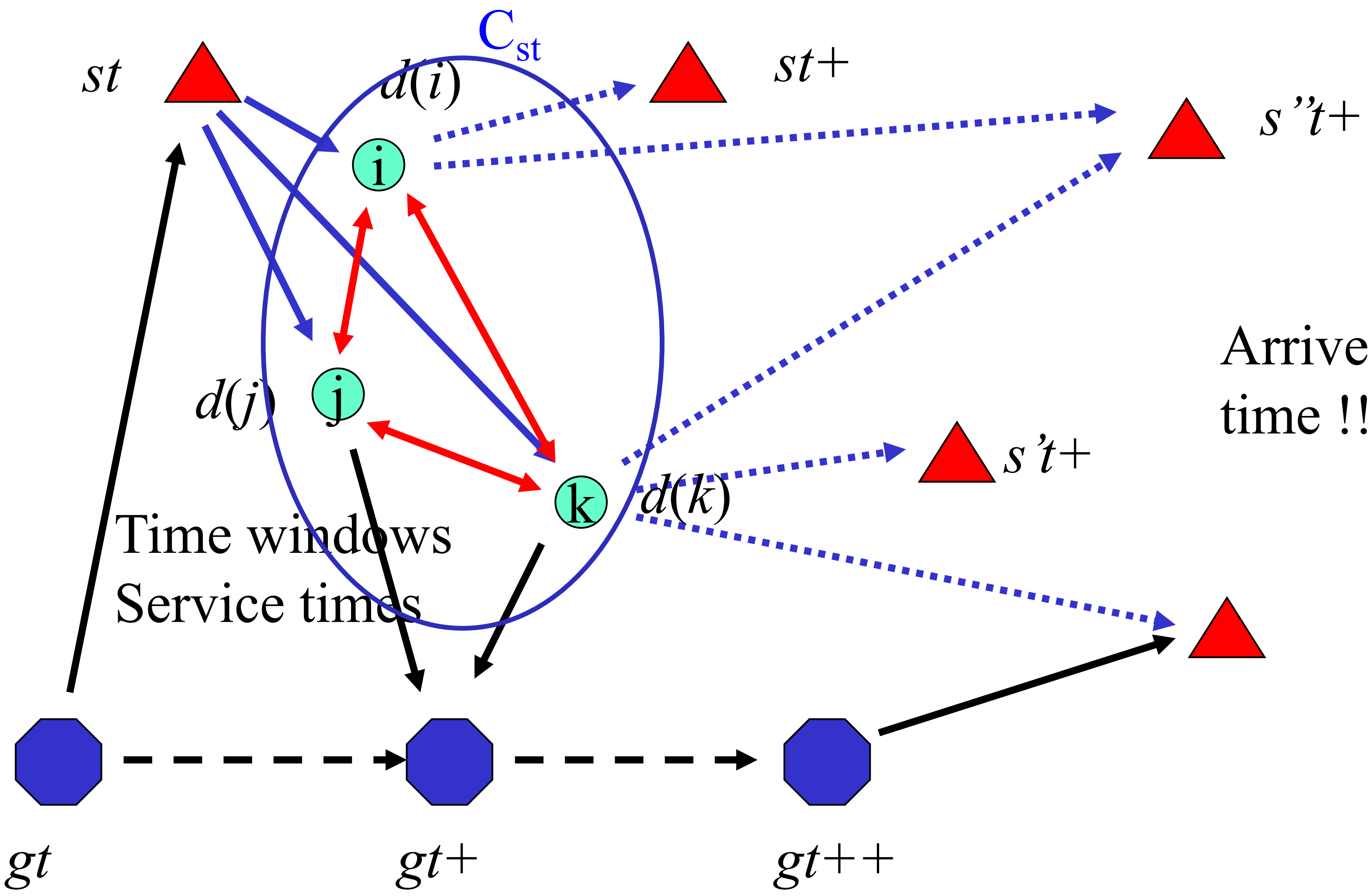


r: $t(r)=t+1$

r': $t(r')=t$

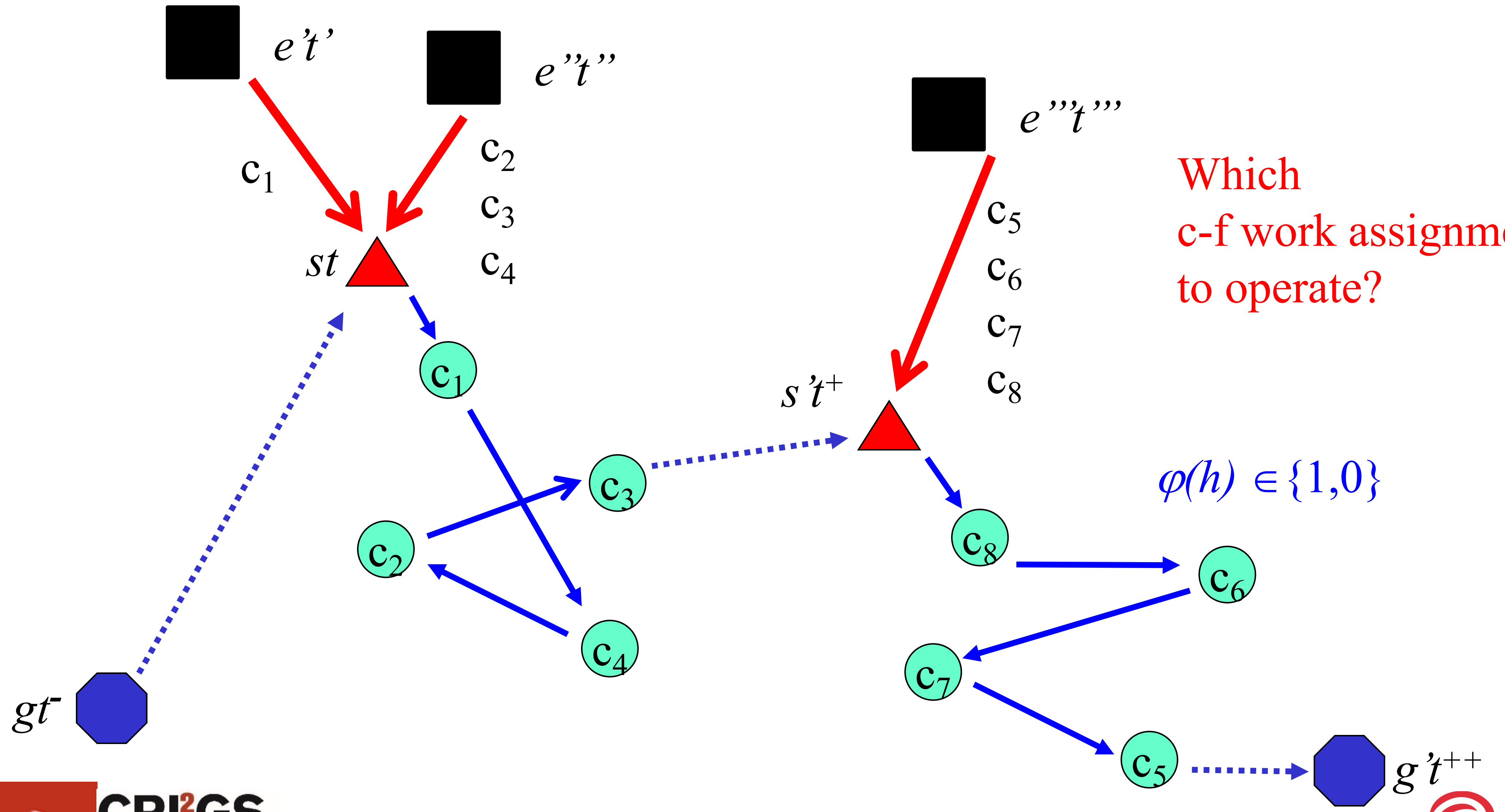
City-freighter Possible Movements – Timing (inbound)

Which work assignments $\varphi(h) \geq 0$ to operate?

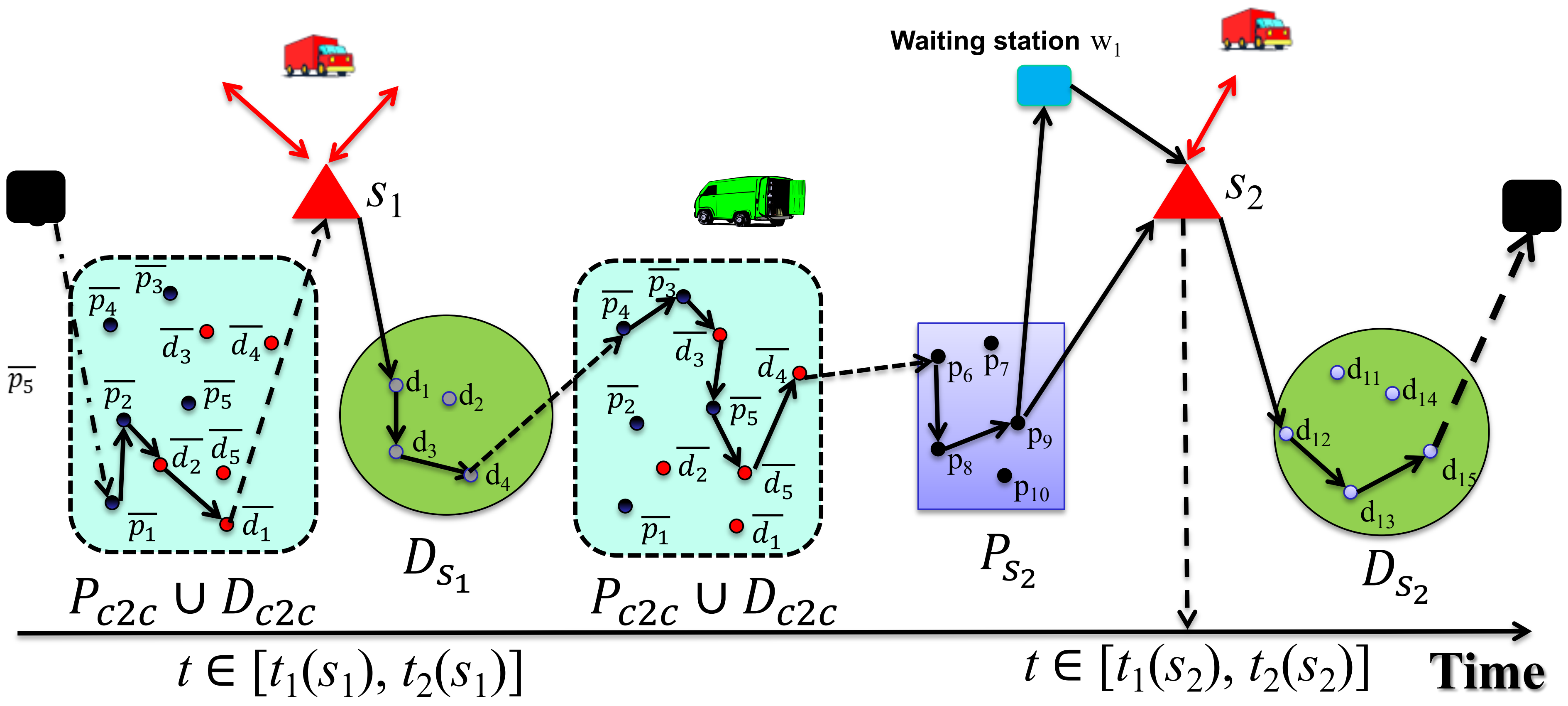


Arrive on time !!

City-Freighter Work Segment & Work Legs (inbound)



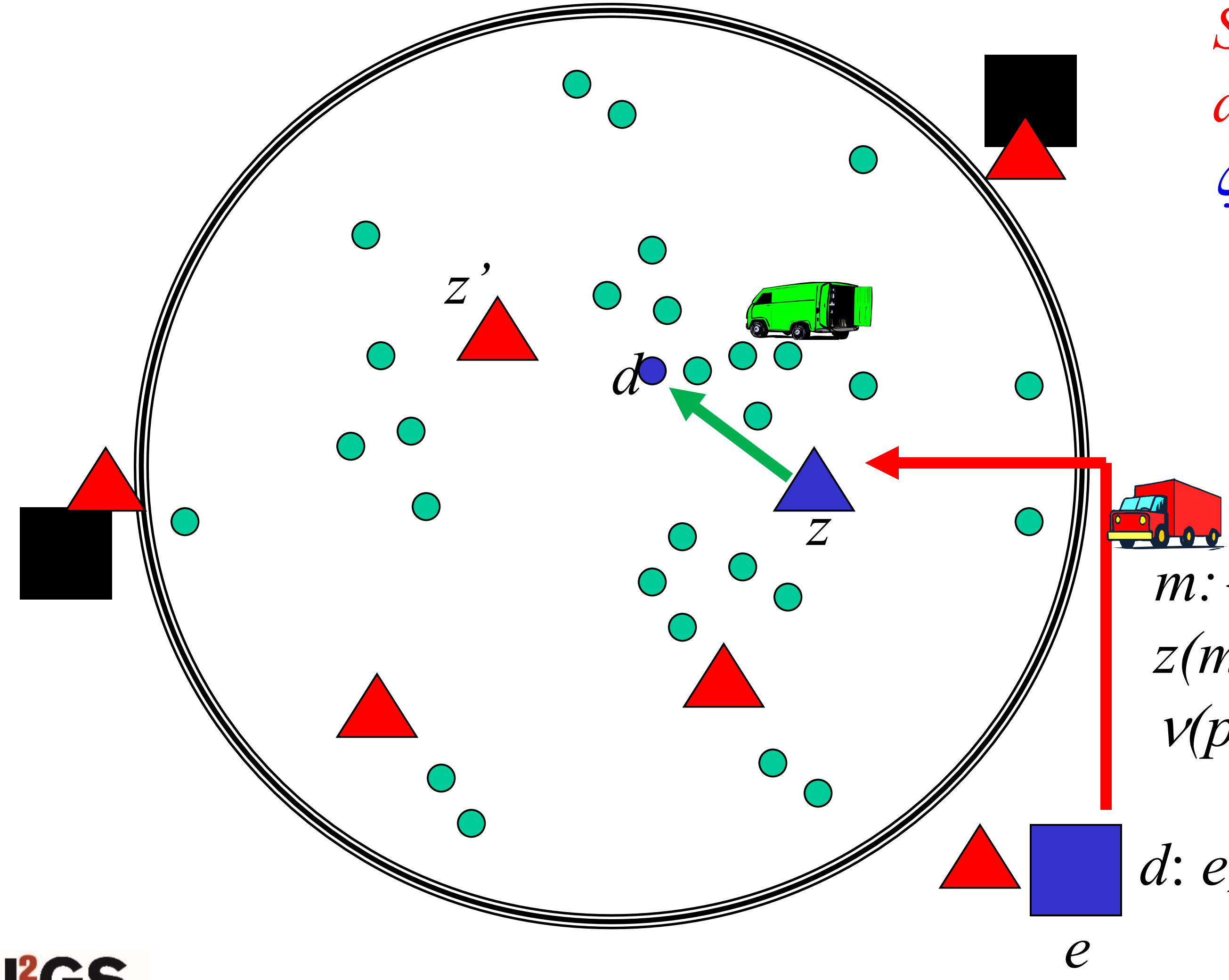
Integrated Routing with Pseudo-Backhauls



Local (pickup & delivery)	Inbound (delivery)	Local (pickup & delivery)	Outbound (pickup)

Demand Itineraries

Select itinerary to deliver cargo on time:
$\zeta(m) \in \{1,0\}$



$m: \{e, r(m), t(m) < t(r),$
$z(m) = z(m) \in \sigma(r(m)),$
$v(p(d)), l(h(m)), c(d)\}$

$d: e, c, p, t, [a,b], vol$

The Model Framework

Generalized cost first-tier services — Generalized cost second-tier work assignments

$$\text{Minimize} \quad \sum_{r \in \mathcal{R}} k(r)\rho(r) + \sum_{h \in \mathcal{H}} k(h)\varphi(h)$$

Subject to

$$\sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,r)} vol(d)\zeta(m) \leq u_\tau \rho(r) \quad r \in \mathcal{R},$$

Linking – u-v capacity

$$\sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,l,h)} vol(d)\zeta(m) \leq u_\nu \varphi(h) \quad l \in \mathcal{C}_l(w), h \in \mathcal{H},$$

Linking – c-f capacity

$$\sum_{m \in \mathcal{M}(d)} \zeta(m) = 1 \quad d \in \mathcal{D},$$

Single itinerary

$$\sum_{t^- = t-\delta(\tau)+1}^{t} \sum_{r \in \mathcal{R}(s,t^-)} \rho(r) \leq u_s^{\mathcal{T}} \quad s \in \mathcal{S},\ t = 1, \ldots, T,$$

$$\sum_{t^- = t-\delta(\tau)+1}^{t} \sum_{h \in \mathcal{H}(s,t^-)} \varphi(h) \leq u_s^{\mathcal{V}} \quad s \in \mathcal{S},\ t = 1, \ldots, T,$$

Satellite capacity for u-v & c-f

$$\sum_{h \in \mathcal{H}(\nu)} \varphi(h) \leq n_\nu \quad \nu \in \mathcal{V},$$

c-f fleet size

$$\rho(r) \in \{0,1\} \quad r \in \mathcal{R},$$

$$\varphi(h) \in \{0,1\} \quad h \in \mathcal{H},$$

$$\zeta(m) \in \{0,1\} \quad m \in \mathcal{M}(d),\ d \in \mathcal{D}.$$

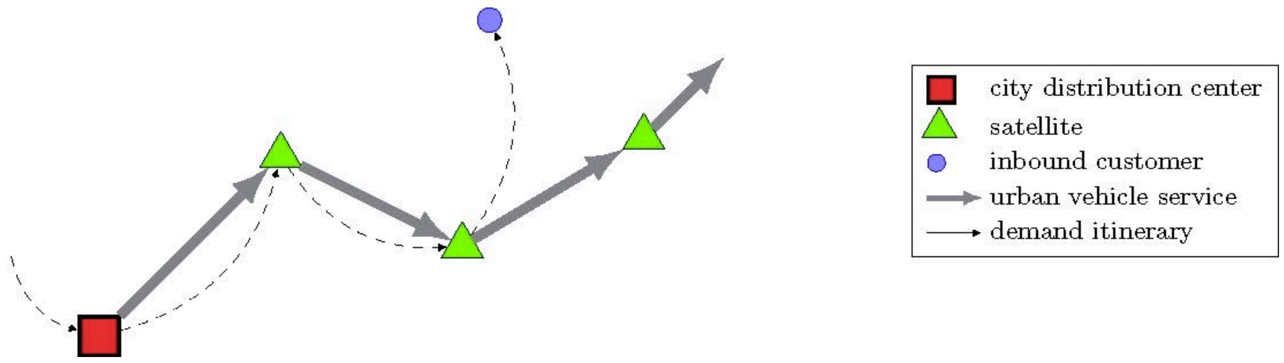
Tactical Planning Modes

- What regularity?
  - Clear for first tier: major flow corridors & resources, terminals, mass transport modes, …
  - Less clear for second-tier routing, where day-to-day variations are the norm
- Then
  - Model for the day-before planning problem
  - Approximate second-tier routing for medium-term tactical planning, or
  - Second-tier routing as recourse in stochastic model

Day-before Tactical Planning Modelling (in & out)

- Selection of services $\rho(r) \in \{1,0\}$
- Distribution of demand: select OD itinerary = assignment to (service, compartment, satellite) combination, implicitly selects the CDC as well

$x(r^c,d,z) = 1$, if demand d is assigned to compartment r^c *and satellite* z; 0, *otherwise*



- Min generalized (operations + impact on city) costs

Formulation

$$\min \sum_{r \in \mathcal{R}} k(r)\rho(r) + \sum_{d \in \mathcal{D}} \sum_{r \in \mathcal{R}} \sum_{r^c \in \mathcal{R}^C(r)} \sum_{z \in \mathcal{Z}} \left(k^Z(d,z,t) + k^E(d,e(r))\right) x(r^c,d,z)$$

Service selection   Demand assignment to (compartment, service, satellite, CDC

Unsplit delivery

$$\sum_{z \in \mathcal{Z}} \sum_{r \in \mathcal{R}} \sum_{r^c \in \mathcal{R}^C(r)} x(r^c,d,z) = 1 \qquad \forall d \in \mathcal{D}$$

Inbound before outbound

$$x(r^c,d_1,z_1) + x(r^c,d_2,z_2) \le 1 \qquad \forall r^c \in \mathcal{R}^C(r), r \in \mathcal{R}, d_1 \in \mathcal{D}^I, d_2 \in \mathcal{D}^O, z_1, z_2 \in \mathcal{Z}(r), z_1 \ge z_2$$

Vehicle capacities

$$\sum_{z \in \mathcal{Z}} \sum_{d \in \mathcal{D}^I} vol(d) x(r^c,d,z) \le u^c_\tau(r)\rho(r) \qquad \forall r^c \in \mathcal{R}^C(r), r \in \mathcal{R}$$

$$\sum_{z \in \mathcal{Z}} \sum_{d \in \mathcal{D}^O} vol(d) x(r^c,d,z) \le u^c_\tau(r)\rho(r) \qquad \forall r^c \in \mathcal{R}^C(r), r \in \mathcal{R}$$

Vehicle availability

$$\sum_{r \in \mathcal{R}(t,\tau,e)} \rho(r) \le n_{e\tau} \qquad \forall \tau \in \mathcal{T}, e \in \mathcal{E}, t = 1,\ldots,T$$

Satellite capacities:

- Total vehicles

$$\sum_{t^- = t-\delta(\tau)+1}^{t} \sum_{r \in \mathcal{R}(z,t^-)} \rho(r) \le u^\tau_{zt} \qquad \forall z \in \mathcal{Z}, t = 1,\ldots,T$$

- Per mode

$$\sum_{t^- = t-\delta(\tau)+1}^{t} \sum_{r \in \mathcal{R}(z,t^-,m)} \rho(r) \le u^m_{zt} \qquad \forall z \in \mathcal{Z}, m \in \mathcal{M}, t = 1,\ldots,T$$

- Transferred volume

$$\sum_{r \in \mathcal{R}(t,z)} \sum_{r^c \in \mathcal{R}^C(r)} \sum_{d \in \mathcal{D}} vol(d) x(r^c,d,z) \le u^V_{zt} \qquad \forall z \in \mathcal{Z}, t = 1,\ldots,T$$

$$\rho(r) \in \{0,1\} \qquad \forall r \in \mathcal{R}$$

$$x(r^c,d,z) \in \{0,1\} \qquad \forall d \in \mathcal{D}, r^c \in \mathcal{R}^C(r), r \in \mathcal{R}, z \in \mathcal{Z}$$

Solution Methods

- Heuristics proposed for full formulation – lots of work to do !!
- Benders decomposition for first tier appears to work well
- Complicating variables: the design variables $\rho(r)$
  - Master problem selects scheduled services
- Easier variables: the assignment variables $x(r^c, d, z)$
  - Slave subproblem: multiple knapsack with precedence constraints
    - Linear relaxation = very good lower bounds ➞ tight cuts

A Few Insights

- Multimodality significantly reduces costs and the numbers of services and vehicles
- Multi-compartment line-based modes are very beneficial and efficient
- Integration of inbound and outbound is beneficial
- Many challenges still ahead

Research Perspectives

- Modelling the full array of CL characteristics yielding formulations consistent over all planning levels, which can be efficiently addressed for realistic problem dimensions
- Modelling
  - Representation of nuisance and impacts
  - Multi-tier, multi-modal settings with inbound, outbound and local demand
  - Business/collaboration models (sharing risks, costs, profits, …)
  - "New" technology and operation modes on last/first-mile
  - Approximating costs and times of multi-attribute (multi-tier) routing
  - Synchronizing multiple scheduled service network design, routing, and terminal services
  - …

Research Perspectives (2)

- Uncertainty, resilience, recovery (disturbing events), & revenue management
  - Important issues for freight transportation and logistics
  - Research in this area promises to yield substantial benefits for both science and applications
  - Uncertainty
    - Demand, travel and service times
    - Correlations
    - Synchronization
- Adapt generic models to particular cities and countries ...

Research Perspectives (3)

- Solution methods for deterministic and stochastic models
  - Exact (validation) & meta/math-heuristic (actual use)
    - Decomposition methods (of path and arc-based models)
      e.g., projecting synchronization relations on tier-specific subproblems
    - Dynamic generation of services and pickup and delivery routes
    - Dynamic generation of multi-tier space-time SSND + P&D network
    - Parallel exact and collaborative search matheuristics
- Cost and benefit analyses (multiple conflicting objectives)
- Integration of urban/regional planning of people, freight, and CL transport

General Perspectives

- The issue of freight transportation in urban areas is here to stay and grow
- What systems and business models for each country and (very) large cities?
- Private and public initiatives
- City Logistics and logistics chains? E-commerce?
- What freight transportation systems for the future?
- The challenge of reconciling “theoretical” efficiency-quality, citizen and political behaviour and acceptance, and managerial activity and ease-of-use

Proposed by the Team from Three Japanese Universities

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