Design des réseaux de service avec horaires pour le transport de fret avec consolidation

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CIRRELT
Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport

Chaire de recherche industrielle du **CRSNG** en management logistique
NSERC Industrial Research Chair in Logistics Management

ESG UQÀM
École des sciences de la gestion
Université du Québec à Montréal

Outline

1. Freight Transportation & Consolidation
2. Rail Freight Transportation
3. Scheduled Service Network Design
4. Multi-layer Time-Space Model
5. The Solution Method
6. Experimentation
7. Enhanced Solution Method
8. Experiments with New Meta-heuristic
9. Conclusions

The CIRRELT

- Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport (CIRRELT); 6 mai 2006
- Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation
- La science des réseaux
- CRT (Centre de recherche sur les transports) + CENTOR + Polygistique + Chaire en management logistique (UQAM) + ...
- Université de Montréal, École Polytechnique Montréal, HEC Montréal
- Université Laval, Université du Québec à Montréal
- 40 ans déjà ...

The CIRRELT

- 70 membres réguliers (professeurs) - toutes les universités du Québec
- 43 membres associés - Québec, Canada, le monde
- 36 chercheurs postdoctoraux, 192 étudiants au doctorat, 183 étudiants à la maîtrise, ...
- 55 personnel (technique, secrétariat)
- Financement infrastructure: universités, organismes publiques (Q) de financement de la recherche, ...
- Financement de la recherche: subventions, contrats, grands projets

The Team

- Endong Zhu, PhD Operations Research, Université de Montréal
- Michel Gendreau, École Polytechnique Montréal

Transportation

- Central and vital for economy & society
- Mobility + buy, sell, exchange goods world-wide
- Billions of $: about 12% of GNP and final cost of products
- Congestion, pollution, ...
- Policy instrument for (sustainable) development
- Requirements & expectations
- Cost & operational efficiency
- On-time & regular service
- Reliable, robust, & resilient

⇒ Good planning

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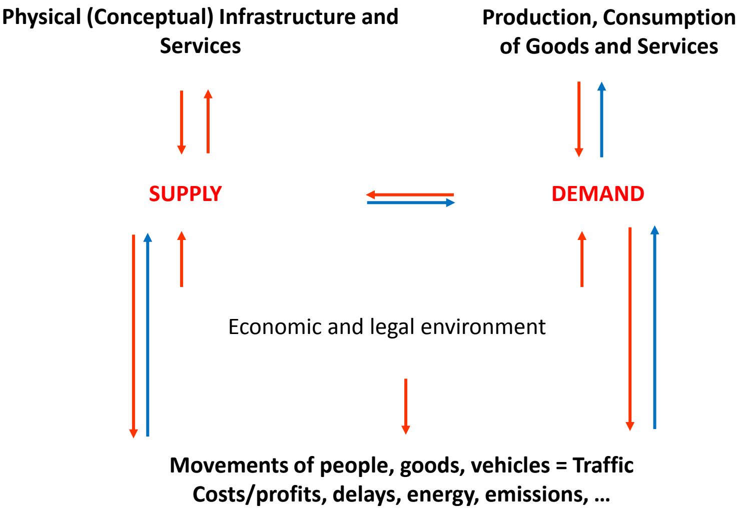

Transportation

Supply	**Demand**
Infrastructure	Point(s) to point(s)
Terminals	Economic criteria
Vehicles & convoys	Quality criteria
Modal & Intermodal services	Contacts & contracts
Routes & schedules	partnerships
Costs & tariffs	Logistic decisions

Points of View on Transportation

- Passenger versus Freight
- User/shipper versus Carrier
- Urban versus Interurban / Regional
- Modal versus Multi/Inter modal
- Integration?
- Intelligent Transportation Systems (ITS)

Today's Point of View on Transportation

- Passenger versus Freight
- User/shipper versus Carrier
- Urban versus Interurban / Regional
- Modal versus Multi/Intermodal
- Integration?
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Passenger Transportation

- Customized ("door-to-door") services
  - Private: Cars, personal plane or boat, bicycle, walking, ...
  - Collective (Public): Taxi
- Consolidation transportation
  - Private (semi): Collective taxis
  - Collective (Public): Buses, trains, subways, planes, ships

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Freight Transportation

- Regional/national planning
- Urban planning - City Logistics
- Carrier planning
  - Private fleets: Producers who own and operate their own fleets (and infrastructure, eventually)
  - For-hire carriers
  - Long haul (intercity): Relatively long distances, few points visited
  - Local (routing, distribution): Pickup and delivery routes serving several customers (within the day)

Freight Carriers - Service Type

- Customized ("door-to-door") services
  - The vehicle (convoy, multimodal service) is dedicated to the demand of a single customer
  - Full-truck motor carriers, for-hire ships, ...
  - Container, postal, and express courier services (customer perspective)
- Consolidation transportation
  - The loads of several customers are grouped, consolidated, into the same shipment and move together in the same vehicle
  - Railroads, Less-Than-Truckload (LTL) motor carriers, Shipping lines, Container transportation, Postal and express couriers (service/firm planning perspective), Regulatory agencies (in some countries)

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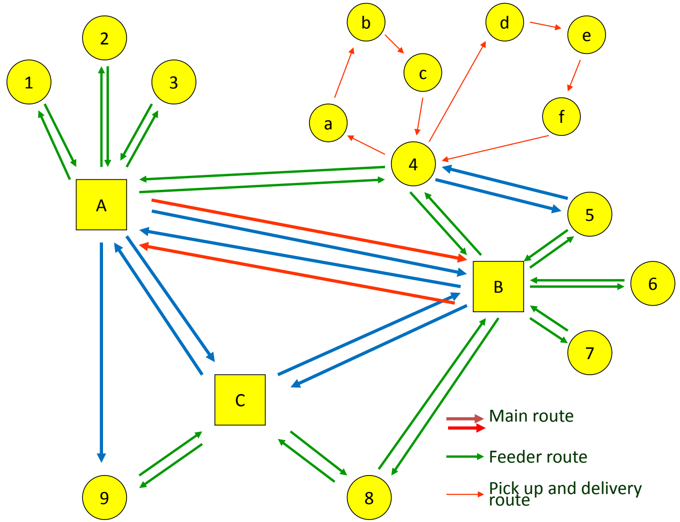
Consolidation Transportation



Consolidation Transportation (2)

- The same vehicle (convoy) serves the demand of several customers
- Regular services $\Rightarrow$ Routes, frequencies, schedules
- Terminals: Major role
  - Sort freight and consolidate it into vehicles
  - Sort vehicles and group them into convoys
  - Make-up/modify convoys
- Many types of services, equipment, and terminals
- Many tradeoffs among operations and performance measures

Consolidation Transportation (3)

- Reduces costs for customers
- Reduces costs for carrier (if correctly planned and performed)
- Reduces the flexibility for customers - published schedules
- Additional operations and delays (terminals) $\Rightarrow$ Reduced reliability
- Operation efficiency $\Leftrightarrow$ Carrier profitability
- Service quality (delays, reliability, ...) $\Leftrightarrow$ Customer satisfaction
- Need for methods to plan and manage operations $\Rightarrow$ Tactical planning

Rail Freight Transportation

- Major long-haul transportation mode
  - Bulk & general goods
  - Intermodal traffic: particular divisions & shuttle networks
  - Policy instrument for sustainable development
- Complex (double) consolidation operations
- Interference with passenger traffic
- Expensive infrastructure and assets
- Need for profitable, efficient & quality (fast, regular, reliable, ...) service

⇒ Planned & scheduled operations

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Consolidation Operations

- Rail transportation = Trains
- Train = More than meets the eye
- Freight is loaded into cars (by customers)
- Cars are *classified* (sorted) and *consolidated* (put together) into blocks at classification yards
- A block is a group of cars moved together as a unit from the block origin to the block destination
- Blocks are grouped together to *make up* trains at classification yards
- Trains move blocks-cars through the rail network
- Blocks may be *transferred* from one train to another at an intermediate yard
- Cars are moved from particular origin to particular destination on sequences of trains and blocks = itineraries

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Services and Schedules

- Service: What the carrier operates to address demand
  - Train route (physical) and intermediate stops (eventually)
  - Type: main/feeder/..., speed/priority, power requirements, etc.
  - Capacity (weight, length, ...)
  - Schedule: frequency, times of departure (origin yard), arrival & departure (intermediary stops), arrival (destination yard)
- Schedule: How the carrier operates
  - Fixed length (e.g., week)
  - Repetitive over the planning horizon (e.g., season)
  - Departure & arrival times of trains at stations (& meeting points)
- To simplify: service = particular train & departure time (from its origin)

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The Scheduled Service Network Design Problem

- Build the operating plan and schedule for next season

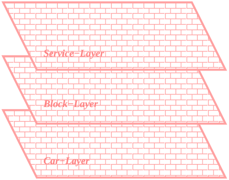
= *Tactical planning* activity

  - Select train services to operate with departure times
  - Select blocks to build: blocking policy
  - Determine block routing = train make up
  - Determine cargo routing = demand itineraries
  - Do not forget empty car distribution, yard capacities, etc.

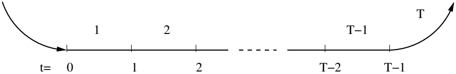
  To minimize costs, minimize delays or on-time delivery, ...

- Several contributions for particular problem settings
- No satisfactory methodology for the comprehensive problem

- Three layers - Service, Block, & Car - for
  selection of movements of each type of flow and consolidation level

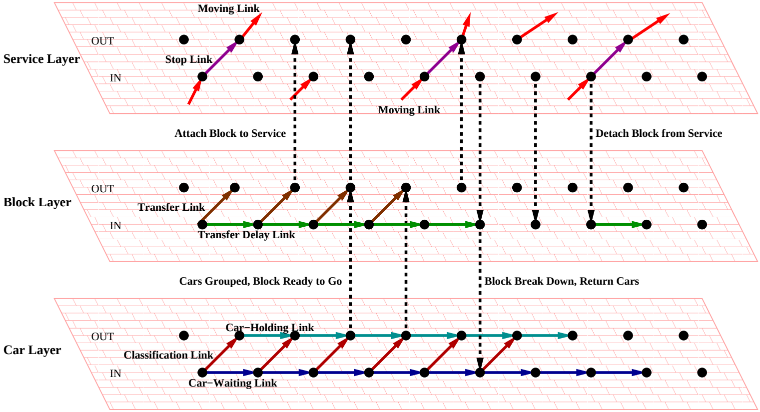


- Inter-cycle arcs
  - Cars to form/break blocks
  - Blocks to make up/break down trains or to transfer (attach/detach)
- *Cyclic* time dimension for repetitive schedule



- Two nodes, IN and OUT, to represent each yard at each time point

A 3-Layer Time-Space Network Illustration

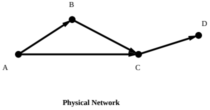


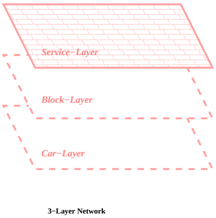
Services

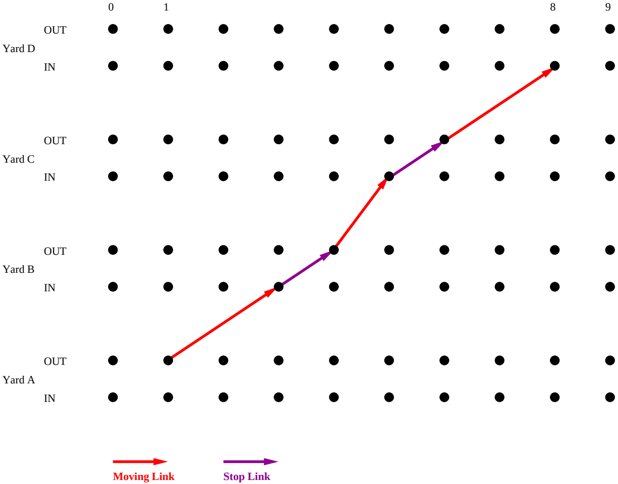
Each service $s \in \mathcal{S}$ is represented by a path in the *service layer*

- Specific departure time and duration time
- Route = sequence of moving (set of tracks & travel time) and stop links
  - Track capacity in terms of number of services
- Fixed cost (power, crew, etc.)
- Unit flow (demand) cost on each car-moving link
- Capacity in terms of number of cars
- Service section: Service provided between two (not necessary consecutive) stops
- Service selection decision variables $z_s \in \{1, 0\}$

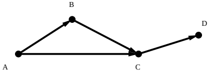
Service Sections & Service Layer



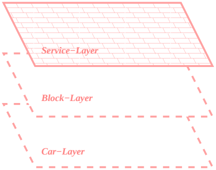




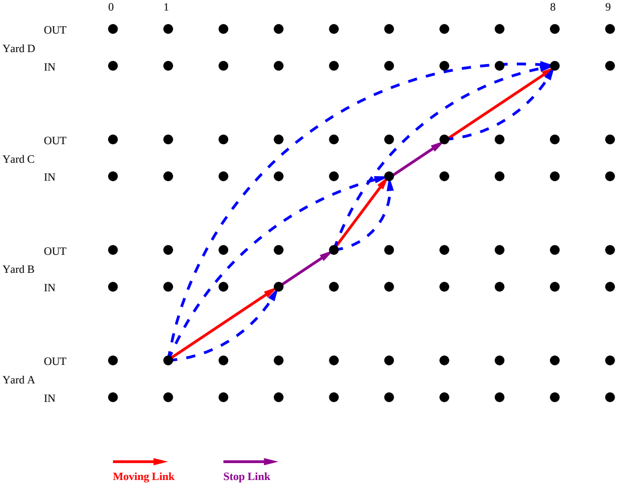
Service Sections & Service Layer



Physical Network



3−Layer Network

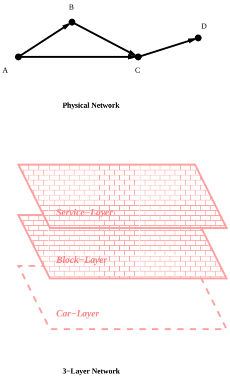


Blocks

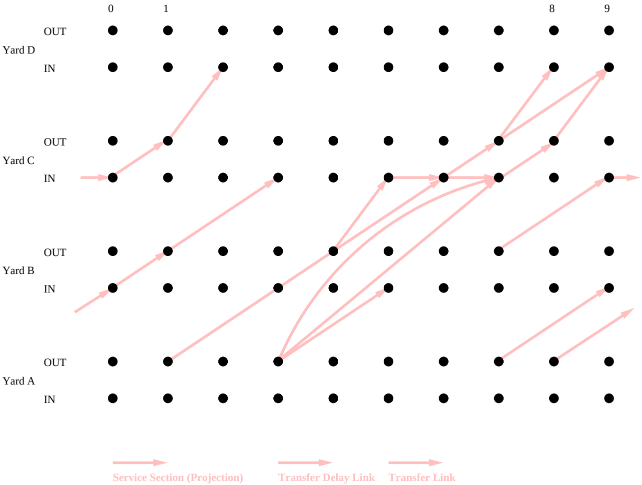
Each block $b \in \mathcal{B}$ is represented by a path in the *block layer*

- Series of block-moving links = service sections (projected)
- Connected by within-layer transfer (inter yards) links, transfer-delay (holding/waiting at yard) links, and
- Inter-layer vertical links to attach/detach the block to train services
- Fixed cost to build and transfer (yard crew & equipment, classification track occupancy)
- Approximated classification-track occupancy time at the origin yard
  - Yard capacity in terms of number of blocks = classification tracks
  - Classification track capacity in terms of number of cars
- Capacity in terms of number of cars
- Unit flow cost on each block-moving link
- Block selection decision variables $y_b \in \{1, 0\}$

Block Layer

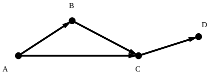


B
D
A
C
Physical Network
Service−Layer
Block−Layer
Car−Layer
3−Layer Network

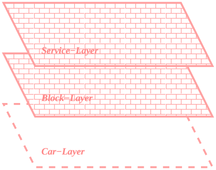


0
1
8
9
Yard D
OUT
IN
Yard C
OUT
IN
Yard B
OUT
IN
Yard A
OUT
IN
Service Section (Projection)
Transfer Delay Link
Transfer Link

Block Layer



Physical Network



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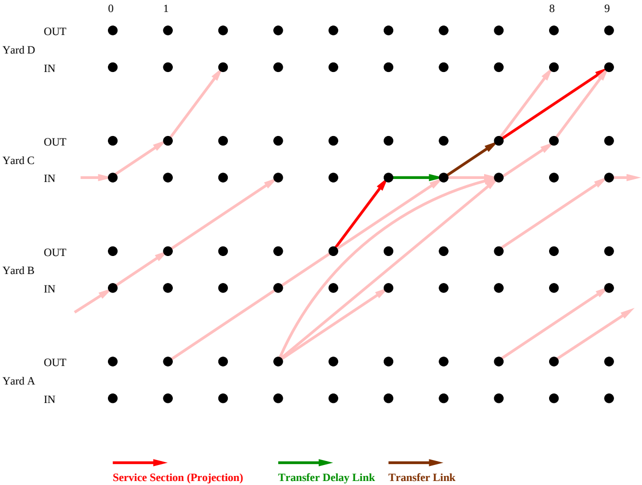

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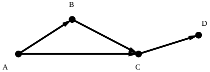

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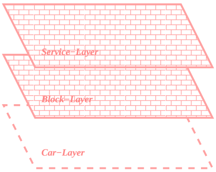

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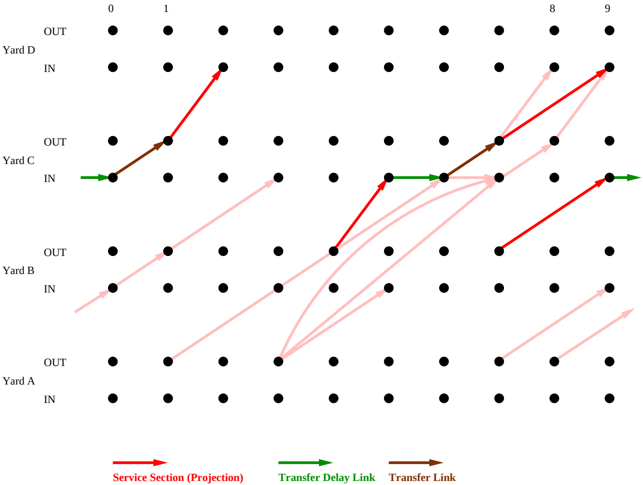
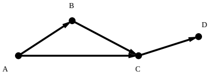


Block Layer



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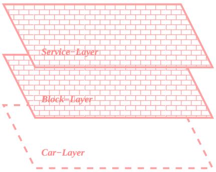

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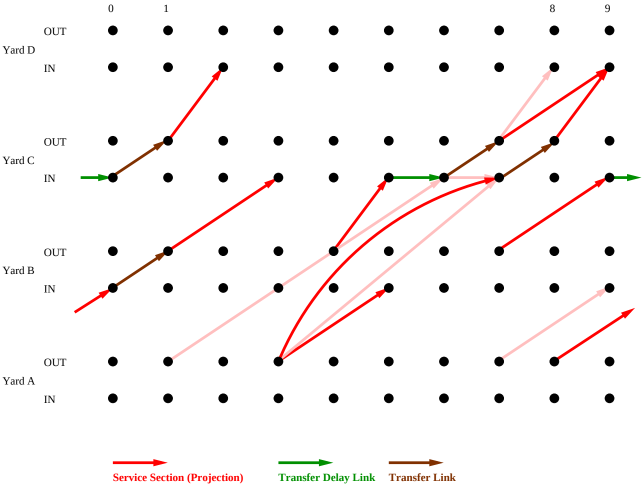
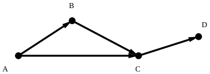


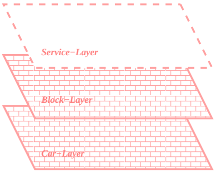
Cars

- Enter & exit the system, are classified (sorted and grouped), and wait in the *car layer*
- Moved as blocks on train services
- The itineraries: Multi-layer series of
  - Classification links
    Move (hump, haul) from receiving to classification tracks
  - Car-waiting links (on receiving tracks): Classification delay
  - Holding links: Waiting on classification tracks for the block to be “full”
  - Car-moving links = blocks (projected)
  - Connected by inter-layer vertical links to indicate blocks are ready to go or arrived and are broken down
- Yard classification capacity in terms of number of cars handled per period
- Unit flow cost on each link
- Car flow-on-link decision variables $x_{ap} \geq 0$

Car Layer



Physical Network



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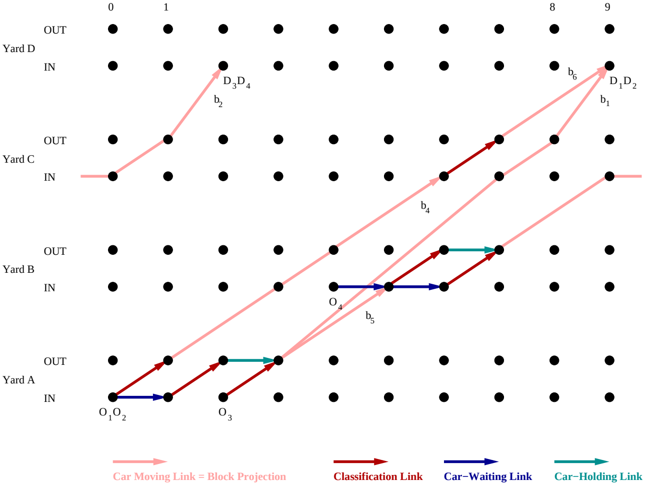
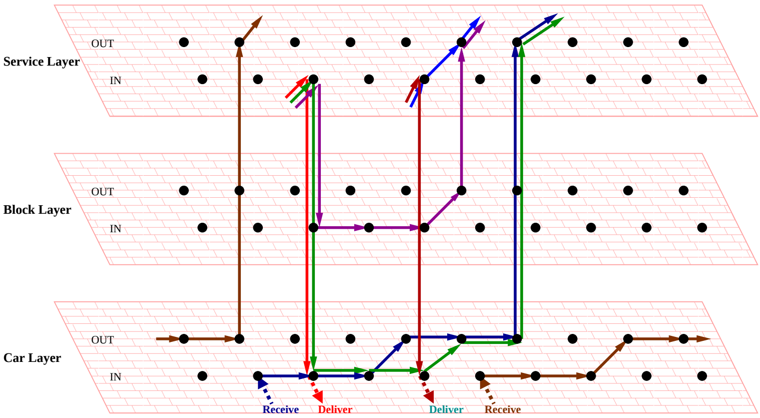


Itineraries in 3-Layer Time-Space Network



Formulation

$$SNDP = \min \sum_{p\in\mathcal{P}} \sum_{a\in\mathcal{A}} c_{ap} \cdot x_{ap} + \sum_{b\in\mathcal{B}} c_b^{\mathrm{F}} \cdot y_b + \sum_{s\in\mathcal{S}} c_s^{\mathrm{F}} \cdot z_s \tag{1}$$

s.t.

$$\sum_{a\in\mathcal{A}^{+}(n)} x_{ap} - \sum_{a\in\mathcal{A}^{-}(n)} x_{ap} = w_n^p \qquad \forall n \in \mathcal{N}^{\mathrm{C}}, \forall p \in \mathcal{P}; \tag{2}$$

$$\sum_{p\in\mathcal{P}} x_{ap} \le u_a \qquad \forall a \in \mathcal{A}^{\mathrm{CC}}; \tag{3}$$

$$\sum_{s\in\mathcal{S}(e,t)} z_s \le u_e \qquad \forall e \in \mathcal{E}, \forall t \in \{0, \cdots, \mathbf{T}-1\}; \tag{4}$$

$$\sum_{b\in\mathcal{B}(v,t)} y_b \le u_v \qquad \forall v \in \mathcal{V}, \forall t \in \{0, \cdots, \mathbf{T}-1\}; \tag{5}$$

$$\sum_{l\in\mathcal{L}(s)|a\in\mathcal{A}^{\mathrm{SM}}(l)} \sum_{b\in\mathcal{B}|l\in\mathcal{L}(b)} \sum_{p\in\mathcal{P}} x_{bp} \le z_s u_s \qquad \forall a \in \mathcal{A}^{\mathrm{SM}}, s \in \mathcal{S}; \tag{6}$$

$$\sum_{p\in\mathcal{P}} x_{bp} \le y_b u_b \qquad \forall b \in \mathcal{B}; \tag{7}$$

$$y_b \le z_{s(l)} \qquad \forall l \in \mathcal{L}(b), b \in \mathcal{B}; \tag{8}$$

$$x_{ap} \ge 0 \qquad \forall a \in \mathcal{A}, \forall p \in \mathcal{P}; \tag{9}$$

$$y_b \in \{0, 1\} \qquad \forall b \in \mathcal{B}; \tag{10}$$

$$z_s \in \{0, 1\} \qquad \forall s \in \mathcal{S}. \tag{11}$$

Algorithmic Observations

- A large-scale *Service Network Design Problem* (SNDP)
- A combinatorial MIP formulation
- Difficult formally and computationally
- Two interlaced layers of design decisions
- Initial experiments indicated a straightforward tabu search on the block search space is not efficient (it works for the direct service case)

Our Approach

Combine a number of interesting concepts

- Slope scaling (SS) for rapid identification of fairly good solutions (Kim and Pardalos 1999)
- Long-term memory perturbation (LMP) for guiding SS out of local optima (Crainc et al. 2004, Kim et al. 2006)
- A new *Ellipsoidal Search* (ES) to improve a set of elite solutions built by SS
  - Define a restricted SNDP from the elite set (Path relinking & local branching ideas to restrict the space)
  - Solve MIP subproblems exactly for feasibility & exploration
  - Long-term memories for guidance

Slope Scaling

- Address a SNDP relaxation by iteratively solving a linear approximation
  - Remove the service (4) and block (5) capacity constraints

  $\Rightarrow$ Relaxed SNDP
  - Approximate the block & service fixed-cost part of R-SNDP objective with a linear function

$$\sum_{p \in \mathcal{P}} \sum_{b \in \mathcal{B}} (\alpha_b + \sum_{l \in \mathcal{L}(b)} \beta_{s(l)}) x_{bp}$$

  - Solve the resulting minimum cost multi-commodity network flow problem

Approximation Problem

$$
\begin{aligned}
AP(\alpha, \beta) = \quad & \min \sum_{p \in \mathcal{P}} \sum_{a \in \mathcal{A}} c_{ap} x_{ap} + \sum_{p \in \mathcal{P}} \sum_{b \in \mathcal{B}} (\alpha_b + \sum_{l \in \mathcal{L}(b)} \beta_{s(l)}) x_{bp} && (12) \\
\text{s.t.} \quad & \sum_{a \in \mathcal{A}^+(n)} x_{ap} - \sum_{a \in \mathcal{A}^-(n)} x_{ap} = w_n^p && \forall n \in \mathcal{N}^{\mathrm{C}}, \forall p \in \mathcal{P}; \\
& \sum_{p \in \mathcal{P}} x_{ap} \leq u_a && \forall a \in \mathcal{A}^{\mathrm{CC}}; \\
& \sum_{l \in \mathcal{L}(s) | a \in \mathcal{A}^{\mathrm{SM}}(l)} \sum_{b \in \mathcal{B} | l \in \mathcal{L}(b)} \sum_{p \in \mathcal{P}} x_{bp} \leq u_s && \forall a \in \mathcal{A}^{\mathrm{SM}}, s \in \mathcal{S}; \\
& \sum_{p \in \mathcal{P}} x_{bp} \leq u_b && \forall b \in \mathcal{B}; \\
& x_{ap} \geq 0 && \forall a \in \mathcal{A}, \forall p \in \mathcal{P}.
\end{aligned}
$$

- Multi-commodity network flow problem
- Augmenting-path heuristic to address large-size instances

Slope Scaling (2)

- Given a flow distribution $\tilde{x}$, a solution to R-SNDP is obtained by opening the blocks & services bearing flow
- To improve the approximation, one enforces

  approximated cost = total block & service fixed cost

$$\sum_{p \in \mathcal{P}} \sum_{b \in \mathcal{B}} (\alpha_b + \sum_{l \in \mathcal{L}(b)} \beta_{s(l)}) \tilde{x}_{bp} = \sum_{b \in \mathcal{B} | \tilde{y}_b = 1} c_b^{\mathrm{F}} + \sum_{s \in \mathcal{S} | \tilde{z}_s = 1} c_s^{\mathrm{F}}$$

  By adjusting the linear factors: fixed cost / total car flow
- Slope scaling stops on identical solutions found for two consecutive approximations

Identify Feasible Solutions: The Sliding Problem

- The approximate solution might not be feasible in terms of block & service capacity
- Restore feasibility by advancing/postponing selected blocks & services

⇒ *Slide* (slightly) blocks & services in time
  - A small SNDP with selected blocks & services and their
  - Parallel neighbours, i.e., same blocks & services with previous and next time period departure
  - MIP solved exactly
- The Procedure
  - Solve the sliding problem
  - Repeat if a new feasible solution is found
  - Stop, otherwise

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- The Procedure
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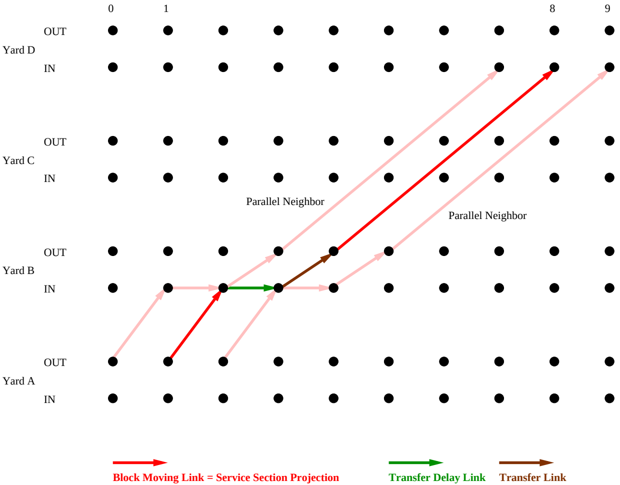
  - Repeat if a new feasible solution is found
  - Stop, otherwise

Illustration of Parallel Neighbours of a Block



The Slope Scaling Algorithm

SS

Given linearization factors α and β

repeat

Heuristically solve $AP(\alpha, \beta)$

Update α_b = block fixed cost/total car flow on the block

Update β_l = service fixed cost/total car flow on the service

Update long-term memories

until No improvement on $AP(\alpha, \beta)$ solution

Obtain feasible solutions by time-sliding procedure

Stop

Long-Term Memories & Perturbations

- SS is known to end up in local optima
- Build long-term statistics on behaviour of blocks and services
  - average flow
  - maximal flow
  - opening frequency
- Perturb the linearization factors based on these memories
  - Intensification: Favor blocks & services with high opening frequency and stable flow
  - Diversification: Favor rarely used blocks & services
- Restart the SS (parameters to control the search phases)

Slope Scaling + Long-term Memory Perturbation (SS+LMP)

SS+LMP

Given α and β

repeat

  Perform SS to find feasible solutions

  Update the best solution

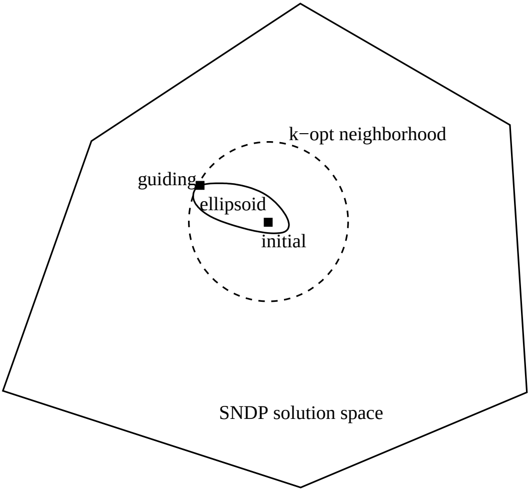
  Perturb α and β based on long-term memories

until Stopping criteria

Ellipsoidal Search

- Improve good solutions found by SS by exploring exactly a restricted space
- Feasible solutions generated by SS+LMP are saved in the *reference set*
- Select *initial* and *guiding* solutions from the reference set
  - Quality (guiding) and diversity (initial)
  - k = hamming (initial, guiding)
- Solve exactly a restricted *elite* SNDP starting from the initial solution
  - First restriction: k-opt neighbourhood of initial solution (local branching idea)
  - Second restriction: shape ellipse by fixing design variables based on long-term memories

Ellipsoid Solution Space Illustration



The Complete SS+ES+LMP Algorithm

SS+ES+LMP

Given α and β
repeat
  Perform SS ($AP(\alpha, \beta)$; time-sliding) updating the elite solution set
  if elite solution set updated **then**
    Perform Ellipsoidal Search
  end if
  Perturb α and β based on long-term memories
until Stopping criteria

Experimental Setting

- Two random problem sets = 30 instances
  - 5-10 yards
  - 14-60 tracks
  - 7 and 10 time periods
  - 100 to 900 demands
- C++; CPLEX 10.1; 10 hours
- 2.4Hz CPU, 16 GB RAM, Linux
- Calibration of SS, ES and LMP

First Set Results

p	block	serv	yard(track)	T	dmd	CplexSol	time	SS+LMP (1000i)	time	SS+ES+LMP (10h)
p01	1855	301	5(14)	7	150	75157	329	75667	266	75157
						0.00%		0.68%	-19.22%	0.00%
p02	2765	266	5(14)	7	200	72471	t	74228	410	72483
						2.69%		2.43%	-98.86%	0.02%
p03	2121	322	5(14)	7	250	78629	816	79616	345	78731
						0.00%		1.25%	-57.74%	0.13%
p04	3241	259	5(18)	7	250	82784	t	83462	688	82784
						0.41%		0.82%	-98.09%	0.00%
p05	1533	273	5(18)	7	300	98705	828	100173	963	98705
						0.00%		1.49%	16.28%	0.00%
p06	7497	413	5(18)	7	350	110333	t	109542	1042	107576
						7.13%		-0.72%	-97.11%	-2.50%
p07	39473	756	7(20)	7	350	267198	t	187930	4154	183527
						39.17%		-29.67%	-88.46%	-31..31%
p08	29449	693	7(20)	7	400	230244	t	171912	4005	166283
						38.23%		-25.34%	-88.88%	-27..78%
p09	19453	623	7(20)	7	450	174471	t	135343	7830	133110
						32.79%		-22.43%	-78.25%	-23..71%
p10	18424	840	7(32)	7	450	176248	t	161141	2891	158486
						19.37%		-8.57%	-91.97%	-10..08%
p11	9093	749	7(32)	7	500	155526	t	140845	2782	132723
						22.97%		-9.44%	-92.27%	-14..66%
p12	11102	700	7(32)	7	550	183386	t	169669	t	167424
						18.07%		-7.48%	0.00%	-8.70%
p13	140105	1834	10(60)	7	600	×	-	216927	t	212204
p14	236628	2016	10(60)	7	700	×	-	201368	t	195208
p15	279230	2674	10(60)	7	800	×	-	229553	t	228770

Second Set Results

p	block	serv	yard(track)	T	dmd	CplexSol	time	SS+LMP (1000i)	time	SS+ES+LMP (10h)
p16	8900	550	5(14)	10	100	94900	t	96345	126	94676
						4.02%		1.52%	-99.65%	-0.24%
p17	4700	490	5(14)	10	150	90967	t	92495	203	89554
						6.78%		1.68%	-99.43%	-1.55%
p18	3600	500	5(14)	10	200	128099	t	130037	304	128097
						2.68%		1.51%	-99.16%	0.00%
p19	1580	340	5(18)	10	150	79418	27534	79566	278	79418
						0.00%		0.19%	-98.99%	0.00%
p20	2570	500	5(18)	10	200	129305	1822	131273	343	129305
						0.00%		1.52%	-81.18%	0.00%
p21	8060	510	5(18)	10	250	105275	t	105144	1006	101656
						9.30%		-0.12%	-97.21%	-3.44%
p22	46150	1230	7(20)	10	200	225581	t	146270	1399	142283
						50.09%		-35.16%	-96.11%	-36.93%
p23	49920	1270	7(20)	10	250	169187	t	165325	1734	158157
						19.04%		-2.28%	-95.18%	-6.52%
p24	50000	1080	7(20)	10	300	293613	t	178798	3350	167934
						53.99%		-39.10%	-90.70%	-42.80%
p25	58930	1350	7(32)	10	250	208201	t	163591	3162	155919
						32.98%		-21.43%	-91.22%	-25.11%
p26	55580	1140	7(32)	10	300	187314	t	149691	3317	145052
						35.07%		-20.09%	-90.79%	-22.56%
p27	22900	1220	7(32)	10	350	226847	t	187950	1900	180356
						29.12%		-17.15%	-94.72%	-20.49%
p28	491150	3080	10(60)	10	500	×	-	273842	t	271156
p29	421370	3030	10(60)	10	700	×	-	264326	t	257230
p30	326550	3050	10(60)	10	900	×	-	326381	t	326575

Assessment

- Modelling the freight railroad scheduled service network design problem
- Tackling simultaneously two embedded consolidation activities and the time dimension
- Large and complex MIP
- The hybrid heuristic performs well on medium-sized instances (Sufficient for quite a number of applications)
- BUT
- Can we do better?
- Yes, by starting to explore dynamic variable generation approaches

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- The hybrid heuristic performs well on medium-sized instances

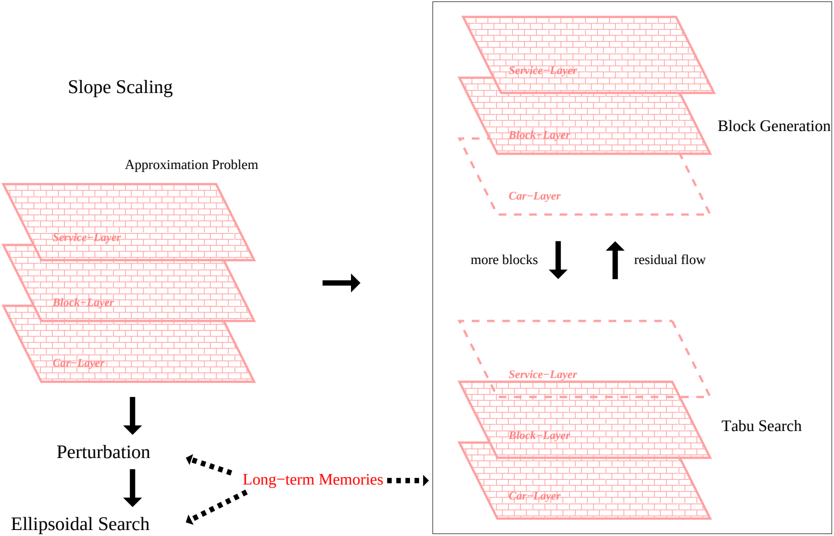
  (Sufficient for quite a number of applications)
- BUT
- Can we do better?
- Yes, by starting to explore dynamic variable generation approaches

Algorithmic Observations

- Two interlaced layers of design decisions
- Very large number of design variables
- Blocks = combinations of service sections
- Consider blocks implicitly and generate them dynamically
    - Define a block-design relaxation for the Slope Scaling

    $\Rightarrow$ A MIP SNDP with block-selection decisions and implicitly considered blocks
    - Generate new blocks at each move of the cycle-based Tabu Search addressing the SNDP

The New Meta-heuristic



The New Meta-heuristic

- Block-dynamic Slope scaling (BD-SS)
  - Address a relaxation by iteratively solving a linear approximation
  - Relaxation of service capacity constraints
  - Approximating the service fixed-cost
  - ⇒ A scheduled block network design problem = MIP formulation
  - Addressed by a cycle-based tabu search meta-heuristic with dynamic block generation
- Long-term memory perturbation (LMP) for guiding BD-SS out of local optima
- *Ellipsoidal Search* (ES) to improve a set of elite solutions built by SS
  - Define a restricted SNDP from the elite set (Path relinking & local branching ideas to restrict the space)
  - Solve MIP subproblems exactly for feasibility & exploration
  - Long-term memories for guidance

Block-Dynamic Slope Scaling

- Address a SNDP relaxation by iteratively solving a block-design MIP approximation problem AP(β)
  - Remove the service (4) capacity constraints $\Rightarrow$ Relaxed SNDP
  - Approximate the service fixed-cost part with a linear function

$$\sum_{p \in \mathcal{P}} \sum_{s \in \mathcal{S}} \beta_s x_{sp}$$

  - Solve the resulting MIP SNDP AP(β)
- Given a solution, c_s^{F} is paid for service s with positive flow
- β_s coefficients are adjusted to satisfy

$$\text{fixed service cost } c_s^{\mathrm{F}} = \text{total flow on service } s \cdot \beta_s \qquad \text{for } s \text{ open}$$

- Next iteration is initiated

Approximation Problem

$$\text{AP}(\beta) = \min \sum_{p \in \mathcal{P}} \sum_{a \in \mathcal{A}} c_{ap} \cdot x_{ap} + \sum_{b \in \mathcal{B}} c_b^{\text{F}} \cdot y_b + \sum_{s \in \mathcal{S}} \sum_{p \in \mathcal{P}} x_{sp} \beta_s$$

Subject to flow conservation and capacity constraints, and
$y_b \in \{0, 1\}. \forall b \in \mathcal{B}$

- A cycle-based Tabu Search addresses the block-network design problem
- The cycle-based neighborhood is evaluated through residual networks

⇒ Add/remove γ flow on the block ⇔ forward/backward arc (projection of services on block layer) with positive/negative cost

Block Generation

- A block = a projected-service path in β, γ-block layer
- A "parallel" block set for each OUT-IN node pair (different yards and time periods)

$\Leftrightarrow$ Parallel forward arcs in residual network

- Shortest path (linearization of transfer costs)

The Block-Dynamic Slope Scaling Algorithm

BD-SS

Given linearization factor β

repeat

Cycle-based Tabu Search for $AP(\alpha, \beta)$; Blocks are dynamically generated at each move

Update $\beta_l =$ service fixed cost/total car flow on the service

Update long-term memories

until No improvement on $AP(\beta)$ solution

Obtain feasible solutions by time-sliding procedure

Stop

Long-Term Memories & Perturbations

- Same as before
- SS is known to end up in local optima
- Build long-term statistics on behaviour of blocks and services
  - average flow
  - maximal flow
  - opening frequency
- Perturb the linearization factors based on these memories
  - Intensification: Favor blocks & services with high opening frequency and stable flow
  - Diversification: Favor rarely used blocks & services

Ellipsoidal Search

- Same as before
- Improve good solutions found by SS by exploring exactly a restricted space
- Feasible solutions generated by SS+LMP are saved in the *elite solution set*
- Select *initial* and *guiding* solutions from the elite solution set
  - Quality (guiding) and diversity (initial)
  - k = hamming (initial, guiding)
- Solve exactly a restricted SNDP
  - First restriction: k-opt neighbourhood of initial solution (local branching idea)
  - Second restriction: shape ellipse by fixing design variables based on long-term memories

The New Meta-heuristic

BD-SS+ES+LMP

Given β
repeat
  Perform block-dynamic SS updating the elite solution set
  if elite solution set updated **then**
    Perform Ellipsoidal Search
  end if
  Perturb β based on long-term memories
until Stopping criteria

Experimental Setting

- Same as before
- Two random problem sets = 30 instances
  - 5-10 yards
  - 14-60 tracks
  - 7 and 10 time periods
  - 100 to 900 demands
- C++; CPLEX 10.1; 10 hours
- 2.4Hz CPU, 16 GB RAM, Linux

Results 7 Time Periods

Inst	CplSol	OptGap	SS+ES+LMP	CplGap	BEST	CplGap	SS+ES+LMP Gap
p01	75157	0.00%	75157	0.00%	75157	0.00%	0.00%
p02	72471	2.69%	72483	0.02%	72575	0.14%	0.13%
p03	78629	0.00%	78731	0.13%	78743	0.14%	0.02%
p04	82784	0.41%	82784	0.00%	82784	0.00%	0.00%
p05	98705	0.00%	98705	0.00%	98760	0.06%	0.06%
p06	110333	7.13%	107576	-2.50%	107785	-2.31%	0.19%
p07	267198	39.17%	183527	-31.31%	186370	-30.25%	1.55%
p08	230244	38.23%	166283	-27.78%	168112	-26.99%	1.10%
p09	174471	32.79%	133110	-23.71%	133197	-23.66%	0.07%
p10	176248	19.37%	158486	-10.08%	158716	-9.95%	0.15%
p11	155526	22.97%	132723	-14.66%	134663	-13.41%	1.46%
p12	183386	18.07%	167424	-8.70%	170195	-7.19%	1.66%
p13	×	-	212204	-	212045	-	-0.07%
p14	×	-	195208	-	185678	-	-4.88%
p15	×	-	228770	-	224068	-	-2.06%
Avg							-0.04%

Results 10 Time Periods

Inst	CplSol	OptGap	SS+ES+LMP	CplGap	BEST	CplGap	SS+ES+LMP Gap
p16	94900	4.02%	94676	-0.24%	94929	0.03%	0.27%
p17	90967	6.78%	89554	-1.55%	90129	-0.92%	0.64%
p18	128099	2.68%	128097	0.00%	128505	0.32%	0.32%
p19	79418	0.00%	79418	0.00%	79563	0.18%	0.18%
p20	129305	0.00%	129305	0.00%	129307	0.00%	0.00%
p21	105275	9.30%	101656	-3.44%	103193	-1.98%	1.51%
p22	225581	50.09%	142283	-36.93%	144070	-36.13%	1.26%
p23	169187	19.04%	158157	-6.52%	158719	-6.19%	0.36%
p24	293613	53.99%	167934	-42.80%	169997	-42.10%	1.23%
p25	208201	32.98%	155919	-25.11%	156230	-24.96%	0.20%
p26	187314	35.07%	145052	-22.56%	147253	-21.39%	1.52%
p27	226847	29.12%	180356	-20.49%	182786	-19.42%	1.35%
p28	×	-	271156	-	261401	-	-3.60%
p29	×	-	257230	-	252635	-	-1.79%
p30	×	-	326575	-	316503	-	-3.08%
Avg							0.02%

Conclusions

- For the application
  - An integrated scheduled service network design model
  - An algorithmic framework able to address interesting-size instances
    Largest instance tested: 30 yards, 135 tracks, 7 time periods, 1000 demands
  - Outperforms state-of-the-art solver
  - Interesting heuristic dynamic generation of path variables within tabu search
- Perspectives for multi-layer network design

Thank you for your attention