Service Design Models in Freight Transportation

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ESG UQAM
&
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Consolidation Freight Transportation

- Long distance freight transportation
- Railways
- Less-Than-Truckload (LTL) motor carriers
- Shipping lines
- Container transportation
- Postal and express couriers: Service (firm) planning perspective
- Regulatory agencies (in some countries)
Consolidation Transportation (2)

- The same vehicle (convoy) serves the demand of several customers
- Regular services ⇒ Routes, frequencies, schedules
- Terminals: Major and central role
  - Sort freight and consolidate it into vehicles
  - Sort vehicles and group them into convoys
  - Manipulate convoys
- Many types of services, equipment, and terminals
- Many trade-offs among operations and among performance measures
Consolidation Transportation (3)

- Reduces costs for customers
- Reduces costs for carrier (if correctly planned and performed)
- Reduces the flexibility of customers
- Additional operations and delays (in terminals) ⇒ Reduced reliability (and costs)
- Operation efficiency ⇔ Carrier profitability
- Service quality (delays, reliability, …) ⇔ Customer satisfaction
- Need for methods to plan and manage operations
Tactical Planning

_Objatives_

ёт Determine the best – optimal – assignment and utilization of resources to fulfil the economic and service (customers) objectives of the carrier

_Means_

ёт Tactical (load, transportation, …) plan

_Yields_

ёт Operation plan for normal/regular operations
ёт Scenario analysis tool
Vocabulary – Physical network

* Infrastructure network on which transport services operate
  * Rail tracks and stations
  * Public roads and terminals (motor carriers, post, express mail, …)
  * Airports, ports, LTL breakbulk and end-of-line terminals, intermodal terminals in general, …
  * Conceptual air, sea, river, … connections
  * …
Physical Network

terminal A

terminal B

terminal C

terminal D

terminal E

terminal F
Vocabulary – Transport Services

❖ For the customers
  ➣ Point-to-point (city-to-city, origin to destination) service offer
  ➣ Frequencies and schedules
  ➣ Tariffs
  ➣ Service targets: “Montreal to Toronto in 24 hours”

❖ For the carrier
  ➣ Origin (terminal), destination (terminal), route through the physical network, stops, equipment type, …
Transport Services – Carrier

- Operations costs
- Frequencies and schedules
- Service targets: “Montreal to Toronto in 24 hours, 80% of the time”
- The origin and destination as seen by a customer are generally not those of a carrier service
  - Pick up and delivery
  - Freight moved by a series of transport services and terminals
- Terminals = services
Vocabulary – Demand

Market = Traffic class
- Origin, destination, product
- Quantity
- Priority level – delay cost

Routing - Itineraries
- Origin, destination, route through service network
- Terminal operations
- Quantity and performance measures
Itineraries: A to E

- Terminal A
- Terminal B
- Terminal C
- Terminal D
- Terminal E
- Terminal F

Modes:

- S1
- S2
- S3
- S4
- S5
- S6
- S7
Itineraries : A to E (2)
Itineraries : A to E (3)

Transfer at C from S3 to S5
Transfer at D from S5 to S6
Itineraries : A to E (4)

Transfer at C from S3 to S5
Consolidation at D from S5 to S6
Itineraries: Extra A to E + B to F

- Terminal A
  - (A, E)
- Terminal B
  - (B, F)
- Terminal C
  - (B, F) et (A, E+)
- Terminal D
  - (A, E)
- Terminal E
  - (A, E)
- Terminal F
  - (B, F)

Modes:

S1, S2, S3, S4, S5, S6, S7
Best Itinerary (there are quite a lot of them)?

 довольно

It depends

- The state of the entire system
  - Moving the entire demand
  - Congestion in (in front of) terminals (lines)
  - Frequency and utilization (loads) of services

- The trade-off between operation costs (to minimize) and the service quality (to maximize)

- Need to optimize the entire set of operations in an integrated way
Bonjour, Jacques!!
Interrelated Decisions

- **Service selection**
  - Routes, types, frequencies, schedules, …

- **Freight routing (distribution)**
  - Itineraries (routes), volumes, …
  - Empty vehicles

- **Terminal utilization policies**
  - Work division

- **Network-wide interactions and trade-offs**
  - Among components/operations/decisions
  - Between cost and quality objectives
Decision Environment

- Interactions occur network-wide ("ripple effect")
- The impact of individual decisions are difficult to forecast and rarely intuitive
- Trade offs are difficult to identify
Service Network Design

- Construction of tactical plan
- Aggregated modelling of the major system components, decisions, operations
  - “Planning, not operations”
  - Integrates trade-offs costs versus service quality
  - Interactions of several types of resources
  - Network-wide level
Service Network Design (2)

❖ Planning horizon
  ❆ Strategic/tactic
  ❆ Tactic/operational

❖ Service network design model (methodology)
  ❆ Static
  ❆ Dynamic (time-dependent)
  ❆ Deterministic (why not stochastic?)

❖ Model objective
  ❆ Static: Selection & Frequencies
  ❆ Dynamic: Schedules (& dispatching)
Static Service Network Design

Objectives

- Strategic/tactic planning ⇒ Transportation plan
- Interaction and trade-off analyses
- Scenario analyses

Typical issues

- Do we operate the service?
- How often over the planning horizon?
- What service type?
- Terminal loads?
- Itineraries for demand and empty vehicles?
Static Service Network Design: Approaches

❖ Selection of services
❖ Frequencies as
  ✿ Consequences of routing decisions (Powell et al)
  ✿ Decisions (Crainic et al)
❖ In all cases, the service network represents the decision structure on which traffic routing decisions are taken
Selecting Services

Decisions

- “To operate or not” each service: \{0,1\} variables
- Demand routing: continuous flow variables

Demand for several “Products”
(appropriate measures: tons, # of vehicles, …)

Each service

- Fixed cost to operate
- Variable cost to transport products
- Capacity
Selecting Services (2)

Modes

terminal A

d_{AE}, d_{AF}, d_{AD}

terminal B

terminal C

terminal D

terminal E

terminal F

S1

S2

S3

S4

S5

S6

S7

y_{S_1}

x_{s_1AE}

u_{s_1}

y_{S_2}

x_{s_2AE}

u_{s_2}

y_{S_3}

x_{S_3AE}

x_{S_3AF}

x_{S_3AD}

u_{S_3}

x_{S_4AD}

x_{S_5AD}

x_{S_5AF}

x_{S_5AE}

u_{S_5}

x_{S_6AD}

x_{S_7AD}

u_{S_7}
Selecting Services: Modelling

Network

- Nodes: Terminals \( i, j \in T \)
- Links = services \( a = (i, j) \in S; i, j \in T \)

Decisions

- Is a service \( a \), from terminal \( i \) to terminal \( j \), to be selected (operated, offered)? \( y_a \in \{1, 0\} \)
- Quantity of demand of market \( o_d \) carried on service \( a \)
  \[ x_{aod} \geq 0 \]
Selecting Services: Formulation

Minimize
$$\sum_{s \in S} f_s y_s + \sum_{p \in P} \sum_{s \in S} C^p_s x_{sp}$$

Subject to
$$\sum_{s \in S} \sum_{j \in S} x_{sji} - \sum_{s \in S} \sum_{j \in S} x_{sij} = \begin{cases} -d_p & \text{if at origin} \\ 0 & \text{if other terminal} \\ d_p & \text{if at destination} \end{cases}$$

Flow conservation
$$\sum_{p \in P} x_{sp} \leq u_s y_s$$

Linking/ capacity
$$y_s \in \{0, 1\}$$
$$x_{sp} \geq 0$$
Service Network Design

- Fixed-cost, capacitated, multicommodity, network design formulations (arc or path)
- Combinatorial and difficult
- Additional constraints from operational considerations
- Solved by
  - Exact methods (B&B, …) for small instances
  - Heuristics and Meta-heuristics in most cases
- Frequency formulations (general integer design variables): even more complex
Frequencies as Decisions

- Applications to railways, LTL motor carriers, courier, etc.
- Determine service frequencies
- Routing of demand for each market
  - Service and terminal work charges derived from frequencies and itineraries
- More complex service routes
- Service and terminals capacity and congestion
- Minimize the generalized cost of operating costs, service quality measures, delay costs, etc.
- Non linear formulation due to frequency/congestion impact
Delays and Congestion

Average delay (time)

= free travel time
* \([1 + 0.70 \text{ total traffic} + 0.80 (\text{total traffic} / \text{capacity})^6]\)
Operations with Congestion

- Single and double rail lines: meets and overtakes
- Congested roads
- Car classification, block and train make up (rail yards)
- Connection: waiting for the next service (terminals)
- Truck waiting at terminal doors
- Ship waiting at port or lock entry
- Freight classification and consolidation (terminals)
- Vehicle loading/unloading, …
- Functions are derived from engineering and queuing formulas, through simulation
Modelling Capacity Restrictions

☞ For modelling & algorithmic reasons, capacity restrictions and other service quality measures are better represented as non-linear penalties in the objective

☞ Hard constraints in actual operation
☞ Hard capacity constraints: more difficult design problem
☞ Overcapacity corresponds to longer delays
☞ The model should be able to go over capacity and “pay the price” if it yields a better overall performance
⇒ The possibility to explore strategies and tradeoffs that strict constraints do not allow to see
Service Network Design

- **Static**: Selection and frequencies
- **Dynamic**: Schedules and dispatching
  - When will the service leave? (If it does…)
  - Moving the freight
  - Repositioning of resources (vehicles, crews, motor power)
Space-Time Network (Diagram)

- Representation tool for time-dependent events (demand, activities, decisions, …) and their relations in time and space
- The network describes the system operations during the current and the following time periods
- Arcs represent inter-period relations (inventories, movements, etc.)
- The objective function minimizes/maximizes the total cost/profit over the entire multi-period planning horizon
Space-Time Network – Schedules

Terminals

Period t

Period t + 1

Periods t + ...

Time

Possible departure

Inventory arc

End of horizon

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Space-Time Network – Cyclic Schedules
Modelling Idea

- Physical network represented at each period
- Arcs represent each possible departure (origins, intermediary stations) of each service
- Waiting/holding (inventory) arcs link nodes representing the same terminals in consecutive periods
- Decision variables
  - \( \{0, 1\} \): The corresponding service leaves (is operated) at the specified time?
  - Continuous: Freight flows
Modelling Idea (2)

- Modelling principles and components of the static formulations apply
- Problem dimensions grow fast !!
- Network design solution approaches
- Adaptations of fleet management (dynamic resource allocation) methodologies
- There is a lot of work required in this field !!
An Example of “New” Challenges

- Dedicated intermodal rail services to move containers & trailers
  - Instrument for E.U. policy
  - Consolidation carriers with/without external services
  - Efficiency and profitability of operations

- Old issues, “new” operation principles, new challenges
Rail Intermodal

- Dedicated carriers (divisions)
- North America
  - Long distances – “land bridges” – linking the coast and the industrial mid-west
  - Long trains (very long 😊)
  - Double stack
  - Scheduled services (almost)
  - Bookings and full-asset-utilization operations (emerging)
Rail Intermodal (2)

Europe

- Separation of infrastructure owners/managers (capacity providers) and operators (service providers)
- Scheduled services: network is congested !!
- Double stack (where possible)
- Bookings (contemplated)
- New services
  - Shuttle services
  - E.U. expansion to Central and East Europe
Rail Intermodal – Trends

- "Full asset utilization" operations
  - Same trains & blocks operated every day, all days (seasonal)
  - Equipment – engines & cars – and personnel operates circular routes

- Bookings
  - Advance reservation of space (slot) on train/day

- Advanced terminals on the drawing boards
  ⇒ Intelligent systems
Rail Intermodal – New Networks in Europe

❖ Expansion of EU
❖ German network very congested
❖ New shuttle networks
   ➤ Link Scandinavia to Central Europe and beyond
   ➤ Use uncongested “Eastern” rail networks: Polish, Czech, …

 Andersen, Christiansen, Crainic 05

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The Polcorridor project

Northern feeder network

Hubs

Southern feeder network
The System

Vienna
Swinoujscie/Szczecin
Zielona Góra
Wroclaw
Poznan
Miedzylesie
Chalupki
Breclav
Gdansk/Gdynia
Swinoujscie/Szczecin

Node in rail network
Intermodal hub
Border crossing node
Rail lines
Czech/Polish border with change of locomotive
Node in external network
External service
Swinoujscie Rail-Ferry Terminal Representation

Arrival of ferry

Quay

Storage area

Transhipment of rail wagons

Loading of containers & semitrailers

Unloading of containers & semitrailers

Rail terminal

Locomotives ready for new departure

TRAIN DEPARTURE

Departure of ferry

Quay

Storage area

Transhipment of rail wagons

Loading of containers & semitrailers

Unloading of containers & semitrailers

Rail terminal

TRAIN ARRIVAL
Two Models

- Strategic/tactical for major design decisions
  - Services: types, routes, frequencies
  - Market “selection” (some pricing issues) and routing
  - Frequency service network design

- Service & schedule planning
  - When service depart given “ideal” frequencies
  - Coordination and synchronization
  - External networks (ferries, other rail services)
  - Multi-carriers & border crossings
Common Characteristics and Issues

- **Cyclic schedules**

  \[ \Rightarrow \text{Cyclic Space-Time Network Representation} \]

![Diagram showing cyclic schedules and space-time network representation](image-url)
Common Characteristics and Issues (2)

- Need to include **locomotive management**
  - “Repositioning” – Circular routes
- Change of locomotive at the Czech – Polish border
  - Need to synchronize/coordinate
Scheduled Service Design + Asset Management + External Service Coordination (Model 2)

- Time-space representation with repetitive service network
- Border crossings with synchronization
- Design new services interacting with existing/external services ⇒ Some departure times are fixed
- Balancing of assets (locomotives) at nodes
  - Repositioning allowed to create feasible locomotive (circular) movements
Model

Minimize total time cost: travel + waiting for various terminal operations (border, connection, …)

The fleet of locomotives must cover all services and repositioning in each time period

Node asset (locomotive) balance

Lower and upper bounds on service frequencies

Node freight (rail car) balance

Train capacity on internal and external services
Design-Balanced Network Design

At the core a “new” variant of multicommodity capacitated network design problem

- Design balance constraints
  - The number of selected design arcs entering a node = number of selected design arcs exiting the node
Arc Formulation (DBCMND)

\[
\begin{align*}
\min \quad & z(X, Y) = \sum_{(i,j) \in A} f_{ij} y_{ij} + \sum_{p \in P} \sum_{(i,j) \in A} c_{ij}^p x_{ij}^p \\
\quad & \sum_{j \in N^+(i)} x_{ij}^p - \sum_{j \in N^-(i)} x_{ji}^p = d_i^p = \begin{cases} \\
& w^p \quad \text{if} \quad i = o(p) \\
& -w^p \quad \text{if} \quad i = s(p) \\
& 0 \quad \text{otherwise} \\
\end{cases} \\
\quad & \sum_{p \in P} x_{ij}^p \leq u_{ij} y_{ij} \quad \forall (i, j) \in A \\
\quad & \sum_{j \in N^+(i)} y_{ij} - \sum_{j \in N^-(i)} y_{ji} = 0, \forall i \in N \\
\quad & x_{ij}^p \geq 0 \quad \forall (i, j) \in A, \forall p \in A \\
\quad & y_{ij} \in \mathbb{N} \quad \forall (i, j) \in A
\end{align*}
\]
Design-Balanced Network Design

- Exact solution methods work on very small instances
- Heuristic methods for particular cases
  - LP relaxation & column generation + cuts + rounding
    - Smilowitz, Atamtürk, Daganzo, 2003
  - Path-based generate + combine to improve
    - Lai and Lo, 2004
- Arc-based general formulation
  - Tabu search-based method yields promising results
    - Pedersen, Crainic, Madsen, 2006
- Interesting cycle-based formulation has been proposed
Consolidation (Intermodal) Transportation

Growing steadily & should continue to grow

Modifications to the economic, regulatory, technological, social and political environment of industry

Globalization, automation, ITS, e-logistics, security, …

New operation policies, new applications

Need for innovative and enhanced planning and management procedures

Opportunities for Operations Research and Transportation Science
Methodological Challenges

- Advance network design methodology
- Transfer methodology to application areas
- Time-dependent design-balanced service network design
  - Formulations & characterization
  - Efficient solution methods, …
- Stochastics and service network design
  - Preliminary studies: plans are different and “better” …
  - Requires work on realistic formulations & efficient solution methods