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A MULTI-STAGE, OPTIMIZATION-BASED APPROACH FOR THE LINER SHIPPING PROBLEM

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Presentation Synopsis

I. Demonstrate a ***holistic*** description of the problem

II. Identify the need for ***optimization-based*** solutions for the ***Liner Shipping Problem***

III. Propose a ***multi-stage methodology*** tackling the Liner Shipping Problem

IV. Comment on the ***applicability*** and the ***efficiency*** of the methodology

V. Make some recommendations for future work taking into account various recent trends

Main reference

- [1] TSILINGIRIS, P. (2005), *A Multi-Stage Decision-Support Methodology for the Optimization-Based Liner-Network Design*, Diploma/M.Eng. Thesis, NTUA.

Related references

- [2] CHRISTIANSEN, M., FAGERHOLT, K., NYGREEN, B. and RONEN, D. (2006), Maritime Transportation, in *Handbooks in Operations Research and Management Science: Transportation*, C. Barnhart and G. Laporte, (eds), North Holland, Amsterdam.
- [3] FAGERHOLT, K. (2004), Designing optimal routes in a liner shipping problem, *Maritime Policy & Management* **31**, 259-268.
- [4] FEILLET, D., DEJAX, P., and GENDREAU, P. (2005), Traveling Salesman Problems with Profits, *Transportation Science* **39**, 188-205.
- [5] PERAKIS, A. and JARAMILLO, D. (1991), Fleet deployment optimization for liner shipping. Part 1: Background, problem formulation and solution approaches, *Maritime Policy and Management* **18**, 183-200.
- [6] POWELL, B. and PERAKIS, A. (1997), Fleet deployment optimization for liner shipping: an integer programming model. *Maritime Policy and Management* **24**, 183-192.

Maritime transport

- ~90% of volume of world trade
- ~70% of value
- EU:
  - ~90% of external
  - ~30% of internal trade

Maritime transport cont’d

- Key factor in world trade
- Key factor of development of many countries
- Source of income in many countries
- Safe, environmentally friendly mode
- Very much linked to other modes

Maritime transport cont'd

- Passenger vs. cargo
- Deepsea vs. shortsea
- Charter vs. liner

Charter vs. liner

- Charter

- Perfect competition
- Schedule not fixed
- Dry / liquid bulk
- Relatively low value
- Relatively slow speed
- Ship full - empty

Charter vs. liner cont'd

- Liner

- Cartelized (conference system)
- Mainly unitized
- Fixed schedule
- Relatively high value
- Relatively high speed
- Containers
- Ro-Ro
- Ship partly full
- Intermodal issues important

"Liner shipping problem" components include

- Ship routing-sequencing
- Schedule- frequency determination
- Allocation of ships to routes (fleet deployment)
- Transshipment
- Empty Container repositioning
- Terminal management
- Berth allocation
- Ship loading- unloading
- Etc.

LEVELS

- Strategic
- Tactical
- Operational

Status

- Liner shipping companies had (to the recent past) attracted the least attention of researchers in terms of application of quantitative methods.[5]
- Major ocean liner carriers have solved simplified versions of the problem in-house and keep it confidential for competitive advantage.
- Liner shipping at EURO is well represented! (vide, stream "Optimization in Liner Shipping" and germane papers in other waterborne transport-related streams.)

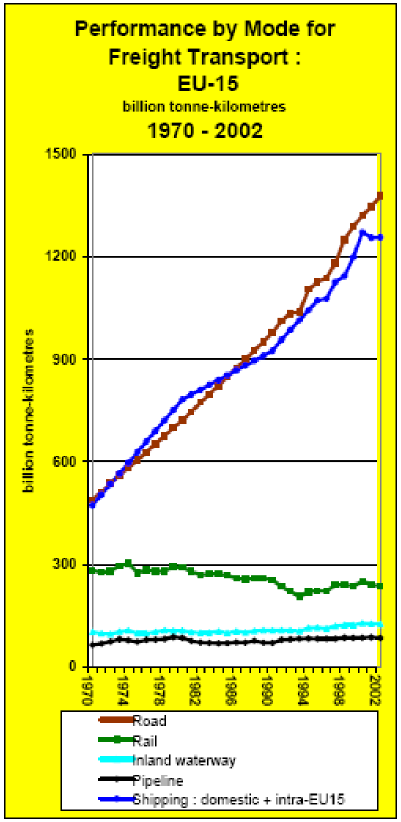
Why bother?

- Why is there an increasing need for sophisticated solutions for the Liner Shipping Problem?

Some reasons

1. Explosive growth of sector:
- Cargo carrying capacity of the world fleet increased 25% over the 1980-2003 period.[2]
- During the same period the capacity of containerships has increased **727%**.[2]

2. Increased competition within sector



Source : tables 3.2.7; 3.2.11 to 3.2.13, estimates
Notes: Road: haulage on national territory
Sea: Intra-EU traffic including domestic traffic. The estimates for maritime traffic are based on different statistical sources as from 2001 and remain subject to revision.

More..

- Mergers leading to more complex fleets and networks.
- Need for efficient intermodal transport networks
- Mega carriers, mega hubs
- In EU: SSS, Marco Polo, TENs, Motorways of the sea

Methodology Philosophy

- Our methodology aspires to solve problems, which belong to different planning levels: ***tactical*** (fleet deployment) and ***operational*** (ship sequencing)

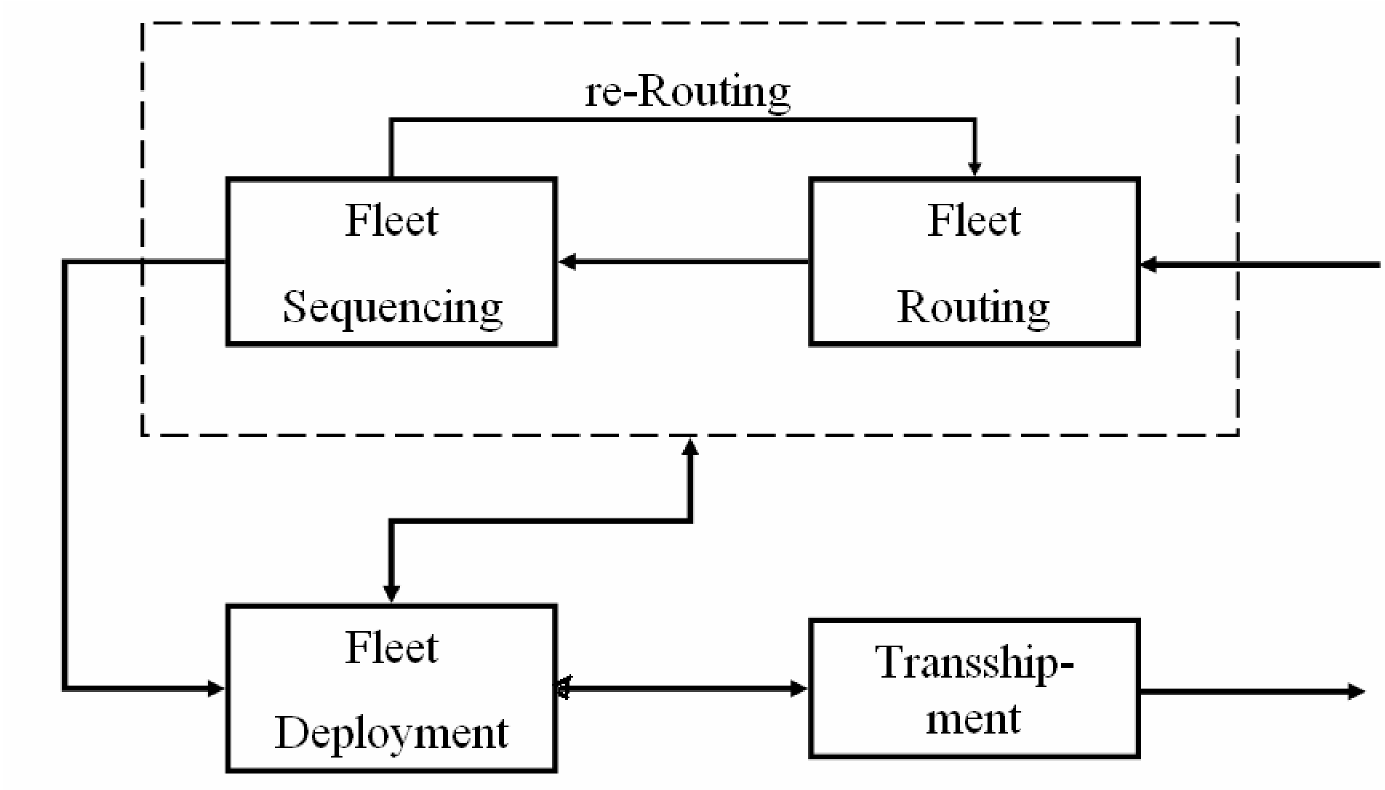
- Regarding routing, we do not take into account ***slight schedule adjustments*** for which the human intervention may be indispensable.

- A ***partial integration*** of the distinct subproblems into a manageable whole is attempted (resembling the "*Component Analysis Heuristics Strategy*").

Model assumptions

- A. Speed of Ships:
  - Most profitable speed should be a priori established in order to circumvent non-linearity ($P=a*S^b$, b~3)
  - *Frequency of service* constant.
- B. Resistance of ships:
  - Once speed is fixed, resistance (hence, fuel consumption) is assumed constant for different loading conditions.
- C. Cargo Movements and Demand Forecasting:
  - Total amount of cargo to be dispatched per annum between pairs of ports is independent of the service frequency
  - Demand is generated uniformly throughout the year.

Optimization flow diagram



Problem components-1

- *Ship Routing & Scheduling*
  - the establishment of a set of routes
  - the assignment of a sequence of ports to a vessel
  - assigning time windows to the various events on a ship's route

Problem components-2

- *Fleet Deployment*
  - refers to the assignment of vessels in the fleet to trade routes
  - is used when vessels are designated to perform multiple consecutive trips

Problem components-3

- *Transshipment*
  - *Hub & Spoke vis-à-vis Direct Calls*

(not examined in detail here)

Stages I-II:

Fleet

Routing & Sequencing

Routing and sequencing

- Methodology chooses among different models depending on:
  - whether the fleet can satisfy all of the demand or not; and
  - the preferences of the decision-maker.

Routing: Non-excessive demand

- Classical TSP
- A program is written in C++ based upon the classical dynamic programming formulation

$$C(\{k\},k)=d_{1k} \quad \text{for all } k=2,\ldots,n.$$
$$C(S,k)=\min_{m\in S-\{k\}}[C(S-\{k\},m)+d_{mk}]$$

Routing: excessive demand

- In instances where, for any logistical reason, the demand cannot be satisfied, problem reduces to one of:
  - **Profitable Tour Problem (PTP);**
  - **Orienteering Problem (OP);**
  - **Prize-Collecting Traveling Salesman Problem (PCTSP).**

- These are all variants of the TSP with profits where it is not necessary to visit all vertices. A profit is associated with each vertex. The overall goal is the simultaneous optimization of the collected revenue and the travel costs.

- Implemented in LINGO.

Routing: excessive demand

Similarities:

- All variants share a common set of constraints:

$$\sum_{v_j \in V \setminus \{v_i\}} x_{ij} = y_i \quad (v_i \in V),$$

$$\sum_{v_i \in V \setminus \{v_j\}} x_{ij} = y_j \quad (v_j \in V),$$

subtour elimination constraints,

$$y_1 = 1,$$

$$x_{ij} \in \{0, 1\} \quad ((v_i, v_j) \in A),$$

$$y_i \in \{0, 1\} \quad (v_i \in V).$$

Differences:

(depends on the way the two objectives are addressed)

PTP:

Max (- Cost + Revenue)

OP:

Max (Revenue) s.t. Cost <= c_{max}

PCTSP:

Min (Cost) s.t. Revenue >= r_{min}

Cargo Levels & Frequency of Service

- Computer program in C++
- Based upon the following formulation (Perakis and Jaramillo, 1991; Tsilingiris, 2005):

$$\text{For i} \neq \text{I}_\text{r} : \underline{\quad\quad} L_{ijr} = \sum_{f=1}^{i} \sum_{g=j}^{f} Q_{fgr}$$

$$\text{For i} \neq \text{I}_\text{r} : \underline{\quad\quad} L_{ijr} = \sum_{f=1}^{I_r} \sum_{g=j}^{f} Q_{fgr} + \sum_{f=1}^{i} \sum_{g=1}^{f} Q_{fgr} + \sum_{f=1}^{i} \sum_{g=j}^{I_r} Q_{fgr}$$

$$\text{L}_\text{r} = \max L_{ijr}$$

$$\text{RC}_\text{r} = \text{L}_\text{r}/(365/\text{F}_\text{r})$$

$$\text{RV}_\text{r} = \text{L}_\text{r}/\text{V}_\text{k}$$

$$\text{F}_\text{r} = 365 / RV_r$$

Additional tools for network efficiency evaluation, rerouting

- Ship/fleet utilization
- Average intermediate port stops for each box
- Average transit time per box
- Frequency vs. Capacity
- Use these as auxiliary hints to possibly modify routes & schedules

Now the utilization of the fleet can be examined via the following formulas:

$$AFU = \frac{1}{K} * \sum_{k=1}^{K} \overline{ASU}_{(k,r)} \qquad (28)$$

$$\overline{AFU} = \frac{1}{K} * \sum_{k=1}^{K} \overline{\overline{ASU}}_{(k,r)} \qquad (29)$$

$$\overline{\overline{AFU}} = \sum_{k=1}^{K} (\overline{\overline{AFU}}_{(k,r)} \times V_k) \times \frac{1}{\sum_{k=1}^{K} V_k} \qquad (30)$$

AFU is the simplified Average Fleet Utilization

$\overline{AFU}$ is the single-stage leveled Average Fleet Utilization

$\overline{\overline{AFU}}$ is the two-stage leveled Average Fleet Utilization.

Stage III:
Fleet Deployment

Fleet deployment

- Integer Programming formulation based on Powell and Perakis (1997) and implemented in LINGO.
- Decision Variables
  - The number of type *k* ships operating on route *r*
  - The number of lay-up days per year of a type *k* ship
  - Includes possibility of using own ships or chartered ships
- Objective Function
  - The minimization of the sum of operating and lay-up costs

FD constraints

- Ship Availability
- Service Frequency (the driving force in liner shipping)
- Route/Ship Incompatibility
- Lay-up Time

$$\text{Minimize} \sum_{k=1}^{K} \sum_{r=1}^{R} C_{kra} N_{kr} + \sum_{k=1}^{K} Y_k e_k \qquad (32)$$

where e_k is the daily lay-up cost for a type k ship

and the decision variables are:

N_{kr} number of type k ships operating on route r

Y_k number of lay-up days per year of a type k ship

Subject to: $\sum_{r=1}^{R} N_{kr} \leq N_k^{max}$ for each type k ship (33)

where: N_k^{max} maximum number of type k ships available

$$\sum_{k=1}^{K} t_{kra} N_{kr} \geq M_r \quad \text{for all } r \qquad (34)$$

$$t_{kra} = T_k / t_{kr} \qquad (35)$$

t_{kr} voyage time of type k ship on route r

t_{kra} yearly voyages of a type k ship on route r

T_k shipping season for a type k ship

M_r number of voyages required per year on route r

N_{kr} =0 for specified (k,r) pairs (36)

$$Y_k = 365\, N_k^{max} - T_k \sum_{r=1}^{R} N_{kr} \qquad (37)$$

FD output

- Allocation of owned ships to routes
- Number and type of ships to charter-in and their allocation to certain routes (if any)
- Whether to lay-up ships, of which type and for how long
- Minimum value of total annual operating costs

Transshipment

- Optional optimization module
- Hub-and-spoke vs. direct calls
- Hub-and-spoke systems can be critical in liner shipping.
- Important component of a company strategy
- Big issue in port competition

- A simulation model works very well for this purpose insofar as simulation models are similar to gaming models except that all human decision-makers are removed from the modeling process.
- Vide, Chistiansen et al. (2006) (strategic version); Tsilingiris (2005).

Computational

- Given that one of the subproblems of the LSP, the TSP, is NP-hard, the same must be true for the LSP itself.

- The classical TSP problem is among the most widely studied combinatorial problems.
- All TSPs with Profits variants can be classified as NP-hard problems inasmuch as:[4]
  - They trivially belong to NP;
  - A TSP instance can be stated as a TSP with Profits instance by defining arbitrarily large profits on vertices;
  - Specifically, PTP and PCTSP are particular cases of the problem; formal proofs have been devised for the OP based on simple reductions.

Computational cont’d

Ship routing-sequencing with non-excessive demand:

- The classic dynamic programming formulation for the TSP (Held & Karp, 1962) is effective for pragmatic LSP instances.
- From a theoretical perspective, we need memory equal to $O(n2^n)$ locations and CPU time equal to $O(n^2 2^n)$.
- This is not a problem since the number of nodes is not that high. (Even in long routes, *viz*., the F. East-N. Europe trade route the average number of port calls is 10.1; Source: Notteboom, 2006)

Ship routing-sequencing with non-excessive demand:

- For 18-node instances the computational time was:
  - 28 seconds for the PTP;
  - 27 seconds for the OP; and
  - 21 seconds for the PCTSP.

- Sensitivity analysis unveiled that the PTP formulation may lead to route outputs with very low cardinality if we increase significantly all the travel costs (indicating the continuous rise in fuel oil) without any similar-scale rise in the profits.

Computational cont'd

- Input (data drawn from Jaramillo and Perakis, 1991)
    - 14 privately owned ships of 6 types
    - 5 ships for charter-in are examined
    - 7 routes
- Output
    - All the privately owned-ships as well as the long-term charter are in use for the entire shipping season
    - Savings of 1.4% on total operational costs
    - Substantial improvement of the frequency of service in certain routes

Fleet deployment:

- Fleet Deployment application: 59 integer variables
- Elapsed run time <1 second.

- The procedure was implemented on an Intel Pentium M processor 1.8 GHz with 512MB of RAM using a branch-and-bound algorithm.

Observations & suggestions for consideration

- The liner-shipping problem (LSP) is prohibitively complex computationally to be practically formulated as a single-stage process.
- To tackle it, we have applied a generic multi-stage optimization-based methodology, which “unifies” previous (ocean-related or not) contributions.

Suggestions for consideration:

- Link with other related problems.
- Develop a (computationally tractable) integrated model .

Thank you very much!!

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