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An analytical framework with a network-based optimization model for rescheduling a delay containership

Hua-An Lu

Department of Shipping and Transportation Management,
National Taiwan Ocean University, Keelung, Taiwan
halu@ntou.edu.tw

Abstract. Schedule reliability is one of the advantages that container liner shipping can play an important role in the global logistics system. However, some environment conditions and special situations will occasionally cause ship delays. This research introduces some viable strategies that can be applied to get a delay containership back on track in actual practice. An analytical framework with a network-based optimization model is proposed herein to assess the possible alternatives for counteracting delays at various target ports. Analysis results for a short sea service present the relationships between extra costs and countermeasures.

Keywords: network-based optimization model; rescheduling; short sea service

Introduction

Container shipping lines play one of the most important roles in the development of industrial globalization because it provides stable service with fixed frequencies and punctual deliveries. However, some factors may affect ships' punctualities in the transit process. Once a serious delay has occurred, the shipping company must try to maintain the original schedule as soon and as smoothly as possible.

Allen *et al*. (1985) discussed the importance of transit time to shippers, receivers and carriers. Notteboom (2006) introduced possible reasons causing schedule delay and possible countermeasures. Vernimmen *et al*. (2007) conducted a large-scale survey for worldwide liner services and found that over 40% of vessels had experienced delays. Notteboom and Rodrigue (2008) reported that the average percentage of on-time vessel arrivals was 53% for main world trade routes during April to September 2006. To the best of literature review in this paper, research devoted to ship rescheduling is relatively limited. Most discussions focus on ship routing, scheduling and network construction for container liner services. Ronen (1983, 1993), Christiansen *et al*. (2004) and Meng *et al*. (2014) made comprehensive reviews in every decade.

The chance of delay seems quite high from the literature. The aim of this study is to explore practical strategies in handling various levels of delay and to propose an analytical framework for handling a delay containership. An analysis for a real-world short sea service case is reported.

Viable approaches in practice

When delays occur, a shipping company needs to shorten the service time as much as possible. Various strategies can be applied, according to the seriousness of delay: (1) Adjusting the schedule in terms of buffer time; (2) Increasing the speed of the ship at sea; (3) Decreasing the number of loading containers to shorten the period of stay at ports; and (4) Skipping visits to one or more ports. Timetables of liner service always include some buffer hours for ensuring sufficient flexibility to run on schedule. When a little delay has taken place, the embedded buffer time may be sufficient to absorb it. When the delay surpasses the buffer time, increasing ship speed during the long distance segments is another alternative if the meteorological conditions at sea permit. However, fuel costs increase at the ship speed higher than the design speed.

For shortening ship stay at ports, the prevailing treatment is to limit the number of loading containers. Normally, empty containers are the first priority to deny loading. Other available methods include shifting some containers to the next voyage, transferring containers to other lines at their points of origin, or unloading containers to another suitable port for further transfer. Finally, skipping calls is the last unavoidable but positive method. However, on-board consignments of skipped ports will entail a complicated problem in transference. If consignments are arranged to load onto the next voyage, this not only reduces the available capacity of temporary holding ports but also extends the transit time of treated containers. This approach may induce huge extra costs in regard to cargo handling. The difficulties of real-world problems are to determine an effective strategy that might combine various approaches mentioned above for a serious case.

Analytical framework and model

The original rotation should still serve as the main structure of adjustment in designing a viable countermeasure. While a delay is noticed, appropriate ports are selected to start handling alternatives and to recover punctuality after arriving at a target port. Therefore, a feasible plan must have a spatial scope from an original port to a candidate port. When many possible candidate ports exist, the alternatives recorded can be examined one by one during this procedure. The decision maker can finally choose the best or most viable one. The flowchart of this analytical framework is shown in Figure 1. Then, what remains to be done is to determine how to obtain the optimal catch-up proposal between two specific ports.

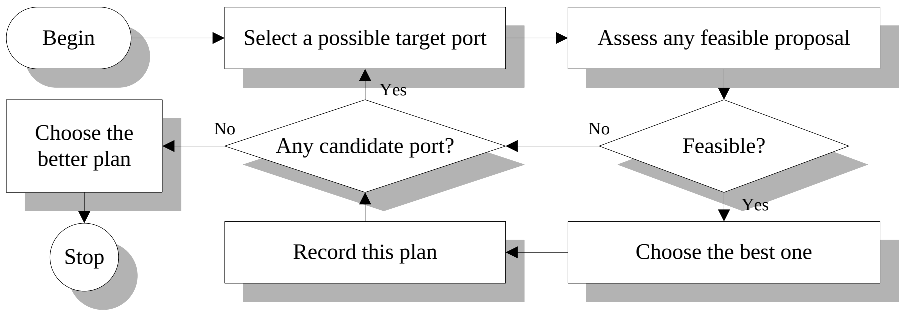

Fig. 1. Flowchart of analysis framework

A network shown in Figure 2 is proposed to describe the planning scope. Its *allowable interval* for schedule recuperation can be calculated by the difference of the scheduled arrival time of the final port, which is defined as *sink node e*, to the estimated departure time from the first one, which is defined as *source node b*. Each port of call between them is represented in terms of two nodes that respectively signify port arrival and departure in the network. Two kinds of nodes are defined as set $\boldsymbol{I}$ for *arrival nodes* and set $\boldsymbol{O}$ for *departure nodes*, respectively. The sequence of nodes can be checked from their corresponding times in the original schedule. All possibilities of sailing are represented by the arcs connecting departure nodes to arrival ones. Theses arcs are defined as set $\boldsymbol{S}$ for s*ailing arcs*. The arcs directed from the arrival node to the departure node represent staying in the same port. Theses arcs are defined as set $\boldsymbol{P}$ for *staying arcs*. Let $\boldsymbol{N}$ be the set of all nodes and $\boldsymbol{A} = \boldsymbol{P} \cup \boldsymbol{S}$. This network is mainly applied to define the movement of the ship. Let the supply/demand of source node be +1, the sink node -1, and other nodes 0 in defining ship flow. In maintaining flow conservation, the flowing result can represent the journey of the delayed ship. The total of time expenses on the arcs involved in the journey must be less than or equal to the allowable interval.

Container movements are counted with TEUs (twenty-foot equivalent units) without considering types. Therefore, all the parameter data related to containers are counted in TEU on average. The concrete loading plan for various container types is assumed can be tailored in detail after the final proposal obtained. Besides sailing and staying arcs, more arcs are appended, as shown in Figure 3, to represent the movement of containers on board to maintain the flow conservation on each node. *Transferring arcs*, which direct from the source node or departure node to the arrival node or sink node, are defined as set $\boldsymbol{G}$ for those transfer containers from the origin to the destination. *Unloading and transferring arc*s, which direct from the arrival node to another arrival node or sink node, are defined as set $\boldsymbol{T}$ for possible ways to unload containers on board and for further transference to the destination. *Postponing delivery arc*s, which direct from the source node or departure node to the arrival node of the successive journey, or the sink node for satisfying flow conservation, are defined as set $\boldsymbol{H}$ for shifting containers at the origin to the next voyage. They are channels with different unit costs to represent the treatment of containers that cannot be normally shipped on board to the destination.

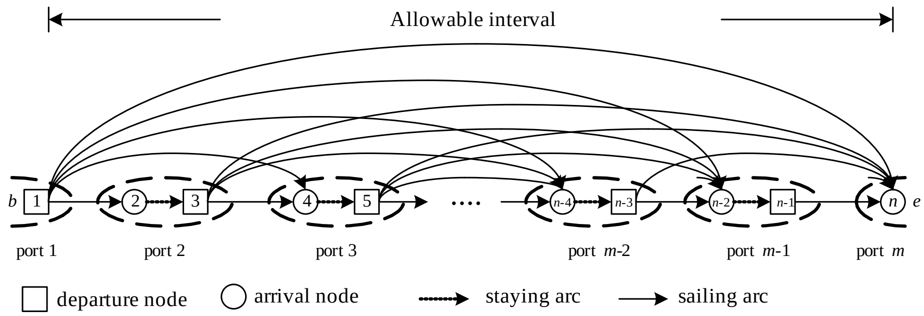

Fig. 2. Design network for ship flow tier

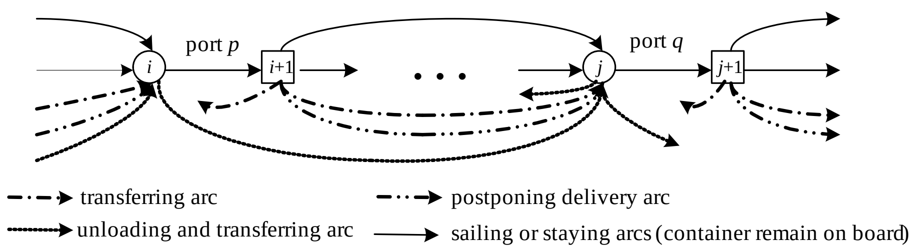

Fig. 3. A part of the network for the container flow tier

Decision variables:

x_{ij} = 1 if arc (i, j) is involved in the passing journal, $(i, j) \in \boldsymbol{A}$; 0 otherwise.
y_{ij} = number of container flows on arc (i, j), $(i, j) \in \boldsymbol{A}$.
r_{ij} = number of unloaded containers at the port corresponded arc (i, j), $(i, j) \in \boldsymbol{P}$.
z_{ij} = number of containers on postponing delivery arc (i, j), $(i, j) \in \boldsymbol{H}$.
f_{ij} = number of containers on transferring arc (i, j), $(i, j) \in \boldsymbol{G}$.
w_{ij} = number of containers on unloading and transferring arc (i, j), $(i, j) \in \boldsymbol{T}$.
t_{ij} = time consuming for arc (i, j) passed by ship, $(i, j) \in \boldsymbol{A}$.
β = difference of the allowable interval with the required period of planning journey.

Parameters:

c_{ij} = sailing costs per hour for the segment $(i, j) \in \boldsymbol{S}$.
d_{ij} = sailing distance for the segment $(i, j) \in \boldsymbol{S}$.
l_{ij} = economic ship speed for the segment $(i, j) \in \boldsymbol{S}$.
q_{ij} = carrying containers from the corresponding port of node i to the corresponding port of node j.
u_{ij} = highest speed applied for the segment $(i, j) \in \boldsymbol{S}$.
L = allowable interval for catching schedule up.
ψ_{ij} = staying time at the corresponding port of arc (i, j) in normal status, $(i, j) \in \boldsymbol{P}$.
α_{ij} = average cost per container used in postponing delivery arc (i, j), $(i, j) \in \boldsymbol{H}$.
β_L = lower bound of the difference of the allowable interval with the planning period.

β_U = upper bound of the difference of the allowable interval with the planning period.
δ_{ij} = average cost per container used in unloading and transferring arc (i, j), $(i, j) \in \boldsymbol{T}$.
ε_{ij} = port charge per call to the corresponding port of arc (i, j), $(i, j) \in \boldsymbol{P}$.
ξ_{ij} = average cost per container used in transferring arc (i, j), $(i, j) \in \boldsymbol{G}$.
η_{ij} = handling fee per container in the corresponding port of arc (i, j), $(i, j) \in \boldsymbol{P}$.
φ_{ij} = handling speed per container in the corresponding port of arc (i, j), $(i, j) \in \boldsymbol{P}$.
B = total of available buffer time in original schedule within planning period.
M = available loading capacity of ship.

Model:

$$Min. \sum_{(i,j)\in \boldsymbol{P}} \varepsilon_{ij} x_{ij} + \sum_{(i,j)\in \boldsymbol{P}} \eta_{ij} r_{ij} + \sum_{(i,j)\in \boldsymbol{H}} \alpha_{ij} z_{ij} + \sum_{(i,j)\in \boldsymbol{G}} \xi_{ij} f_{ij} + \sum_{(i,j)\in \boldsymbol{T}} \delta_{ij} w_{ij} + \sum_{(i,j)\in \boldsymbol{S}} c_{ij} t_{ij} \tag{1}$$

s.t.

$$\sum_{(i,j)\in \boldsymbol{A}} x_{ij} - \sum_{(j,i)\in \boldsymbol{A}} x_{ji} = \begin{cases} 1, & i = b \\ 0, & otherwise \\ -1, & i = e \end{cases} \qquad \forall i \in \boldsymbol{N} \tag{2}$$

$$\sum_{(i,j)\in \boldsymbol{S}} y_{ij} - \sum_{(j,i)\in \boldsymbol{P}} y_{ji} + \sum_{(i,k)\in \boldsymbol{H}} z_{ik} + \sum_{(i,k)\in \boldsymbol{G}} f_{ik} = \sum_{k} q_{ik} \qquad \forall i \in \boldsymbol{O} \tag{3}$$

$$\sum_{(i,j)\in \boldsymbol{P}} y_{ij} - \sum_{(j,i)\in \boldsymbol{S}} y_{ji} - \sum_{(k,i)\in \boldsymbol{H}} z_{ki} - \sum_{(k,i)\in \boldsymbol{G}} f_{ki} + \sum_{(i,k)\in \boldsymbol{T}} w_{ik} - \sum_{(k,i)\in \boldsymbol{T}} w_{ki} = -\sum_{k} q_{ki} \quad \forall i \in \boldsymbol{I} \tag{4}$$

$$(\sum_{k} y_{ki} - y_{ij}) + (\sum_{k} y_{jk} - y_{ij}) = r_{ij} \qquad \forall (i, j) \in \boldsymbol{P} \tag{5}$$

$$\sum_{(i,k)\in \boldsymbol{T}} w_{ik} \le M x_{ij} \qquad \forall (i, j) \in \boldsymbol{P} \tag{6}$$

$$\sum_{(k,i)\in \boldsymbol{T}} w_{ki} \le M(1 - x_{ij}) \qquad \forall (i, j) \in \boldsymbol{P} \tag{7}$$

$$z_{ij} + f_{ij} \le q_{ij} \qquad \forall (i, j) \in \boldsymbol{H} \cup \boldsymbol{G} \tag{8}$$

$$y_{ij} \le M x_{ij} \qquad \forall (i, j) \in \boldsymbol{A} \tag{9}$$

$$t_{ij} \le \frac{d_{ij}}{l_{ij}} x_{ij} \qquad \forall (i, j) \in \boldsymbol{S} \tag{10}$$

$$t_{ij} \ge \frac{d_{ij}}{u_{ij}} x_{ij} \qquad \forall (i, j) \in \boldsymbol{S} \tag{11}$$

$$t_{ij} \ge \psi_{ij} x_{ij} - \left(\frac{\sum_{k} z_{jk} + \sum_{k} z_{ki} + \sum_{k} f_{jk} + \sum_{k} f_{ki} - \sum_{k} w_{ik}}{\varphi_{ij}}\right) \qquad \forall (i, j) \in \boldsymbol{P} \tag{12}$$

$$\sum_{(i,j)\in \boldsymbol{A}} t_{ij} + \beta = L + B \tag{13}$$

$$\beta_L \le \beta \le \beta_U \tag{14}$$

$$x_{ij} \in \{0,\ 1\};\quad f_{ij}, r_{ij}, w_{ij}, y_{ij}, z_{ij} \ge 0 \ \ and \ \ integer;\ \ t_{ij} \ge 0 \tag{15}$$

This model minimizes the total of all concerned cost items as in Equation (1), including total port charges, container handling costs, postponing delivery costs, transferred costs for different ways, and sailing costs. In constraint part, Equation (2) maintains the flow conservation of the ship's journey. Equations (3) and (4) signify the flow conservation of container movement. Equation (5) calculates the exact number of containers discharged and loaded for each port. Equations (6) and (7) construct the relationship between containers unloaded and transferred in ship calls, i.e., the ship must visit a certain port for discharging containers to transfer at it. Equation (8) limits the total amount of containers for postponing delivery and transference at origin less than or equal to the estimated demand from a certain port. Equation (9) enforces the capacity limitation for each sailing segment. Equations (10) and (11) ensure the sailing time falling within the range of economic and highest speed used if the segment is passed, 0 otherwise. Equation (12) calculates the staying time of call for each port, but is redundant for skipping over. Equations (13) and (14) offer a little allowance for the total planning time. Equation (15) represents variable attributes. This model is a mixed integer programming problem which solving complexity depends on the numbers of arcs and constraints.

Example analysis

The JTC loop of Yang Ming Marine Transport Corp. was selected for the test. This line has 15 visits among Japan, Taiwan, Hong Kong, and Thailand within 28 days, for weekly calling by 4 full container ships of 1,200 TEU, with economic sailing speed of 15 knots. Its visiting sequence follows the rotation in Table 1. South bound, whose ports are italicised in Table 1, is our test example. The scheduled period of the whole south voyage is 371 hours, including 34 buffer hours. This analysis tested various delay levels ranged 5% in each case from 5% to 30%, and the delay occurs from TYO. Four possible on-time target ports, i.e. KHH, HKG, BKK and LCB, are the focus. Table 2 shows the allowable interval after delay happen for each instance. The aim of these tests is to present what countermeasures can be selected, rather than to mean the delay level can be controlled by the decision makers. The optimization package CPLEX 7.0 is used to solve all of the following instances.

Table 1. Timetable of the tested route

JTC Rotation																
	TYO	*YOK*	*NGO*	*OSA*	*UKB*	*OIT*	*KEL(S)*	*KHH(S)*	*HKG(S)*	*BKK*	*LCB*	*KHH(N)*	*HKG(N)*	*TXG*	*KEL(N)*	*TYO*
ARR.	THU 16:00	FRI 10:00	SAT 09:30	SUN 08:00	SUN 16:00	TUE 09:00	THU 13:00	FRI 16:00	SUN 08:00	FRI 08:00	SAT 19:00	THU 09:00	FRI 18:00	SUN 18:30	MON 09:00	THU 16:00
DEP.	FRI 08:00	FRI 16:00	SAT 16:00	SUN 14:00	MON 16:00	TUE 13:00	THU 23:00	SAT 10:00	MON 08:00	SAT 09:00	SUN 07:00	THU 20:00	SAT 19:00	MON 00:00	MON 17:00	FRI 08:00

Source: the web site of the studied carrier (http://www.yml.com.tw/).

Table 2. Test cases for various delay levels

Cases	*Delay levels of S.B. journey*	*Delay departed at TYO (hrs.)*	*Allowable interval before on-time target ports (hrs.)*			
			KHH	*HKG*	*BKK*	*LCB*
1	5%	18	163	198	318	353
2	10%	37	144	179	299	334
3	15%	56	125	160	280	315
4	20%	74	107	142	262	297
5	25%	93	88	123	243	278
6	30%	111	70	105	225	260

The test data we adopt are similar to reality except for the cost parameters. The cost function of sailing speed is evaluated from the fleet data with the regression model. It is applied to the long distance segments with the allowable ranges of speed between 15 to 18 knots. The speeds of short distance segments are fixed at the lower speed. 6 cases which have a total of 24 optimization problems are solved.

The buffer time before each on-time target port is able to absorb delay completely for level 5%, i.e., 18 hours. For delay level 10%, the solutions not only use the existent buffer hours, but also require the ship speeding up during some segments. In the solutions for a 15% delay, i.e., 56 hours, some containers need to be delivered late if the carrier would like to recovery punctuality before KHH or HKG. However, the ship can still speed up at sea to get back on schedule before BKK and LCB. When the delay level reaches 20%, both speeding up at sea and absorbing by buffer time cannot totally cover the propagation of delay before LCB. Some containers are hold to deliver or transfer to their destinations. The ship has to skip calling if an on-time target port is set at KHH or HKG. Delay level 25%, which approximates 4 days, is very serious to give up calling at more than one port. The expense is even double when a carrier considers recovering its schedule before KHH. Delay level 30% has no possible treatment to handle such serious delay before KHH. Strategies for other on-time target ports are the same as level 25%, but with greater cost. Table 3 reveals the increased percentages on total operating costs and their components for 15% to 30% delay levels.

Table 3. Cost increment analysis for various delay level

Delay level	*Costs concerned*	*On-time target ports*			
		KHH	*HKG*	*BKK*	*LCB*
10%	Total operating costs	0.014%	0.010%	0.006%	0.001%
	Sailing costs	0.101%	0.076%	0.031%	0.006%
	Port & freight handling costs	–	–	–	–

Delay level	*Costs concerned*	*On-time target ports*			
		KHH	*HKG*	*BKK*	*LCB*
15%	Total operating costs	5.77%	2.35%	0.06%	0.03%
	Sailing costs	0.26%	0.25%	0.30%	0.16%
	Port & freight handling costs	6.61%	2.67%	–	–
20%	Total operating costs	22.49%	11.27%	1.97%	0.45%
	Sailing costs	-5.04%	-5.78%	0.52%	0.51%
	Port & freight handling costs	27.25%	13.90%	2.30%	0.44%
25%	Total operating costs	99.18%	32.96%	7.20%	2.96%
	Sailing costs	-15.29%	-11.77%	-3.00%	-2.97%
	Port & freight handling costs	117.61%	39.87%	9.53%	4.16%
30%	Total operating costs	×	57.70%	17.13%	6.92%
	Sailing costs	×	-16.04%	-3.01%	0.42%
	Port & freight handling costs	×	69.07%	21.74%	8.24%

–: No increment; ×: Instance without feasible solution

Conclusions and suggestions

This research has constructed an analytical framework which can assess the advantages of a variety of available countermeasures for a delay containership. It employs a network-based concept to formulate a promising model to derive optimal decisions within an allowable time interval. The assessment results can provide carriers with the means to select a suitable countermeasure and to understand the resultant expenses. When a ship encounters delay, the influence may impact other ships serving in the same loop, as well as a large amount of cargo transfers. Rescheduling multiple ships is another valuable topic for future research.

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