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Optimum MULTIPLE-CALL ROUTING in SHIPPING LOGISTICS ; comprehensive applications of Linear Programming

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s u m m a r y

A previous report (83/149) addressed the issue of establishing an optimum "least cost" fleet-sailing list with three classes (sizes) of vessels along four alternative routes, and various additional items such as the lay-up costs and the organization of time-charters and backhauls. The present report expands the organization of non-stop routing to optional port calls "en route". The results of the exercise show that moderately small size computer equipment is able to catch a detail such as requested in the operation of a heterogeneous fleet with a variety of alternative market and routing opportunities.

c o n t e n t s

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1. Introduction

A previous discussion addressed an elementary LP assignment problem, in which a company serves four different routes by a given fleet-capacity. The dominant design restriction was that the "outbound" section had to be identified as the leg of a route on which the cargo demand was greater than or equal to the available backload demand. This imposed no specific problems of spatial data organization, since all connections were separately, though simultaneously, operated . The introduction of potential additional port calls "on the route" requests a preliminar elaboration of the alternative patterns by which the spatial demand pattern may appear(1).

Multiple Call design is indeed fairly different from simply adding an additional roundtrip-with-an-intermedeate-stop to an existing pattern of non-stop schedules. These port-calls which come up for consideration need to be integrated within the existing dispatching. This integration can take various forms all of which correspond to alternative real-life situations.

The issue is analyzed by introducing a fifth route duplicating the fourth route except for the intermedeate stop. The two connections thus serve the same origin and destination, but the fifth route adds two new LINKS around the new port half-a-way the fourth route. In the initial problem design, one thus obtains between the origin "A" and the destination "B" (2):

- a non-stop connection, being the fourth route,
- and two links connecting the additional port "C" with "A" and "B".

2. Simple link-route juxtaposition

The just suggested simplified situation is pictured in Table 1, in which the operating conditions on the "A-C" and "C-B" links are simply added to those governing the fourth non-stop route (A-B). Thus for each successive link the condition is imposed that the number of full backloads should not exceed the outbound departures. Since backhauls are accounted at marginal costs, this procedure warrants a full-cost recovery for any roundtrip. For the remaining the "link-operations" do not interfere with the current non-stop operations on route te 4. Thus, none of the vessels operating on route 4 is presupposed to call at the intermedeate port "C", unless in a mutual exchange (cfr. infra, end of this section).

On the fourth route *(A-B & back)*, we recall the conditions that all ships have to return either fully loaded or empty, with:

$$
\begin{aligned}
X_4 - X_{20} &\geqq 0 \quad && \textit{for class 1 (1500 TEU)} \\
X_8 - X_{24} &\geqq 0 && \textit{class 2 (850 TEU)} \\
X_{12} - X_{28} &\geqq 0 && \textit{class 3 (500 TEU)}
\end{aligned}
\qquad (1)
$$

Similarly for the two additional link-operations, we add:

$$
\begin{aligned}
X_{36} - X_{39} &\geqq 0 \qquad & X_{42} - X_{45} &\geqq 0 \qquad && \textit{class 1 (1500 TEU)} \\
X_{37} - X_{40} &\geqq 0 & X_{43} - X_{46} &\geqq 0 && \textit{class 2 (850 TEU)} \\
X_{38} - X_{41} &\geqq 0 & X_{44} - X_{47} &\geqq 0 && \textit{class 3 (500 TEU)}
\end{aligned}
\qquad (2)
$$

route 4/a (A-C-A) *route 4/b (C-B-C)*

Furthermore , those two links might be integrated in that:

a/ the ships operating on the dominant link (4/a) also operate on the less busy link (4/b), with the possibility

b/ that some of them may only perform single shuttles on the dominant link and skip operations between C and B:

$$
\begin{aligned}
X_{36} - X_{42} &\geqq 0 \\
X_{37} - X_{43} &\geqq 0 \\
X_{38} - X_{44} &\geqq 0
\end{aligned}
\qquad (3)
$$

Table 1 : Trip frequency variables

P O R T of O R I G I N "A"					
20,000		5,000	4,000	demand	LINK 4/a
X_4	X_{20}	X_{36}	X_{39}	trips class 1.	LINK 4/a
X_8	X_{24}	X_{37}	X_{40}	2.	LINK 4/a
X_{12}	X_{28}	X_{38}	X_{41}	3.	LINK 4/a
	20,000 NON-STOP ROUTE	PORT CALL "C"			
		3,000	2,000	demand	LINK 4/b
		X_{42}	X_{45}	trips class 1.	LINK 4/b
		X_{43}	X_{46}	2.	LINK 4/b
		X_{44}	X_{47}	3.	LINK 4/b
P O R T of D E S T I N A T I O N "B"					
outbound	backload	outbound	backload		
35.-	25.-	15.-	15.-	penalty-values	
X_{16}	X_{32}	X_{48};X_{49}	X_{50};X_{51}	penalties	

Thus for both the non-stop route service as for the link shuttles the outbound traffic dominates the actual and potential backloads. It should be noted that this assumption had previously imposed with only route services being at stake. There it did not add any restriction since routes could be organized from any origin. In the present case the relative dominance of the four link-legs in that particular order does impose strong restrictions which are consequently relaxed in the next section. Thus, condition (3) is only optional for a particular operational structure (ie all ships have to return to their home-port "A" at least once a month) but is not imposed as a technical programming condition.

The previous market and operations conditions are further amended for the new situation:

a/ both links have a demand of respectively:
L4/a: 5,000 TEU with 4,000 potential backload,
L4/b: 3,000 TEU with 2,000 potential backload.

b/ penalty-values which are 35.- and 25.- on the non-stop route service are set at 15.- for each TEU on any of the links or 30.- for two successive links.

c/ the operating costs on the non-stop service by ship's class : 1 were 15,000 with 500.- for a full backload,

class :	1	15,000	500.-
	2	10,000	400.-
	3	9,000	350.-

to which we add for both links and by class of ships:

L4/a:	1	10,000	500.-
	2	5,500	400.-
	3	5,000	350.-
L4/b:	1	6,000	500.-
	2	5,000	400.-
	3	4,500	350.-

such that for any type of ship the operating costs are obviously higher because of the additional port-call costs. That cost increment both applies to ship's costs and loading and unloading expenses.

Finally, the fleet capacity requirements have to be corrected for the time lost in the additional port call. For that constant we take 0.6 months (i.e. 1.8 day) for large 1500 TEU units, and 0.3 months (i.e. 0.9 day) for smaller units of 850 and 500 TEU. The potentially higher call time may represent the situation that for larger units, fewer port quays are available at the right moment.

The fleet-capacity constraints then become:

(class)

$$-\ldots + 1.0\ X_4 + X_{33} + 0.6\ X_{36} + 0.6\ X_{42} = 5 \quad ;\ 1.$$

$$-\ldots + 0.5\ X_8 + X_{34} + 0.3\ X_{37} + 0.3\ X_{43} = 8 \quad ;\ 2. \qquad (4)$$

$$-\ldots + 0.5\ X_{12} + X_{35} + 0.3\ X_{38} + 0.3\ X_{44} = 10 \quad ;\ 3.$$

other routes	roundtrip times 4th route A-B	ships laying -up	roundtrips-times for link 4a & 4b in ship-months.

The optimum sailing list is given in Table 2. The link-operations are only executed by vessels of class 2 at 2.2 trips per month. Thus, class 2. performs 15.5 monthly roundtrips of which 13.3 non-stop.

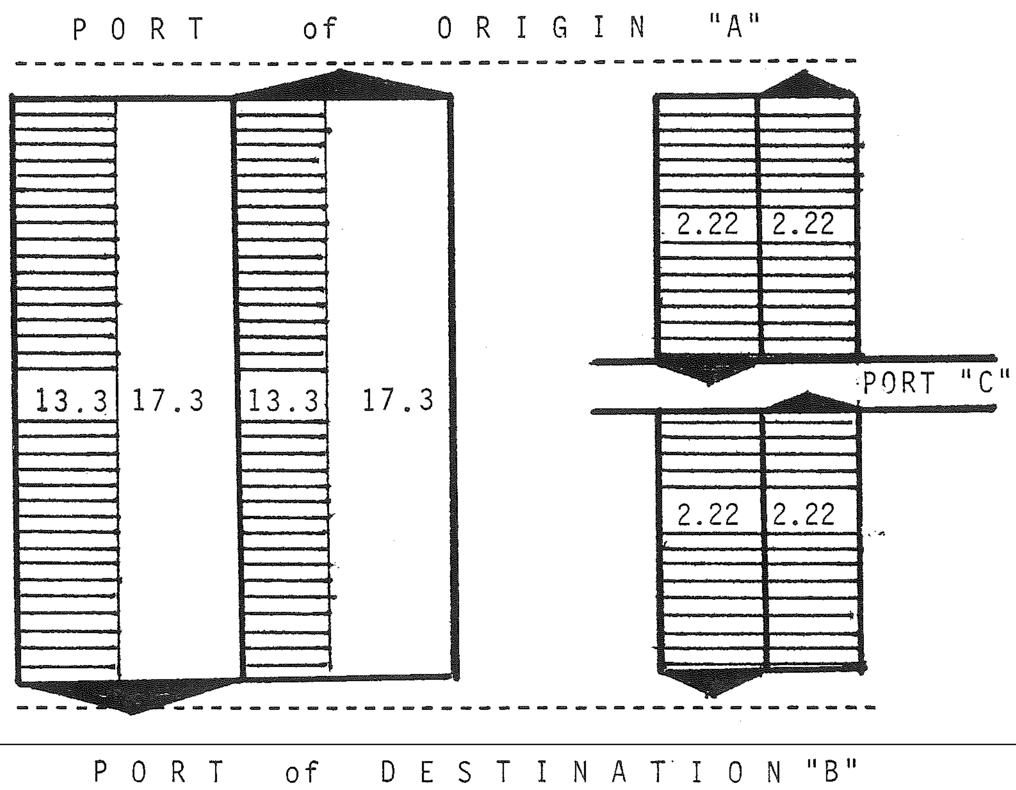
The local link services carry 1890 TEU (850 x 2.223) each link-leg, neglecting the remaining demand. Thus, penalties are activated to the extent the market demand (ranging from 2,000 to 5,000) exceeds the 1890 TEU operating standard. Those link-services are operated with capacity removed from the first and second route, which are now only served to the extent that the backloads match the outbound tonnage.

The present result is satisfying in that on the fourth route the same class 2. vessels *(850 TEU)* operates as those already sailing on the non-stop journeys. Such outcome relaxed the assumptions of not using integer trip-frequencies. Indeed, some non-stop services may change to the link service on the backhaul and vice versa. By so playing on the averages, the dispatching procedures may be tuned to improved regularity without integer trips being imposed by the problem format itself. However, this form of integration has been a "happy event" but can be introduced more systematically in the problem definition.

Table 2. : Sailing list with separate link & route service

route	1.	2.	3.	4. non-stop	4. link a	4. link b	
demand	10,000	20,000	5,000	20,000	5,000	3,000	outbound
trips: 1.	3.33	4.45	3.33	-	-	-	outbound
trips: 2.	-	-	-	13.33	2.22	2.22	outbound
trips: 3.	-	6.67	-	17.3	-	-	outbound
penalties	5,000	10,000	0	0	3,110	1,110	outbound
penalties	0	0	0	0	2,110	110	backhaul
trips: 1.	3.33	4.45	3.33	-	-	-	backhaul
trips: 2.	-	-	-	13.33	2.22	2.22	backhaul
trips: 3.	-	6.67	-	17.3	-	-	backhaul
demand	5,000	10,000	5,000	20,000	4,000	2,000	backhaul

Table 2/b : Sailing graph of the fourth route by class



3. Integrated link-operation within a route-service

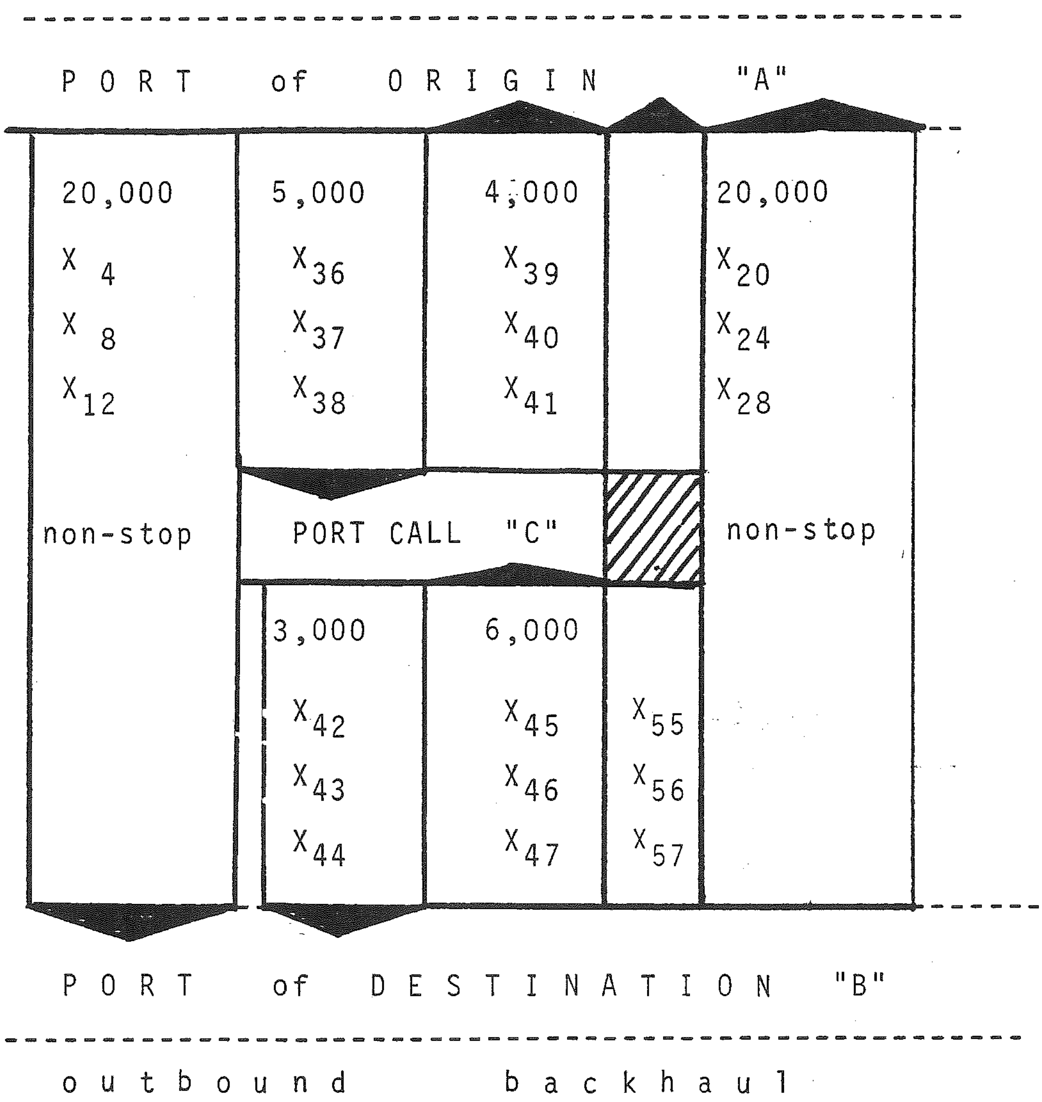
In the previous section it was assumed that the short-distance link shuttles (links AC & CB) follow the same outbound surplus-structure as occurs in the non-stop route service between "A" and "B". However, it may prevail that on some of the links the demand pattern exhibits an opposite outbound dominance to that on the non-stop legs. In such situations the previous program format will generate some empty backhauls both on the route and link services but in opposite direction, an outcome which is not very efficient. The over-all efficiency may be improved by balancing the load factors on link and route-services through the integration of the sailing list. A snapshot of such situation is given in Table 3 in which the backloads on link 4/b now face a potential demand of 6,000 TEU instead of the former 2,000.

Those new assumptions are introduced in the program format by relaxing the link-operations constraints (1 and 2) into a combined statement for:

$$
\begin{array}{llll}
\underline{\text{link } 4/a}: & (X_4 - X_{20}) \geqq (X_{39} - X_{36}) & \text{; ship's class} & 1 \\
& (X_8 - X_{24}) \geqq (X_{40} - X_{37}) & & 2 \\
& (X_{12} - X_{28}) \geqq (X_{41} - X_{38}) & & 3 \\
\underline{\text{link } 4/b}: & (X_4 - X_{20}) \geqq (X_{45} - X_{42}) & & 1 \\
& (X_8 - X_{24}) \geqq (X_{46} - X_{43}) & & 2 \\
& (X_{12} - X_{28}) \geqq (X_{47} - X_{44}) & & 3
\end{array}
\qquad (7)
$$

The new set of constraints state that on the links backhauls may indeed exceed outbound trips but only to the extent there is empty backload space available on the non-stop service. The last point is essential since backloads are imputed a marginal cost tag and full cost-recovery is to be warranted.

Table 3 : Integrated trip-frequency variables



However, those inequalities produce six slack variables which represent the fraction of the outbound surplus-capacity on the non-stop route which returns empty, i.e. :

- without a backload on the non-stop service, and
- which is not shifted to the backhaul link-services.

In fact only three of those slacks are relevant since the intermedeate stop at "C" applies to both links. That correction can be introduced by changing the inequalities into equalities and replacing the six slack variables by three "artificial variables" *(i.e. which do not enter in the objective function)*. Thus, for link:

4/a	$X_4 - X_{20} - X_{52} = X_{39} - X_{36}$	for ship's class	1,	
	$X_8 - X_{24} - X_{53} = X_{40} - X_{37}$		2,	
	$X_{12} - X_{28} - X_{54} = X_{41} - X_{38}$		3,	
				(7')
4/b	$X_4 - X_{20} - X_{52} = X_{45} - X_{42}$		1,	
	$X_8 - X_{24} - X_{53} = X_{46} - X_{43}$		2,	
	$X_{12} - X_{28} - X_{54} = X_{47} - X_{44}$		3.	

The fact that X_{52}, X_{53} and X_{54} are repeated in both link-constraints means that vessels can only be shifted from the non-stop services to the link-operations when they are offered a full backload on both links *(the remaining to be handled by the short distance link-shuttles)*. Partly this additional requirement is redundant when the cost figures are relevantly introduced. But the requirement allows us to define the number of non-stop vessels which call at port "C" on their backhaul, by:

$X_4 - X_{20} - X_{52} = X_{55}$	ship's class	1.	
$X_8 - X_{24} - X_{53} = X_{56}$	" "	2.	(8)
$X_{12} - X_{28} - X_{54} = X_{57}$	" "	3.	

Because of the explicit introduction of those stop-overs they can be introduced in the objective function and get associated with the representative incremental costs of performing the additional call at "C".

Those port-call costs are defined by class of ship and set equal to the marginal costs of loading backloads in "B", or respectively 500.-, 400.- and 350.-. By this procedure the backhauls are in principle as expensive for the non-stop service with occasional calls at "C" as they are for scheduled link-shuttles, stopping at "C" both on the outbound and backhaul section. It should finally be noted that no correction should be made for the longer time requirements through the additional port call at "C". This correction is implicitly made through the organization of the (7') constraints which :

- count only the fully non-stop trips at the LHS,
- and bring all non-stop route services, which make an occasional stop-over at "C", to the right hand side where they are confronted with longer trip times,

Thus, the variables X_{52}, X_{53} and X_{54} are the basic information of port calls at "C" which are indeed aggregated both for link- and for route-services.

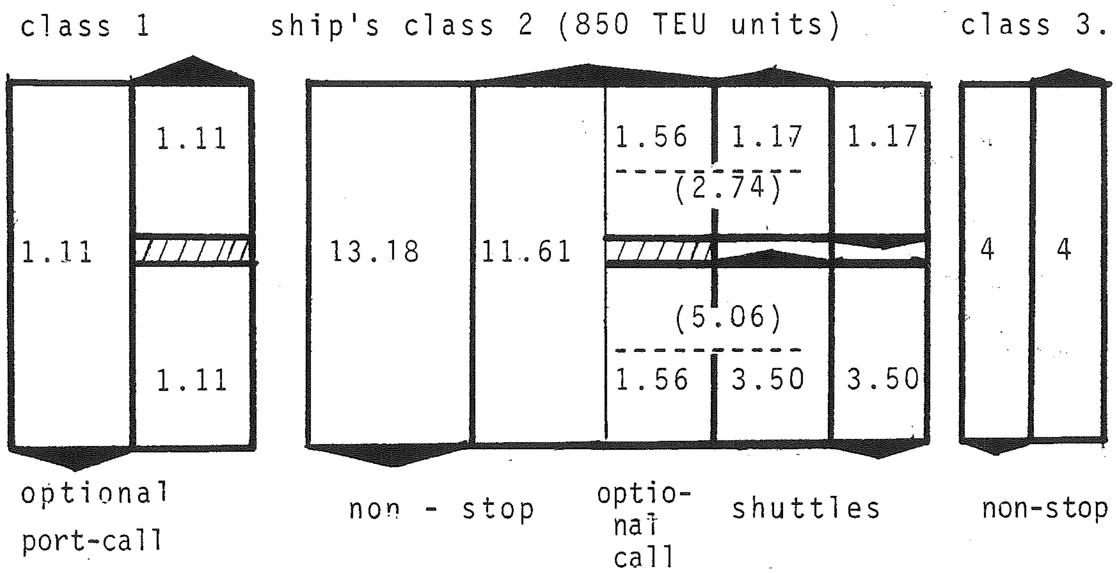
This new set of (7') and (8) conditions replace conditions(3), though this replacement is not required. The (3) conditions imposed the integration of successive links in terms of vessel operations, an integration which is now guaranteed within the route service as a whole, though in another way.

The sailing list as produced by an integrated route/link operations-structure is exibited in Figure 4. As could be expected the graph on the fourth route has lost its previous symmetry.

Table 4 : Sailing list with integrated links & routes

route		1.	2.	3.	4(non-stop)	4/a	4/b	
demand		10,000	20,000	5,000	20,000	5,000	3,000	outbound
trips:	1.	6.67	-	3.33	1.11	-	-	outbound
	2.	-	-	-	13.18	1.17	3.5	outbound
	3.	-	40	-	4	-	-	outbound
penalties		0	0	0	5,130	4,000	0	outbound
penalties		0	0	0	8,130	0	0	backhaul
trips	1.	3.33	-	3.33	0	1.11	1.11	backhaul
	2.	-	-	-	11.61	2.74	5.1	backhaul
	3.	-	20	-	4	-	-	backhaul
demand		5,000	10,000	5,000	20,000	4,000	6,000	backhaul

Table 4/b : Sailing graph on the fourth route by class.



The integrated service chart shows that all demand is handled on routes 1 through 3 even with 50 % load factors on the backhaul sections of routes 1. and 2. This result apparently surprises since on the fourth route (non-stop service) substantial TEU quantities are left without shipment. The fourth route exibits a fairly complicated sailing schedule with (see Figure 4/b):

a/ class 1 vessels performing 1.11 non-stop outbound trips all of which return to "A" after an intermedeate call at "C",

b/ class 3. vessels only running non-stop connections on both directions à 4 roundtrips per month,

c/ class 2. vessels combining:
- 13.2 non-stop outbound departures of which only 11.6 return on the direct route-service, and
- the remaining 1.56 backhauls call at "C" in order to load an equal number of TEU between "C" and "A" as they shipped on the B-C link,
- 1.17 monthly sailings on the least busy link (A-C),
- and 3.50 monthly shuttles on the dominant "C-B" link.

4. Evaluation

The detail obtained in the discussion is still able of being reached at less than 2 minutes CPU time (representing about 2 U.S. $) on standard medium size equipment. The use of 57 variables and 36 constraints is furthermore compatible with a lot of micro-computers and/or terminal facilities. As such the procedure is cheap the more it uses standard LP software. The only additional input is the conceptual editing work which we have elaborated in a progressively standardized manner.

It follows from the bewildering variety of actual shipping operations that such class of problem-statement is never to be put in a once-for-all general problem format which should match all applications. Rather the art consists in formulating a minimum of constraints tailored to the problem at stake. Therefore, the exact problem definition is as vital to the relevance of the outcome as is the preciseness of the input data.

Apart from the promising technical possibilities it is interesting to conclude by expanding on two basic programming features :

1/ the procedure is fairly sensitive to costs inputs, both in terms of monetary costs as in the sense of time-costs, which calls for due detail in data screening,
2/ as such, the procedure remains open to a variety of adaptations and traffic-engineering amendments, such as being dealt with in "voyage estimating" (3) procedures or in more systematical cost-accounting (4) methods. Those adaptations may as well apply to the basic problem definition as to the cost- and operations data.

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5. References and notes

(1) For the introductory part of this note, see E. Claessens, Shipping Logistics, A Revisitation of applications of Linear Programming, SESO rapport 83/149, December 1983, 62 p.

(2) The notion of link versus route service follows the standard transport programming network-terminology, e.g. STEENBRINK, Optimization of Transport Networks, Wiley, 1974, p.11 e.s. In the present example, the "fifth route" covers the two successive links which duplicate the non-stop service on the fourth route. Those links are afterwards referred to as 4/a and 4/b.

(3) see W. V. PACKARD, Voyage Estimating, Tramp Ship Series, Fairplay Publications, 1981, 79 p.

(4) see R.O. GOSS and M.C. Mann, The Cost of ship's time, in R.O. GOSS, Advances in Maritime Economics, Cambridge University Press, 1977, pp.138-172.

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6. List of variables

a/ number of monthly (loaded) outbound trips

ship class / routes	1.	2.	3.	4(non-stop)	4/link a	4/link b
1.	X_1	X_2	X_3	X_4	X_{36}	X_{42}
2.	X_5	X_6	X_7	X_8	X_{37}	X_{43}
3.	X_9	X_{10}	X_{11}	X_{12}	X_{38}	X_{44}

b/ idem (fully loaded backloads)

ship class						
1.	X_{17}	X_{18}	X_{19}	X_{20}	X_{39}	X_{45}
2.	X_{21}	X_{22}	X_{23}	X_{24}	X_{40}	X_{46}
3.	X_{25}	X_{26}	X_{27}	X_{28}	X_{41}	X_{47}

c/ outbound penalties

X_{13} X_{14} X_{15} X_{16} X_{48} X_{49}

d/ backhaul penalties

X_{29} X_{30} X_{31} X_{32} X_{50} X_{52}

e/ outbound surplus sailings (non stop service)

class 1. : X_{52} ; class 2. : X_{53} ; class 3.: X_{54}

f/ optional port calls of non-stop service at "C"

class 1. : X_{55} ; class 2. : X_{56} ; class 3.: X_{57}

(note: variables X_{55} through X_{57} may be ommitted by directly introducing the corrected coefficients of X_{36} through X_{41} in the objective function cfr.(7'); then, the optional port calls cannot be obtained by simple reading).