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Volker Windeck

A Liner Shipping Network Design

Routing and Scheduling Considering Environmental Influences

Foreword by Prof. Dr. Hartmut Stadtler

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Foreword

Transport by ship is regarded as the most economical and ecological means of transport for carrying large and heavy volumes over long distances. Still or as a result, total world-wide container shipping is due to its mere size one of the largest carbon dioxide (CO2) and sulphur oxides (SOX) polluters today. Hence, recommendations for reducing these emissions are most welcome.

This thesis not only presents a decision support system for designing a liner shipping network and its operation. It is also a nice example for how Operations Research models and algorithms can help to improve both economical and ecological objectives simultaneously!

This research is based on detailed real-world data for currents, winds and waves a ship may face on a given passage. It is used as an input to a shortest path and a strategic mathematical model. As means to reduce emissions and fuel consumption, slow steaming as well as additional propulsion systems are incorporated into the models. A large computational test with container ships equipped with the latest technology for an additional wind propulsion system (i.e., a kite) shows that significant reductions of fuel consumption can be expected only on specific passages (like the North Atlantic). Much more important in this respect is the choice of an appropriate speed (including slow steaming) for each leg on a ships round trip.

Although Volker Windeck has put much emphasis on making use of the latest and most accurate data, it is recommended not to generalize his findings on the potential reduction of fuel consumption and emissions. Instead, shipping companies should implement the model suite developed and documented in this thesis and perform their own calculations considering their fleet of container ships and customer base.

It has been a great pleasure to have been able to collaborate with Volker Windeck during the last four years and to see a fascinating topic ripening and yielding computational results which in this breadth could neither be achieved by simple human reasoning nor by real-word experiments.

I sincerely hope that his model suite including a highly innovative matheuristic will not only be of interest to the academic world but will also be used intensively by shipping companies.

Hartmut Stadtler

Preface

In this thesis the results of the research are presented which were carried out at the Institute for Logistics and Transportation of the University of Hamburg.

I am very grateful to Prof. Dr. Hartmut Stadtler for giving me the opportunity to engage in this research topic which is linked to very challenging, technical questions and contains a great portion of maritime flair, too. Whenever necessary he offered his time and always got me back on track with his enormous experience and stimulating suggestions.

Prof. Dr. Knut Haase deserves special thanks for reviewing my thesis as a co-supervisor and also providing valuable advice on how to solve my shortest path problem. Also, I thank Prof. Dr. Stefan Voß for taking on the chair on the dissertation committee and being an obviously interested reader of my dissertation which he expressed in enriching suggestions and questions during my thesis defence.

My thanks also to the core of in-house supporters and dear colleagues Christopher Haub, Florian Kröger and Julian Wulf for proofreading and multiple good suggestions and Sylvia Kilian and Stefanie Nonnsen for providing a friendly atmosphere. Much support was given from my former colleagues Dr. Martin Albrecht, Dr. Carolin Püttmann and Dr. Christian Seipl who were always offering their help to get me started with my research.

My sincere thanks go to all the companies and organizations, that offered me their time when discussing my research project. Among them Dr. Thomas Bruns and Mr. Heinz-G. Hill of the DWD (German Meteorological Service) who deserve a special thanks for their interest and support and especially providing me with weather data on wind and waves being a most valuable basis of my research.

Finally, I would like to thank my wife and family for accompanying me with unlimited love and support, which allowed me to accomplish this set goal.

Volker Windeck

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Abbreviations

DWD	Deutscher Wetterdienst, governmental German weather service
dwt	Deadweight tonnage, ship carrying capacity measured in metric tons
GMES	Global Monitoring for Environment and Security
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
ITTC	International Towing Tank Conference
LFCP	Least Fuel Consumption Problem
LNG	Liquefied natural gas
LTA	Latest Time of Arrival
MIP-model	Mixed Integer Programming Model
MPLSFP	Multi-Period Liner Ship Fleet Planning Problem
MTTP	Minimum Travel Time Problem
NG	Natural Gas
NOX	Nitrogen Oxides
OD	OD
PDP	Pick-up and Delivery Problem
Ro-Ro	Roll-on-Roll-off
SDNP	Service Network Design Problem
SOX	sulphur oxides
SPP	Shortest Path Problem
SPPRC	Shortest Path Problems with Resource Constraints
SPPTW	Shortest Path Problem with Time Window Constraints
TEU	20 feet equivalent unit
TSP	Travelling Salesman Problem
TW	Time Window

UAVs	Unmanned Aerial Vehicles
VNS	Variable Neighbourhood Search
VRP	Vehicle Routing Problem

Nomenclature

α_W	Angle between true and apparent wind
α_{CU}	Angle between direction of ocean current and ship's desired course
β_W	Angle between the true wind and the fair wind
Δ	Total travelled distance of one round trip
η_D	Efficiency of propulsion
η_S	Efficiency of transmission
γ_P	Pitch angle of flying kite
γ_W	Incidence angle between apparent wind and ships' direction
γ_{AW}	Wind direction of apparent wind
∇	Displacement of a ship
ν	Kinematic viscosity
ρ_A	Density of air
ρ_{SW}	Density of sea water (SW)
ζ	Wave height
a_i	Earliest arrival time at network point i
A_K	Size of kite
a_k	Ship type k dependent coefficient for the fuel consumption formula
A_S	Wetted surface area of a ships hull
A_{AWS}	Above water surface of a ship
B	Breadth of a ship
b_i	Latest arrival time at network point i
b_k	Ship type k dependent coefficient for the fuel consumption formula
C	Centre point of SPP network
C_∇	Ship's volume-length coefficient
C_F	Friction coefficient
C_i^p	Fuel consumed when reaching network point i on path p

C_M	main frame surface area
C_P	Ship's prismatic coefficient
C_R	Remaining drag coefficient
C_T	Total drag coefficient
c_W	Kite wind resistance coefficient
$C_{\pm i}$	Additional centre points along a line through centre point C
$C_{B,AYRE}$	Ship's Ayre block coefficient
$C_{I1,I2}$	Course between two interception points I_1 and I_2
c_{ij}	Costs arising when traversing on an arc between two network points i and j
CO_2	Carbon dioxide
D_c^{GC}	Great circle distance between cargo c's loading and unloading harbour
$D_{I1,I2}$	Great circle distance measured in degree between interception points I_1 and I_2
D_{I_1,I_2}	Distance between interception points I_1 and I_2
D_{sek}	Denotes the two turning point harbours s and e for each ship type k
EC_{nor}	original, normal energy consumption
EC_{red}	specific energy consumption at reduced speed
F	Visiting frequency
F_N	Froude's number
g	Earth's gravity
I_i	Interception points of a network arc
k_{yy}	Longitudinal radius of gyration about an axis through the centre of gravity
L	Length of a ship
L_i	Label storing all information of network point i within a label-setting algorithm
LCB	Longitudinal position of centre of buoyancy from midships
N_1, N_2	Origin and destination points of a network arc
N_H	Number of visited harbours
N_S	Number of ships needed to uphold a promised visiting frequency
P_B	Braking power
P_i^p	Set of paths to reach node i indexed by p
$pred(L)$	Predecessor node of a label
R_G	Gross resistance, combination of all resistances
R_G	Sum of all ship resistances
R_K	Kite propulsion force

R_T	Calm water resistance
R_W	Wind resistance
$R_{KD}(\gamma_{AW})$	Apparent wind direction dependent kite propulsion force component
R_{KV}	Kite propulsion force
$R_{KV}(V_{AW})$	Apparent wind velocity dependent kite propulsion force component
$R_{sea,K}$	Additional wave resistance as proposed by Kreitner (1939)
$R_{sea,MM}$	Dimensionless additional wave resistance according to Moor and Murdy (1968)
Re	Reynolds number
T	Draught of a ship
T_H	Average time spent in harbour for loading and unloading activities
T_i^p	Needed travel time to reach network point i on path p
t_{ij}	Travel time needed when traversing on an arc between two network points i and j
tt_{ijk}	Travel time, a ship of type k needs to travel from harbour i to harbour j
V	Average fleet speed
v_p	Speed taken within a label-setting algorithm on path p
V_s	Ship speed
V_{AW}	Wind velocity of apparent wind
V_{CO}	Velocity of a ship over ground in course direction
V_{CU}	Ocean current velocity
V_{FW}	Fair wind
V_{nor}	original, normal speed setting
V_{red}	reduced speed
V_{TW}	True wind
V_T	Tip velocity
a, b, c, d	Parameters for estimating apparent wind direction dependent kite force
g	Gram
kg	Kilogram
km	Kilometre
kn	Speed in knots
lat	Latitude of a a coordinate
lon	Longitude of a coordinate
nm	Nautical mile
t	Metric ton

Parameters and Random Variables

β	Progressing time between two consecutive service arcs
$\overline{inv_i}$	Upper bound on inventory level of LNG in harbour i
$\overline{tw_i}, \underline{tw_i}$	Time interval for each harbour and cargo combination i
$\overline{u_{dij}}$	Upper bound on passenger flow on an arc connecting harbours i and j
$\overline{u_{ij}}$	Upper bound on ferry flow on an arc connecting harbours i and j
$\underline{inv_i}$	Lower bound on inventory level of LNG in harbour i
$\underline{v_k}; \overline{v_k}$	Given minimum and maximum speed a ship of type k can travel at
c_{ijk}	Cost for traversing an arc from harbour i to j for a ship of type k
c_{ij}	Costs for operating a trip between harbours i and j
cap	Ferry capacity
cap_k	Capacity of a ship of type k
cap_{ijk}	Capacity of a ship of type k when travelling from harbour i to harbour j
cf	Fixed costs for hiring or owning a ferry per day
$charter_k$	Daily charter-rates representing the fixed costs to operate a ship of type k for one day
$costs_{ijkv}$	Speed dependent variable travel costs for a ship of type k when travelling directly from harbour i to j
cp_{it}	Costs for producing LNG in harbour i and time period t
ct_{kr}	Costs for a ship of type k travelling on route r
d_i	Demand at harbour i
d_{di}	Passenger demand of origin destination pair d for harbours $i \in N_d$
$demand_c$	Weekly amount of cargo c in TEU
$demand_{ij}$	Expected amount of container available for transportation from their origin harbour i to destination harbour j
f	Maximum amount of ferries
h_i	Harbour visiting indicator has value 1 for delivery harbours and -1 for pick-up harbours i
l_{iktr}	Number of tanks unloaded from ship of type k at harbour i in t on route r
$loadH_c$	Loading harbour of cargo c
lta_j	Latest arrival time at harbour j
m	Sufficiently large number

$ncap_i$	Number of ships that can unload simultaneously in harbour i
p_j	Pick-up load to be picked up in harbour j
p_{it}	Upper bound on production of LNG in harbour i and time period t
q_k	Capacity of a ship of type k
q_{iktr}	(Un-)Loading volume at harbour i by a ship of type k in time period t on route r
qc_i	Weight of cargo from harbour i
rev_c	Revenue per TEU for transporting cargo c
rev_d^c	Revenue for origin destination pair d
rev_i^h	Revenue for loading cargo from harbour i
rev_{ij}	Revenue obtained from transporting a container from its origin i to its destination harbour j
rev_{it}^g	Revenue obtained from transporting and selling gas in harbour i and time period t
s_{ik}	Necessary time to service harbour i by a ship of type k
s_{it}^{LNG}	Lower bound on sales of LNG in harbour i and time period t
t_c^{max}	Allowed maximum transportation time of cargo c
t_k	Availability of a ship of type k measured in days
t_{ijk}	Time for traversing an arc from harbour i to j by a ship of type k
t_{ij}	Travel time between harbour i and j
$tcap_k$	Maximum number of tanks in ship of type k
$tijt_{cdek}^{v^{min}}$	Total travel time between the loading harbour d and unloading harbours e of cargo c, for all four direction combinations, when travelling at slowest possible speed v^{min} on a ship of type k
tl_{ik}	Required loading and unloading time of a ship of type k in harbour i
$tload_{ck}$	loading time of cargo c on board of a ship of type k
tt_d	Travel time of origin destination pair d for direct service
tt_k^{max}	Maximum total travel time for a ship of type k
tt_{ijdkv}	Time a ship of type k needs when travelling from harbour i to j
$ttt_{i(c)d(i)j(c)d(j)k}^{max}$	Maximum allowed travel time of cargo c from its loading harbour $i(c)$ to its unloading harbour $j(c)$, which can either be on the inbound or outbound part of a round trip indicated by $d(i)$ and $d(j)$ for the loading and unloading

	harbour respectively
$tunload_{ck}$	unloading time of cargo c from board of a ship of type k
tv	Travel time value
$unloadH_c$	Unloading harbour of cargo c
w_k	Number of tanks on ship k
wv	Waiting time value
x_{ijktr}	1, if a ship of type k (un-)loads at harbour i in t before travelling to harbour j on route r; 0, otherwise
z_{iktr}	1, if ship k visits harbour i in t on route r; 0, otherwise

Indices, Sets and Index Sets

0	Depot, mainland harbour
$c \in C$	Cargo
$CargoRoute_{hdk}$	Set of all cargoes $(c, d(i), d(j))$ that stay on board of a ship of type k when passing harbour h in direction d)
$d \in R$	Set of origin and destination pairs
D_d	Destination arcs of the passenger network
$DirL_{cdekghf}$	All direct connections $d \in D$, $(g, h) \in H$ on the partial-trip from a cargo's loading harbour d_i to its unloading harbour d_j, where a ship of type k can transport cargo c
$e, d \in D$	Outbound or inbound direction of round trip
$e, h, i, j, e, s \in H$	Harbour index
$H_c \subset H_p$	Set of pick-up harbours for mandatory cargo
H_d	Set of delivery harbours
H_k	Cargo at set of Harbours, corresponding to cargo a ship of type k can load
$H_o \subset H_p$	Set of pick-up harbours for optional cargo
H_p	Set of pick-up harbours
$H_{pk}; H_{dk}$	Set of all pick-up and delivery harbours for cargo a ship of type k can load
$k \in K$	Set of ship types
$Load_i$	Set of cargoes c, that can be picked up in harbour i
N, A	Set of nodes and arcs for the ferry network
$N^b, N^e \subset N$	Set of nodes at the beginning and ending of the planning interval
N^D	Set of delivery harbours
N^P	Set of pick-up harbours
N_d, A_d	Set of nodes and arcs for the passenger network
O_d	Origin arcs of the passenger network
$o_k; d_k$	Origin and destination of a ship of type k, either harbour

	or artificial position at sea
$r \in R_k$	Set of routes for ships of type k
S, S_d	Set of service arcs for the ferry and passenger network
$t \in T$	Set of time periods
$Unload_i$	Set of all cargoes that can be unloaded in harbour i
$v \in V$	Set of possible average speed settings between two harbours
W, W_d	Set of waiting arcs for the ferry and passenger network

Variables

Λ_{kr}	Number of round trips a ship of type k makes on its assigned route r during one planning interval
A_i	Arrival time at harbour i
D_{sek}	1, if s and e are turning point harbours for ship of type k; 0, otherwise
H_{idk}	1, if harbour i is visited by a ship of type k either on the inbound (d=1) or outbound (d=2) part of the round trip; 0, otherwise
$Har_{(id)k}$	point in time when a ship of type k arrives at harbour i
$Hde_{(id)k}$	Point in time when a ship of type k leaves harbour i on the in- or outbound part of its round trip
L_{jk}	Cargo on board of a ship of type k after leaving harbour j
N_k	Number of round trips a ship of type k makes on its assigned route during one planning interval
$NShips_k$	Number of ships of type k that are needed to guarantee a weekly (every 168 h) visit to all visited harbours on the round trip
S_{it}	Inventory level of storage in harbour i in time period t
$Ship_k$	1, if a ship of type k is in use; 0, otherwise
$Slack_{idk}$	Either waiting time for a ship of type k lying in the roads at harbour i in direction d or time used for repairs and overhauls
TH^E_{jk}	1, if harbour j is the most easterly harbour of the round trip of a ship of type k; 0, otherwise
TH^W_{ik}	1, if harbour i is the most westerly harbour of the round trip of a ship of type k; 0 , otherwise
$TijT_{cdek}$	Lower bound of travel time for a ship of type k when transporting cargo c from its loading to its unloading harbour
TT_{ijk}	Travel time of the direct connection between harbours i and j for a ship of type k's round trip
V_{ijdkv}	1, if ships of type k are travelling with speed v from harbour

	i to j in direction d; 0, otherwise
V_{ijk}	Speed a ship of type k should travel at, when traversing on an arc from harbour i to harbour j
X_{dij}	Passenger flow in a time-space network of origin destination pair d
X_{ijdk}	1, if a ship of type k is travelling directly from harbour i to harbour j in direction d, without stopping at harbours that lie in between; 0, otherwise
X_{ijk}	1, if a ship of type k is traversing an arc from harbour i to j; 0, otherwise
Y_{cdk}	1, if cargo c is picked up on the inbound or outbound part d of the round trip of a ship of type k; 0, otherwise
Y_{ijk}	Number of cargo loaded in TEU by a ship of type k from an origin harbour i to a destination harbour j
Y_{ij}	Ferry flow in the ferry time-space network
Y_{it}	Sales or production of LNG in harbour i in time period t
$Z_{cd(i)d(j)k}$	1, if cargo c is picked up at its origin harbour i and dropped off at its destination harbour j on either the inbound or outbound trip $(d(i), d(j))$ of a ship of type k's round trip; 0, otherwise