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# Produktion und Logistik

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Diese Reihe dient der Veröffentlichung neuer Forschungsergebnisse auf den Gebieten der Produktion und Logistik. Aufgenommen werden vor allem herausragende quantitativ orientierte Dissertationen und Habilitationsschriften. Die Publikationen vermitteln innovative Beiträge zur Lösung praktischer Anwendungsprobleme der Produktion und Logistik unter Einsatz quantitativer Methoden und moderner Informationstechnologie.

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Volker Windeck

# A Liner Shipping Network Design

Routing and Scheduling Considering  
Environmental Influences

Foreword by Prof. Dr. Hartmut Stadler

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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 (CO<sub>2</sub>) 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 math-heuristic will not only be of interest to the academic world but will also be used intensively by shipping companies.

Hartmut Stadler

# 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.

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Volker Windeck

# Contents

List of Figures	xi
List of Tables	xv
Abbreviations	xvii
Nomenclature	xix
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation . . . . .	1
1.2 Outline . . . . .	2
<b>2 Maritime Transportation</b>	<b>5</b>
2.1 Freight Transportation Systems . . . . .	7
2.2 Terms and Definitions . . . . .	11
2.3 Routing and Scheduling . . . . .	15
2.4 Routing and Scheduling in Maritime Shipping . . . . .	28
2.4.1 Examples of Operational and Tactical Planning . . . . .	30
2.4.2 Examples of Strategic Planning . . . . .	35
<b>3 Environmental Routing</b>	<b>39</b>
3.1 Literature Review . . . . .	40
3.2 SPP Network Design . . . . .	44
3.3 Shortest Path Problem . . . . .	48
3.4 Calculation of Ship Fuel Consumption . . . . .	53
3.5 Weather Data . . . . .	61
3.6 Computational Tests . . . . .	62
<b>4 Strategic Liner Network Design</b>	<b>79</b>
4.1 Literature . . . . .	79
4.2 Decision Problem and Mixed Integer Programming Model . . . . .	86
4.2.1 Decision Problem . . . . .	86



4.2.2	Mixed Integer Programming Model . . . . .	89
4.3	A Hybrid Algorithm . . . . .	97
<b>5</b>	<b>Computational Tests</b>	<b>103</b>
5.1	Generation of Test Data . . . . .	103
5.2	Evaluation of the Test Results . . . . .	108
5.2.1	Evaluation of Solution Approaches . . . . .	108
5.2.2	Testing the Effect of a Kite Propulsion System . . . . .	111
5.2.3	Consideration of the Effects of some Parameters . . . . .	114
<b>6</b>	<b>Summary and Outlook</b>	<b>119</b>
<b>A</b>	<b>Appendix</b>	<b>123</b>
A.1	Kite Propulsion Force Data Input . . . . .	123
A.2	Ship Data . . . . .	124
A.3	Wave Resistance Data Input . . . . .	125
A.4	Great Circle Navigation Formulas . . . . .	125
A.5	Computational Tests - Changing Revenue . . . . .	126
	<b>Bibliography</b>	<b>127</b>

# List of Figures

2.1	Global container handling from 2000 to 2009 and forecasts for 2010 and 2011, according to Tiedemann (2011) . . . . .	6
2.2	Ship routes without and with subtours . . . . .	18
2.3	Tramp ship routing example, on the basis of Lin and Liu (2011, p. 415) . . . . .	22
2.4	Passenger and ferry time-space network, according to Lai and Lo (2004, p. 309, 310) . . . . .	26
3.1	Constructing Isochrones, according to Szlapczynska and Smierzchalski (2007, p. 637) . . . . .	43
3.2	Constructing a network, according to (Hagiwara 1989, p. 24) .	44
3.3	Example of a network connecting harbours Cadiz and New York - Newark, network displayed with Google Earth . . . . .	46
3.4	Constructing center points, according to Lee et al. (2002, p. 128) . . . . .	46
3.5	Creating interception arcs to given grid resolution . . . . .	47
3.6	Determination of course between interception point $I_1$ and $I_2$	47
3.7	Pseudo code according to Grünert and Irnich (2005, p. 297) .	50
3.8	Label-setting example, step 1 . . . . .	51
3.9	Example data . . . . .	52
3.10	Labelsetting example, further iteration steps . . . . .	52
3.11	Label-setting example, optimal solution . . . . .	53
3.12	Wind directions and angles according to ships heading . . . . .	57
3.13	SkySails, possible courses (SkySails 2009) . . . . .	60
3.14	SPPTW from Le Havre to Miami network with resolution of 60nm (top) and resolution of 240nm (bottom), displayed with Google Earth. . . . .	64
3.15	SPP from Cadiz to Miami, with (white) and without (black line) sail at 23 kn, displayed with Google Earth. . . . .	68
3.16	Fuel consumption by ship type . . . . .	69

3.17	Fuel consumption for travelling across the Atlantic Ocean without sail assistance on ship of type Laetitia. . . . .	71
3.18	Travelled distances for travelling across the Atlantic Ocean without sail assistance on ship of type Laetitia. . . . .	72
3.19	Fuel consumption and travelled distances for travelling within the Gulf of Mexico. . . . .	73
3.20	Mean fuel savings in % when using sail assistance. . . . .	74
3.21	Carrying capacity in TEU and installed machine power for all ship types. . . . .	75
3.22	Mean fuel savings in % when using the SPPTW algorithm compared to the LFCP algorithm. . . . .	75
3.23	Mean travel time saved in % when using the SPPTW algorithm compared to the LFCP algorithm. . . . .	76
3.24	Mean fuel savings in % when using the SPPTW algorithm compared to the regular SPP algorithm. . . . .	77
3.25	Mean distance and travel time saved in % when using the SPPTW algorithm compared to the regular SPP algorithm. . . . .	78
4.1	Example of harbour call sequences according to (Rana and Vickson 1991, p. 203) . . . . .	82
4.2	Maersk Transatlantic (TA2) – east- and westbound, Maersk (2011) . . . . .	88
4.3	Hapag-Lloyd South China Sea Expr. (SCX) – east- and westbound, Hapag-Lloyd (2011) . . . . .	88
4.4	CMA CGM French Asia Line 12, CGM (2011) . . . . .	88
4.5	Possible routes of a cargo from load harbour $i = 4$ to unload harbour $j = 5$ on a ship’s round trip. . . . .	90
4.6	Visualisation of the Hybrid Algorithm . . . . .	97
4.7	Vector setting example. . . . .	99
4.8	The VNS Pseudo code . . . . .	100
4.9	Neighbourhood and Local Search heuristics. . . . .	101
5.1	Progress of the objective function value during the Matheuristic run for test set (23, 3lSwS, 04, 650, 4.9, 0.5, 5, 5, 10). . . . .	111
5.2	Harbour visiting sequence of ships of type ‘Rafaela’ (white line) ‘Alicante’ (grey line) and ‘Moliere’ (black line) and their corresponding schedules (see tables at harbours; Arr = arrival time; Dep = departure time)(©2011 Google). To view this figure in colour please refer to: <a href="http://www.springer-gabler.de/Buch/978-3-658-00698-3/A-Liner-Shipping-Network-Design.html">www.springer-gabler.de/Buch/978-3-658-00698-3/A-Liner-Shipping-Network-Design.html</a> . . . . .	113

A.1 Kite propulsion force gradient . . . . . 123  
A.2 Wave resistance factor according to (Yaozong 1989, p. 19-20) . 125  
A.3 Determination of a great circle route . . . . . 125

# List of Tables

2.1	Comparison of operational characteristics of freight transportation modes (Christiansen et al. 2007, p 192) . . . . .	9
2.2	Strategic, tactical and operational planning tasks in maritime transportation according to Christiansen et al. (2007, p. 196) .	14
3.1	Literature overview on environmental routing . . . . .	42
3.2	Value constraints for remaining drag coefficient approximation function (Schneekluth 1988, p. 495) . . . . .	56
3.3	List of all 33 harbours considered. . . . .	65
3.4	Harbour to harbour connections . . . . .	67
3.5	Ships maximum service speeds . . . . .	70
4.4	Classification scheme according to Kjeldsen (2009) . . . . .	85
5.1	Ship data . . . . .	104
5.2	Ship test settings . . . . .	106
5.3	Comparison of solution quality between Matheuristic and the original mixed integer programming model . . . . .	109
5.4	Evaluating the effect of an alternative kite propulsion system .	112
5.5	Evaluating the effect of changing fuel costs . . . . .	115
5.6	Evaluating the effect of changing charter rates . . . . .	117
A.1	Data input for a kite of 160 $m^2$ . . . . .	123
A.2	Ship data . . . . .	124
A.3	Evaluating the effect of changing revenues . . . . .	126

# 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

$\alpha_W$	Angle between true and apparent wind
$\alpha_{CU}$	Angle between direction of ocean current and ship's desired course
$\beta_W$	Angle between the true wind and the fair wind
$\Delta$	Total travelled distance of one round trip
$\eta_D$	Efficiency of propulsion
$\eta_S$	Efficiency of transmission
$\gamma_P$	Pitch angle of flying kite
$\gamma_W$	Incidence angle between apparent wind and ships' direction
$\gamma_{AW}$	Wind direction of apparent wind
$\nabla$	Displacement of a ship
$\nu$	Kinematic viscosity
$\rho_A$	Density of air
$\rho_{SW}$	Density of sea water (SW)
$\zeta$	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
$C_{\nabla}$	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
$C_{I_1, I_2}$	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
$D_{I_1, I_2}$	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 coordinate
lon	Longitude of a coordinate
nm	Nautical mile
t	Metric ton

# Parameters and Random Variables

$\beta$	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 $k$
$t_{ij}t_{cdek}^{v^{min}}$	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 $j$
$tt_{i(c)d(i)j(c)d(j)k}^{max}$	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
$t_{unload}_{ck}$	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

$\Lambda_{kr}$	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
$TH_{jk}^E$	1, if harbour $j$ is the most easterly harbour of the round trip of a ship of type $k$ ; 0, otherwise
$TH_{ik}^W$	1, if harbour $i$ is the most westerly harbour of the round trip of a ship of type $k$ ; 0, otherwise
$T_{ij}T_{cdek}$	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
$V_{jdkv}$	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