Short Sea Shipping route and stowage plan optimization

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ABSTRACT: Short Sea Shipping is the name given to the use of ships to transport cargo within a country, or between neighboring countries. The European Union considers all intra-European sea transport as Short Sea Shipping, and has defined its efficient use as a strategic goal. This form of transport has many recognized advantages over rail and road, but suffers from lack of flexibility. In this paper we propose a logistic model for short sea shipping that greatly increases flexibility, and that may reduce costs substantially. The model is described and formalized, and a genetic algorithm based optimization procedure is presented, to assign cargo and routes to each ship, as well as provide stowage plans. The proposed method is used on a small problem that illustrates the advantages that can be obtained.

1 INTRODUCTION

Short sea shipping is considered by the European Union as one of the pillars for its transport policy since the 2000 European Conference of Ministers of Transport EU_Comission (2001). During the last few years, there have been several studies about the subject, aiming to determine when short sea shipping is more advantageous than road transport **Medda**, **Pels** et al. (2010), how the maritime transport has lower CO_2 emissions than land transport Vanherle and Delhaye (2010), and several others.

Gathering data from the available sources, short sea shipping advantages and downsides can be generically identified. On one side, it is commonly accepted by EU member states that:

(1) it is environmentally sound;
(2) it contributes to road safety;
(3) it has low infrastructure costs (the sea itself is the "motorway");
(4) it can reach most of Europe's "peripheral" regions.

On the other, one can also point out that there are disadvantages:

(5) the bureaucracy attached to customs;
(6) port services costs and efficiency;
(7) travel duration;
(8) inflexibility of routes;
(9) dependency on environmental factors.

The work that has been developed, tackles disadvantages (7) and (8), purposing a managing model for a fleet of cargo ships with no pre-defined routes, and where these are defined dynamically, depending on cargo arrival at ports, due dates and delivery deadlines. The model complexity depends on the vessels and type of cargo, since if containerships are considered the container stowage problem has to be incorporated, while the cargo distribution problem for bulk carriers is simpler.

Focusing in the containership problem, there are three different challenges that are addressed:

i. how to select navigation routes for the fleet;
ii. how to distribute the cargo by the available vessels;
iii. how to stow cargo on the vessel.

2 STATE OF THE ART

As mentioned in Avriel, Penn et al. (1998), "the problem of efficiently operating a fleet of containerships serving many ports is composed of several sub-problems, among them finding the optimal sizes and optimal routing of the ships".

Generically, this can be extrapolated to cargo transport by sea, and within this subject of optimization two major research areas have appeared, namely the container stowage problem (CSP) Avriel, Penn et al. (1998), Wilson and Roach (1999) and the vehicle routing problem (VRP) Christiansen and Nygreen (1998).

2.1 *Container stowage problem (CSP)*

As far as the CSP is concerned, following the same approach to the problem of references Avriel, Penn et al. (1998), Wilson and Roach (1999) and Martins, Lobo et al. (2009), it is defined as the problem of assigning different containers to slots on board a containership, bearing in mind their origin and destination, as well as the different ports of call of the vessel during her journey, aiming to reduce the inevitable containers manoeuvres at every port. All these manoeuvres have a related cost and time

duration, and may be motivated by several reasons, namely:

a. containers that are unloaded since they reached their destination;
b. containers that have to be moved because they block the access to others that have to be unloaded (there are usually called over-stows);
c. containers that are stacked on the top of cargo hatches and that have to be moved to access to the cargo bay (a particular case of the previous ones);
d. containers that are re-positioned to improve the overall stowage (including stability), and make the next port handling easier (which are known as re-handles);
e. new containers that are brought on board to send to another port of call.

When assigning containers, care must be taken to consider several constraints related to the container-ship herself, such as space limitations, stability and strength, speed, autonomy and seaworthiness; and to the containers requirements and characteristics, which among others are size, weight, structural resistance, refrigeration requirements, etc.

In the literature there have been several approaches and methods to solve the problem, such as the use of Binary Linear Programming formulations were used in Botter and Brinati (1992),Ambrosino, Sciomachen et al. (2006); simulation based approaches can be found in Wilson and Roach (1999); and other in many other cases metaheuristics methods, as for example Simulated Annealing (Dubrovsky, Levitin et al. (2002)) and Genetic Algorithms Martins, Lobo et al. (2009).

In particular, Genetic algorithms provided good results and large flexibility when implementing a large number of both crisp and fuzzy constraints.

2.2 Vessels routing problem

The vessel's routing problem referenced in the literature, as far as we know, is dedicated to cargo transport in bulk carriers where only one kind of cargo is transported per journeyAppelgren (1969; Appelgren (1971; Brown, Graves et al. (1987; Fisher and Rosenwein (1989), though some models present time and inventory constraints Christiansen and Nygreen (1998).

Such approaches use graph theory to solve the problem. In the particular case of Christiansen and Nygreen (1998), in which deadlines are concerned (time - windows), the problem is sub-divided into two. It begins to consider two distinct input variables, the ship routes and port sequence (pick up and delivery). Once several feasible ship routes are selected there is an interaction between this solution and the port sequence, that is formulated as a shortest path sequence, using Dantzig –Wolfe decomposition and branch-and-bound search. In both sub-problems, time is measured considering ports (nodes) and the travelled distances (arcs).

3 CONTAINER STOWAGE AND SHIP ROUTING PROBLEM (CSSRP)

The Container Stowage and Ship Routing Problem (CSSRP), as far as we know, was first presented in Martins, Moura et al. (2010) and it incorporates both of the previous problems applied to cargo transfer using containerships.

Commonly, ships follow pre-determined fixed routes visiting ports in a sequence that, in many cases, is "circular", and carrying large amounts of cargo. In fact, as far as long distance transports are considered, this is probably the most efficient way since ports are apart.

On the other hand, as far as short sea shipping is considered, ports are much closer, cargo quantities can vary significantly as well as their origin and destination, and therefore, ship routing may affect the overcome profit of a journey.

3.1 Conceptual model

Assuming that in each port considered there are several containers each one with its origin, destination and time delivery constraints (deadlines and due dates). To transport them there is a fleet of ships

Table 1. CSSRP definition of variables, constraints and cost function characteristics

Input variables	Decision variables	Constraints	Cost function
- n° of containers		- to move a container all the ones above must be moved	
- container's origin			
- container's destination	- ship routes	- a container can only occupy a slot at the bottom, on a hatch, or above another one	- minimize transportation cost
- container's characteristics (weight, dimensions, etc)	- port visit sequences		- minimize port visit cost
	- container's location within the vessel	- vessel's carrying limit	- minimize harbor's containers shift cost
- distances between ports		- vessel's stability and weight distribution limits	
- n.° of ships			- minimize time at port
- ships' characteristics		- if cargo exists at a port, than it must be visited	

available, each one characterized with her own speed, cargo transport limitation (weight, stability, strength). Hence it is necessary to decide:

- how to select navigation routes for the fleet;
- how to distribute the cargo by the available vessels;
- how to stow cargo on each vessel.

The first two sub-problems are similar to the routing problem mentioned before, however in this case the transported cargo is not the same, and so route planning must take into consideration that each container has its own origin and destination, which must be taken into account when evaluating port sequence and may require multiple calls to each port.

Further it also has to consider the ports distances (arcs) and port (nodes). For each candidate route that arises from the previous step CSP must be solved. In other words, containers must be stowed taking into account the previous both the container's position constraints (motion constraints and slot constraints) and vessel's constraints (cargo limit, stability).

All of the above must be done aiming to reduce the net distribution cost, which is not only related with the vessel's operation and the visited ports' fees, but also to the costs of container handling in ports and the time the vessel stays at port to do so (minimize container's shifts at each port). Table 1 summarizes the characteristics of this problem from a optimization point of view.

Figure 1 is an example of the model application. One can see five ports (A,B,C,D,E) of which three of them have containers (each rectangle stand for x containers) to be delivered to the ports with the corresponding color within the time limit specified. To do so there are two ships (1- black, 2- orange) that can follow any route possible. In the figure two solutions are specified, where the 2-orange ship follows always the same route but 1-black ship can follow the dashed route or the filled route. Further, after selecting the route one must determine the cargo distribution that is not represented.
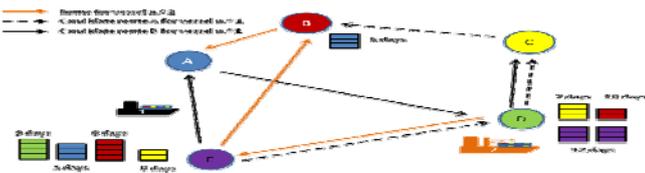

Figure 1. CSSRP graphical representation.

4 MATHEMATICAL FORMULATION

Having introduced the concept of CSSRP and characterised the optimization problem and all that is necessary to proceed with the formulation, then it will be presented in several sections, beginning to define the input, auxiliary and decision variables, the cost function, and finally the constraints to which the problem is subjected to.

4.1 *Input variables*

As mentioned before, the input variables are the ones that characterise the problem, i.e. cargo, vessels and ports. Therefore, assuming that:

$$\forall i, j \in P : i \neq j \qquad \forall k \in V \qquad \forall \phi \in \Phi$$

$$\forall \alpha \in C \qquad \forall (z_x, z_y, z_z) \in \Omega_k \qquad (1)$$

the following variables can be defined:

$G(P, A)$	A directed graph;
$P = \{1, ..., p\}$	G's set of nodes. The nodes 1 to p represent the ports that could be visited;
$A = \{(i, j) : i, j \in P, i \neq j\}$	
	G's set of arcs joint node i to j that represents a journey performed by a vessel;
$V = \{1, ..., k_{max}\}$	Set of vessels (k) that may be used;
$C = \{1, ..., \alpha_{max}\}$	Set of containers c were α_{max} is the total number of containers to delivery;
Ω_k	Matrix ($z_x z_y z_z$) of slots placed in vessel k. A slot is equal to 1 if it is possible to load a container and 0 if not;
$\Phi = \{1, ..., \phi_{max}\}$	Set of journeys (ϕ) for any vessel that represents the number of arcs (i, j) travelled by a vessel in a route.
d_{ij}	Arc length (i, j) corresponding to the distance between port i and j in miles;
$L_k, B_k, T_k, D_k, \Delta_k, GT, Q_k, s\_fuel_k$	
	Vessel's k characteristics: length, beam, draught, depth, displacement, gross tonnage, maximum pay load weight, specific fuel consumption;

vel_k	Vessel's k travel velocity (assumed constant);
q_α	Total weight of container α;
a_α	Deadline delivery time of container α;
$o_\alpha ; e_\alpha$	Origin and destination port of container α, respectively;
$l_\alpha, w_\alpha, h_\alpha$	Container α dimensions of container;
f_i	Port i fixed tariffs in Euros;
$r_{ik\alpha\phi}$	Cost of a movement (load or unload) of a container α placed in vessel k in port i and journey ϕ;
$b_{ik\alpha\phi}$	Time of a movement (load or unload) of a container α placed in vessel k in port i and journey ϕ.

4.2 *Auxiliary variables*

This set of variables is put together to help to understand the problem and make the constraints and cost function mathematical expressions easier:

$u_{ik\phi} = u_{crew} + u_{port}$	Visiting cost in Euros by time unit (hours) of vessel k at port i, during journey ϕ (includes crew's and taxes' costs);
$c_k = c_{fuelk} + c_{crewk}$	Cost travel operation (per unit distance, in Euros) of vessel k (includes crew's and fuel costs);
$\mu_{ik\alpha\phi} = 2 * r_{ik\alpha\phi}$	Total cost to shift a container placed in vessel k at port i during journey ϕ;
$\tau_{ik\alpha\phi} = 2 * b_{ik\alpha\phi}$	Total time to shift a container placed in vessel k in port i during journey ϕ, that depends of the time needed to perform a movement $b_{ik\alpha\phi}$;

$$Corig_{ik\phi} = \#\left\{ \alpha : o_\alpha = i \wedge \sum_{(i,z_x,z_y,z_z)}^{\Omega_k} \gamma_{ik\phi\alpha(z_x,z_y,z_z)} = 1 \right\}$$

Number of containers α to load in vessel k at port i during journey ϕ;

$$Cdest_{jk\phi} = \#\left\{ \alpha : e_\alpha = j \wedge \sum_{(i,j,z_x,z_y,z_z)}^{\Omega_k} \gamma_{ik\phi\alpha(z_x,z_y,z_z)} x_{ijk\phi} = 1 \right\}$$

Number of containers α to unload in vessel k at port i during journey ϕ;

$\beta_{ik\phi}$	Number of shifts performed by vessel k at port i during journey ϕ;

$$move_{ik\phi} = Corig_{ik\phi} + Cdest_{ik\phi}$$

Number of movements performed by vessel k at port i during journey ϕ;

$s_{ik\phi}$	Time at which vessel k arrives port i in journey ϕ;

$$t_{ik\phi} = \tau_{ik\alpha\phi} * \beta_{ik\phi} + b_{ik\alpha\phi} * move_{ik\phi}$$

Service time of vessel k at port i at journey ϕ.

4.3 *Decision variables*

As explained during the conceptual model discussion, there are two sets of variables:

$x_{ijk\phi}$	This is a binary variable that defines vessel k route. Equals 1 if vessel k visits port j immediately after port i in journey and 0 otherwise;
$\gamma_{ik\phi\alpha(z_x,z_y,z_z)}$	This is a binary variable that defines the container α position in vessel k. Equals 1 if, after vessel k leaves port i the slot $(z_x \, z_y \, z_z)$ is occupied by the container α and 0 otherwise.

4.4 *Cost function*

As mentioned before, and indicated in table 1, the aim of the problem is to minimize cost. In the formulation we incorporated into three main components, to which we are multiplying a cost, since it may be of interest of the decision maker to reduce a specific kind cost in future analysis. Hence, expression (2) adds up:

– the first component includes the operation cost between two sequenced ports and the fixed tariffs of the port which is visited;
– the second component includes the cost of containers' shifts (including crane maneuvers and time components);

– the third is the cost of loading/ unloading containers.

$$\min \ W_1 \sum_{i=1}^{p} \sum_{j=1 \wedge j \neq i}^{p} \sum_{k=1}^{v} \sum_{\phi=1}^{\phi_{max}} (d_{ij} c_k x_{ijk\phi} + x_{ijk\phi} f_i) \ +$$

$$W_2 \sum_{i=1}^{p} \sum_{k=1}^{v} \sum_{\phi=1}^{\phi_{max}} \beta_{ik\phi} \mu_{ik\phi} \ + \tag{2}$$

$$W_3 \sum_{i=1}^{p} \sum_{j=1 \wedge j \neq i}^{p} \sum_{k=1}^{v} \sum_{\phi=1}^{\phi_{max}} \sum_{\alpha=1}^{c} (Corig_{ik\phi} r_{jk\alpha\phi} + Cdest_{jk\phi} r_{ik\alpha\phi})$$

4.5 Constraints

To ensure that the solution found is viable, candidate solutions must comply with several constraints. The ones introduced in the model are the ones stated bellow; however, with further research there may be the need to introduce some others.

Expression (3) presents the flow conservation constraint that aims to ensure that if a vessel k arrives to port i then in the next journey he will part from that same port.

$$\sum_{i=1}^{p-1} x_{ilk\phi} - \sum_{j=2}^{p} x_{ljk\phi} = 0 \ , \quad i \neq j \neq l , \ \forall k \in V , \ \forall \phi \in \Phi$$

$$\tag{3}$$

Expression (4) guarantees that the port's service does not begin before the vessel arrives into the port. The service time depends on the time and distance travelled by the vessel and the summation of the service time in each previously visited port by the same vessel (if the actual port is not the first port visited). M1 is a Big-M constant.

$$s_{ik\phi} + t_{ik\phi} + d_{ij} \times vel_k - s_{jk\phi} \leq M_1 (1 - x_{ijk\phi}) \ ,$$

$$\forall i,j \in P \wedge i \neq j , \ \forall k \in V , \ \forall \phi \in \Phi \tag{4}$$

Expressions (5), (6) and (7) are related to the containers and their delivery obligations. The first guarantees that the containers deadline is not violated, the second one the weight capacity of the vessels is not exceeded, and the third guarantees that each container is transported by one and just one vessel between ports.

$$s_{ik\phi} \gamma_{(i-1)k\phi\alpha(z_x,z_y,z_z)} \leq a_\alpha$$

$$\forall i \in P, \forall k \in V ,$$
$$\forall \phi \in \Phi , \forall \alpha \in C , \forall (z_x,z_y,z_z) \in \Omega_k \tag{5}$$

$$\sum_{z_x,z_y,z_z} \sum_{\alpha=1}^{\alpha_{max}} q_\alpha \gamma_{ik\phi\alpha(z_x,z_y,z_z)} \leq Q_k$$

$$\forall k \in V , \ \forall \phi < \Phi , \forall i \in P \tag{6}$$

$$\sum_{z_x,z_y,z_z} \sum_{k=1}^{k_{max}} \gamma_{ik\phi\alpha(z_x,z_y,z_z)} = 1$$

$$\exists^1 i \in P , \ \exists^1 \phi \in \Phi , \ \forall \alpha \in C \tag{7}$$

Expression (8) binds the container loading variables to the vehicle routing problem variables, i.e. if a container is placed inside vessel k then that vessel has to visit the port to which the container is destined to go.

$$\sum_{z_x,z_y,z_z} \sum_{i=1}^{p} \gamma_{ik\phi\alpha(z_x,z_y,z_z)} x_{ijk\phi} \geq 1$$

$$j = e_\alpha , \forall k \in V , \forall \phi \in \Phi , \ \forall \alpha \in C \tag{8}$$

Expression (9) guarantees that if a slot is occupied with a container then all the slots below are also occupied.

$$\gamma_{ik\phi\alpha(z_x,z_y,z_z)} - \gamma_{ik\phi\alpha(z_x,z_y,z_z+1)} \geq 0$$

$$\forall i \in P , \ \forall \phi \in \Phi , \ \forall \alpha \in C , \forall (z_x,z_y,z_z) \in \Omega_k \tag{9}$$

5 DISCUSSION AND RESULTS

A simulation of the routing problem for five ports and two containerships (similar to figure 1 conceptual drawing) was solved using genetic algorithms (GA). Unfortunately, it was not yet introduced the container stowage problem into the solution though this work is underway.

The GA implementation was done using MATLAB ™, with its own standard crossover and mutation operators. As to encode possible solution was we defined chromosomes (set of genes) that incorporate the routes for all ships, as represented in figure 2.
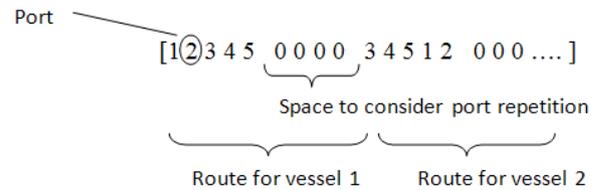

Figure 2. Chromosome creation.

Figure 3 presents the scenario used as example, where each rectangle stands for 100 containers distributed by the ports A to E , where at each port:

– 50% of the containers must be delivered to the port furthest away, 30% to next furthest, and 10% to each one of the other two ports;

- 80% of the containers have a deadline to be delivered of 15 days, 10% a deadline of 8 days and the last 10% a deadline of 20 days.

The containerships used for cargo transport are the vessels AXE and HEAVY that are based on two real ships, and in this scenario are assumed to be positioned at ports *A* and *C* respectively.
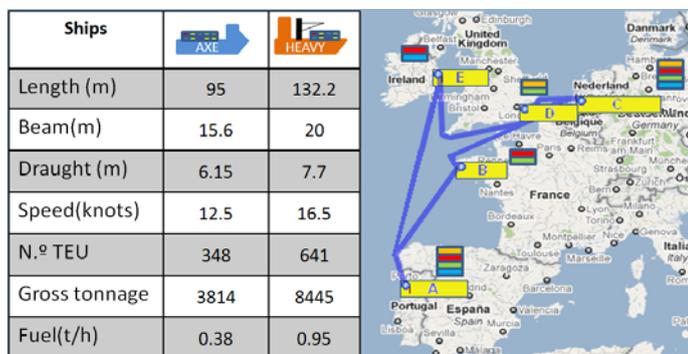

Figure 3. Scenario definition.

The results obtained with GA were promising. As table three shows, in only one round of visits to the ports is not possible to deliver all containers, and therefore more than one visit to each port was allowed. In such case, if a "circular" type strict route planning is used after nine port calls there are still 100 containers that were not delivered. On the other hand, if the ship's are allowed to change their routes as a function of cargo delivery needs, not only all containers were delivered but also only 68 containers in a total of 1400 containers surpassed their deadlines.

Containers distribution by ports			port A – 400 TEU port D – 200 TEU	port B – 200 TEU port E – 200 TEU	C – 400 TEU
	Ship	Route	Travelled miles	Time interval	Deadlines surpassed	Total cost
Circular type routes	Axe	A – B – C – D – E	No solution was found			
	Heavy	C – D – E – A – B				
	Axe	A – B – C – D – E – A – B – C – D	100 containers not delivered			
	Heavy	C – D – E – A – B – C – D – E – A				
GA solution	Axe	A – B – D – E – B – A – B – D – E	3134	315.5 h	68	634960
	Heavy	C – B – A – B – E – B – D – C	2653	236 h		

Table 2. Results comparison of different routes to deliver all containers specified in the exemple.

These results are probably not the optimal solution since Genetic algorithms not always provide the optimum solution and may be trapped in a local minimum of the solutions space. Nevertheless, it is better than most.

6 CONCLUSIONS

A new logistic model for the management of small fleets of ships used in Short Sea Shipping was proposed. This model dynamically assigns routes to ships, assigns cargo to them, provides an optimized stowage plan. This paper presents the full mathematical formalization of the problem, seen as a linear optimization problem. It also presents a genetic algorithm based solution to it, that proves to be very efficient. The proposed method was applied to a small problem to illustrate the details of the method and the improvement that can be achieved.

The results show that the proposed model is much more flexible than traditional models, and can provide better results.

7 REFERENCES

Ambrosino, D., A. Sciomachen, et al. (2006). "A decomposition heuristics for the container ship stowage problem." Journal of Heuristics **12**(3): 211-233.

Appelgren, L. H. (1969). "A column generation algorithm for a ship scheduling problem." Transportation Science **3**: 53-68.

Appelgren, L. H. (1971). "Integer programming methods for a vessel scheduling problem." Transportation Science **5**: 64-78.

Avriel, M., M. Penn, et al. (1998). "Stowage Planning for Container Ships to Reduce the Number of Shifts." Annals of Operations Research **76**: 55-71.

Botter, R. C. and M. A. Brinati (1992). Stowage Container Planning: A Model for Getting an Optimal Solution. *IFIP Transactions B (Applications in Technology)* B-5.

Brown, G. G., G. W. Graves, et al. (1987). "Scheduling ocean transportation of crude oil." Management Science **33**: 335-346.

Christiansen, M. and B. Nygreen (1998). "A method for solving ship routing problemswith inventory constraints " Annals of Operations Research **81**: 357-378.

Dubrovsky, O., G. Levitin, et al. (2002). "A genetic algorithm with a compact solution encoding for the container ship stowage problem." Journal of Heuristics **8**: 585-599.

EU_Comission (2001). White Paper on European Transport Policy for 2010: Time to decide. COM (2001) 317 Final, . Brussels, Commission of the European Communities.

Fisher, M. L. and M. B. Rosenwein (1989). "An interactive optimization system for bulk-cargo ship scheduling." Naval Research Logistics **36**: 27-42.

Martins, T., V. Lobo, et al. (2009). Container Stowage Problem Solution for Short Sea Shipping. 14º Congresso da Associação Portuguesa de Análise Operacional. Universidade Nova de Lisboa, Monte da Caparica.

Martins, T., A. Moura, et al. (2010). Genetic Algorithms approach for containerships fleet management dependent on cargo and their deadlines. IAME 2010 Annual Conference. C. Edições. Lisbon.

Medda, F. R., **E. Pels**, et al. (2010). Incentive mechanism for the development of short sea shipping. 2010 Annual conference of the International Association of Maritime Economists. Lisbon, Cargo Edições, Lda.

Vanherle, K. and E. Delhaye (2010). Road versus short sea shipping: comparing emissions and external costs. 2010 Annual conference of the International Association of Maritime Economists. Lisbon, Cargo Edições, Lda.

Wilson, I. D. and P. A. Roach (1999). "Principles of Combinatorial Optimization Applied to Container-Ship Stowage Planning." Journal of Heuristics **5**(4): 403-418(16).