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The time constrained multi-commodity network flow problem and its application to liner shipping network design

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ABSTRACT

The multi-commodity network flow problem is an important sub-problem in several heuristics and exact methods for designing route networks for container ships. The sub-problem decides how cargoes should be transported through the network provided by shipping routes. This paper studies the multi-commodity network flow problem with transit time constraints which puts limits on the duration of the transit of the commodities through the network. It is shown that for the particular application it does not increase the solution time to include the transit time constraints and that including the transit time is essential to offer customers a competitive product.

1. Introduction

According to IMO (2014) 90% of global trade is carried out via the sea, and ships flying EU flags emit more than 20 million tons of CO_2 (Maritime CO_2, 2014). Container Shipping involves the transportation of a major share of the worlds goods and has been steadily growing (with a small decrease around 2009 due to the economic crisis). Reliance on container shipping to transport goods internationally is only expected to increase due to its economic advantages compared to other transportation modes. Additionally, the CO_2 emissions per ton cargo transported using maritime transport is significantly lower than road and rail transport. Hence, even small improvements in the underlying network of a liner shipping company can have a significant impact, both economically and environmentally. Despite this, the *Liner Shipping Network Design* (LSND) problem has not received a lot of attention in the Operations Research literature and it is far from being a well-solved problem (Meng et al., 2014). Christiansen et al. (2004, 2013) provide comprehensive reviews of the literature published within the field of maritime optimization and liner shipping.

A liner shipping network consists of a number of rotations, which are round trips. It is common to have weekly departures at each port, hence a sufficient number of vessels are deployed to each rotation, to ensure the requested frequency. Fig. 1 shows an example of a real-world rotation. Different vessels have varying capacity and speed, and the transport of a commodity through the network may include the use of several rotations to connect between the origin and destination port. The switch from one rotation to another is referred to as *transshipment* and there is a cost associated with this since the container must be handled by the quay-cranes at the transshipment ports and possibly stored temporarily at the container yard. On top of this, the container will experience a wait time during the transfer process. Because of the associated cost and transit

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time and the risk of goods being damaged containers are at most subject to a few transshipments, when traveling from their origin to destination. The *transit time* is the time it takes a commodity to travel from origin to destination. Transit time is counted in days and allowed transit times may vary from one day to several months Brouer et al. (2014b). Liner shipping networks that are optimized only with respect to cost get an unrealistically high network utilization as containers are allowed on detours that offer unused capacity but in practice they will violate transit time restrictions.

Given a candidate network a multi-commodity network flow (MCF) problem is solved in order to decide, which of the available cargoes should be shipped on which routes. An extensive treatment of the MCF problem can be found in e.g., Ahuja et al. (1993). The MCF problem can be formulated as a linear programming problem which can be solved in polynomial time and there are many algorithms for solving it. One of these methods is by delayed column generation, see Desaulniers et al. (2005) and Ahuja et al. (1993). In order to include the transit time constraint one has to solve an extended version of the problem, the time constrained MCF problem, which is NP-hard. This is easily shown by reduction from the shortest weight constrained path problem (Garey and Johnson, 1979). (We transform this problem into a time constrained MCF by having only one commodity with source and destination as given by the shortest path problem.) This paper presents an algorithm for the time constrained MCF problem and given the LSND application several possible improvements are presented.

To the best of our knowledge, most algorithms for the LSND problem do not include transit time restrictions for shipped commodities. This paper studies the consequence of neglecting the transit time restrictions in existing networks. This is done by taking the networks produced by a LSND heuristic and comparing the estimated revenue with and without including the time constraint in the cargo flow calculations. The results show a substantial difference, and we therefore recommend that future LSND algorithms should include the transit time constraint if possible.

The remainder of the paper is organized as follows. In Section 2 we discuss the *level of service* in liner shipping and review relevant literature. In Section 3 we introduce the multi-commodity flow problem with time constraints and describe a delayed column generation procedure for solving it. Furthermore, we discuss a way to tailor the resource constrained shortest path problem, which arise as the sub-problem in the column generation process, in order to solve it efficiently. Section 4 describes a contraction scheme for the graph, which reduces the number of edges in certain instances of the graph to speed up the sub-problem computations. Section 5 introduces novel ways of modeling the transshipments to accommodate different network design model scopes. Finally, we conduct computational experiments in Section 6 and investigate the sensitivity of the travel time restrictions.

2. The level of service in liner shipping

Several factors such as price, transit time, transshipments, port coverage, frequency, reliability, administration, equipment, environmental friendliness and schedules can be relevant and important for a shipper when considering different carriers (Brouer et al., 2014b). Hence it is important to meet these constraints when constructing and evaluating liner shipping networks. The cost and transit time are often identified as the most important factors (Meng et al., 2014; Brouer et al., 2014b; Gelareh et al., 2010; Notteboom and Vernimmen, 2009; Notteboom, 2006), however, most previous work within LSND neglects transit time and mainly considers cost.

Designing networks with focus only on cost has the apparently attractive benefit that reducing cost goes hand in hand with reducing CO_2 emissions as fuel is the largest cost component. Reducing CO_2 emissions is an important goal of several governments, and it is generally attractive for carriers as well as shippers to have a green profile. Slow steaming is one common way of both reducing cost and emissions, but this requires a broader introduction of the level of service requirements in the network design models. There is an inherent trade off between reducing bunker consumption and thereby emissions through speed reduction and offering competitive transit times for commodities.

On the other hand, by offering a time competitive mode of transport more cargo will be transported this way, reducing the global CO_2 emissions. By introducing a maximum transit time for each commodity in the network, the number of

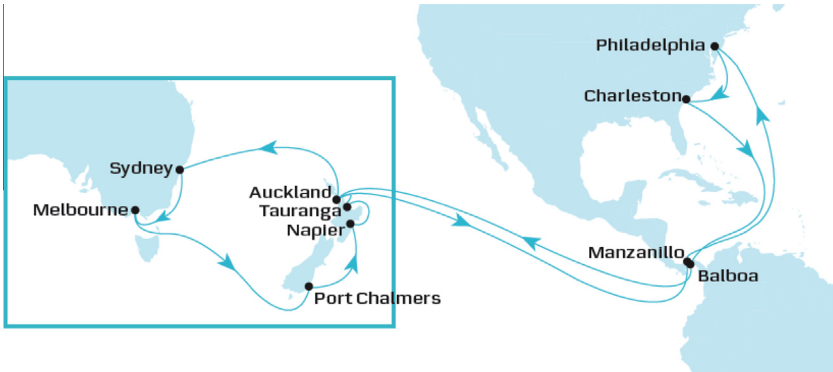

Fig. 1. An example of a sailing route (rotation) in the Maersk Line network, from Maersk (2014).