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A service flow model for the liner shipping network design problem

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ABSTRACT

Global liner shipping is a competitive industry, requiring liner carriers to carefully deploy their vessels efficiently to construct a cost competitive network. This paper presents a novel compact formulation of the liner shipping network design problem (LSNDP) based on service flows. The formulation alleviates issues faced by arc flow formulations with regards to handling multiple calls to the same port. A problem which has not been fully dealt with earlier by LSNDP formulations. Multiple calls are handled by introducing service nodes, together with port nodes in a graph representation of the problem, and by introducing numbered arcs between a port and a novel service node. An arc from a port node to a service node indicate whether a service is calling the port or not. This representation allows recurrent calls of a service to a port, which previously could not be handled by LSNDP models. The model ensures strictly weekly frequencies of services, ensures that port-vessel draft capabilities are not violated, respects vessel capacities and the number of vessels available. The profit of the generated network is maximized, i.e. the revenue of flowed cargo subtracted operational costs of the network and a penalty for not flowed cargo. The model can be used to design liner shipping networks to utilize a container carrier's assets efficiently and to investigate possible scenarios of changed market conditions. The model is solved as a Mixed Integer Program. Results are presented for the two smallest instances of the benchmark suite LINER-LIB-2012 presented in Brouer, Alvarez, Plum, Pisinger, and Sigurd (2013).

1. Introduction

When manufactured goods are transported from one corner of the world to another it is likely to happen in a container. These containers are carried by up to 400 meter long container vessels transporting tens of thousands of containers. Liner shipping carriers operating these vast vessels construct intricate networks of shipping routes that in their interaction provide fast and, relative to other transport modes, cheap transport that operate at the core of the worlds supply chains.

A global container shipping network is extremely costly to operate, with Maersk Line using a two-digit billion USD amount yearly for this purpose. Therefore, even a small improvement of the network's utilization, costs, service levels, etc. can have a significant impact. At the same time the cost structure of the network can be very volatile; by developing models that can investigate an increased cost or reduced demand, the network can rapidly be modified to adapt for these changed market conditions.

The basic cost components of a container shipping network are: vessel costs, bunker fuel costs, port call fees and container move costs in ports. These have been very volatile in the past years, with fuel costs reaching record levels in 2008, to fall again during the financial crisis, followed by a rise in prices during the later recovery (Bunkerworld12, 2012). Vessel charter rates are similarly fluctuating and have fallen dramatically as the financial crisis hit world trade (TCCBS09, 2009). Furthermore, there is an increasing interest in limiting CO2 emission, related to the fuel consumption. This is already an important aspect of a shipping line company's public profile, which is expected to have increased focus in the years to come. All these factors add to the importance of liner shipping network design. This paper presents a novel model of the *Liner Shipping Network Design Problem* (LSNDP).

A liner shipping network consists of a number of *services*, each service being a roundtrip sailed by a fixed number of vessels, much like a bus transit network. These services are able to tranship containers between each other at ports. Each port to port sailing by a service is denoted the service's *legs*. Each port call on the roundtrip will be served at a fixed frequency, predominantly weekly (as a bus route served every 20th minute), by a vessel. To utilize vessels best possible, service roundtrip times are thus generally a multiplier of 7 days.

These services constitute the network, through which the *demand* should be flown. Each demand is a fixed weekly volume of containers requiring transport from a specified origin to a

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specified destination. The demand will pay a revenue for being served, but it is acceptable to leave some demand at the cost of paying a goodwill penalty. The path of the demand will incur additional cost for moving containers on and off the vessels. The goal is then to construct a liner shipping network, consisting of some services, allowing for the transport of containers, with the aim of maximizing the profit of operating the network, e.g. the revenue subtracting costs for services, moving containers on and of vessels (*move cost*) and goodwill penalties.

In the proposed model, services are constructed by opening links from each service (the number of considered services being fixed) to a number of ports, using specialized service-port arcs. This can be reconstructed to a service traversing between the ports, using auxiliary variables. Likewise, the demands will flow from origin port to a service and from a service to destination port (or transhipment), on specialized service-port arcs. The specific port to port path can be reconstructed using auxiliary variables. As compared to LSNDP models of related problems this model has the advantages of allowing non-simple cycles with any number of calls to one or more *butterfly ports*. Services with one or more butterfly ports is often denoted *butterfly routes*, such routes are usefull in service design for different reasons:

- Increased capacity on the legs between the butterfly port calls, as the service will carry less cargo on these legs. This capacity can be used for other cargo. E.g. in Fig. 1 more capacity will be available between the first and second call to port A, as exports from A to region X are not carried here, but instead are lifted in the second call to A. An example could be Singapore as a butterfly port on a Europe to North Asia/Japan service.
- Two services with non-weekly frequency can be combined to a service with weekly frequency. E.g. Let D, E, F be some given ports, then service 1 calling ($D \to E \to D$) with a 4 day roundtrip time and service 2 ($D \to F \to D$) with a 10 day roundtrip time, can be combined to a service 3 ($D \to E \to D \to F \to D$) with a 14 day roundtrip time and thus satisfying the weekly frequency requirement, by allowing butterfly calls at port D.
- Draft limits at later ports may require that the vessel is eased before port call, a butterfly port call will alleviate this on port calls in between.
- Improving transit time, as the extra port call will allow for faster imports or exports to remaining ports on the service. E.g. in Fig. 1 exports from port A to region X will be faster with butterfly calls.

Note that draft dependent on vessel load and transit time is not considered in the present model, but still it is a cause for using butterfly routes. Thus it is important for a LSNDP model, to accurately model butterfly port calls (see Fig 2).

LSNDP is a strategic problem, where network design decisions are made on a 6–12 months time horizon, subject to amendments at a later stage. One concern with the LSNDP is that all demand is considered deterministic, with a fixed demand between the worlds ports every week. This assumption is far from reality, as container demand is subject to large fluctuations from week to week. However, a deterministic approach is still relevant, as the demand on an aggregated level gives a more stable picture. E.g. when looking at demand from continent to continent, the forecasts will be more accurate. A deterministically designed network can to some degree be corrected by short term amendments to vessel schedules, using third party tonnage or rolling cargo to the next sailing. An alternative approach to formulate liner shipping network design problems could be a stochastic approach. However, stochastic models generally greatly add to the complexity compared to deterministic models. As the deterministic version of LSNDP is very hard to solve, it is unlikely that a stochastic approach will scale to anything reasonable, hence this approach has not been investigated.

This *service flow model for the liner shipping network design problem* will be abbreviated SFM.

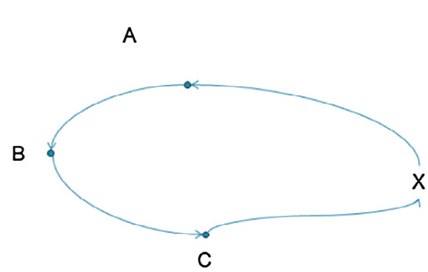
The model has been implemented as a MIP, solved by a commercial solver. Results are reported on data from the LSNDP Benchmark instances LINER-LIB-2012 (Brouer, Alvarez, Plum, Pisinger, & Sigurd, 2013).

1.1. Overview of the paper

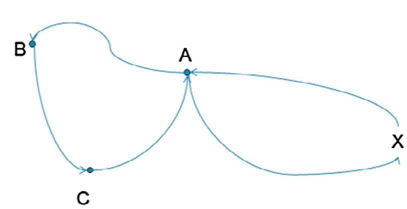
Relevant literature is introduced in Section 2. In Section 3 we introduce the mathematical notation used in the paper and explain details on the problem structure. The concept of service flow is central for this paper and explained in detail in Section 3.1. This is used to formulate a model for the LSNDP in Section 3.2. This MIP model has been implemented and solved with a commercial solver. Computational results are reported in Section 4, with the key contributions of providing solutions for two instances of LINER-LIB-2012, while considering operational constraints as capacity, port draft and butterfly ports, which no method previously has. We conclude on the paper in Section 5 and discuss directions for future research.

2. Literature

In this section we summarize the literature related to the considered problem. For a general introduction to the maritime industry please refer to Stopford (2009). For a review of research in maritime optimization refer to Christiansen, Fagerholt, and Ronen (2004) and Christiansen et al. (2007). For a detailed introduction to liner shipping network design and details on the structure of the liner shipping business, its operational requirements and cost structure we refer to Brouer et al. (2013). A recent overview of



(a) A part of a service departing from a region X, calling ports A, B and C once each, then returning to region X.



(b) A part of a service departing from a region X, calling ports A, B, C and A again, then returning to region X. A Butterfly service with A as a *butterfly port*.

Fig. 1. Examples of two services with and without a *butterfly port*.