An iterative tabu-GRASP based heuristic for the Feeder Network Design Problem

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1. Introduction.

The liner shipping industry is a vital part of the global economy, as it constitutes one of the cheapest and most energy efficient modes of cargo transport. Today, the vast majority of international trade is transported by container vessels. One of the main feature in liner shipping is the operation of *services*, i.e. cyclic itineraries of ports sailed by a number of similar container vessels. Liner shipping organises the shipping network as *hub-and-spoke* networks. Ports are divided by regions, and each region typically has a few large ports, called *hubs*, and many smaller ports, called *spokes* or *feeder ports*. Large vessels mainly visit hub ports, where they pick-up and delivery all the containers associated to the hub. From the hubs, smaller vessels operate feeder lines, where the containers are transported to the feeder ports. Hence, it is of utmost importance to have an efficient feeder network for the small vessels in order to better utilise the overall shipping network.

2. Problem Statement.

We study the *Feeder Network Design Problem* (FNDP). This problem arises from the planning of services for a fleet of container vessels in regional feeder networks. Given a collection of ports, a group of origin-destination demands and a heterogeneous fleet of container vessels, the task consists in designing a set of services for the fleet so that all demands can be routed through the resulting network, while respecting the capacity of the vessels and the maximum transit times of the demands. The *objective* is to maximise the total revenue for transporting the demands and the minimisation of the overall operational expenses for serving the shipping network. We assume that all services operate at *constant speed*, and maintain a *weekly service frequency*. Furthermore, each service must depart from, and return to, the single *hub port*. The remaining ports are denoted as *feeder ports*. Each feeder port has associated at most two origin-destination demands: the *loading* and the *discharge* demands. Moreover, the problem assumes *splittable demand* at each feeder port.

Therefore, according to Berbeglia et al. (2007), the FNDP can be characterised as a variant of the one-to-many-to-one pick-up and delivery problem with combined demands. Furthermore, in case that serving the demand is not profitable, the demand can be *rejected*. Since the problem is a generalisation of the *Vehicle Routing Problem with Simultaneous Pickup and Delivery Problem* (VRSPDP), it is $\mathcal{NP}$-hard to solve.

3. Solution Approach.

Among the most common algorithms used in literature to solve shipping network design problems, the *two-stage algorithms* stand out (Christiansen et al. 2019). During the *first stage*, the service network is constructed. In our implementation, we only consider the deployment and operational costs of the services. Instead of working with full services, we work exclusively with simple routes, i.e. non-complex cyclic itineraries of ports. The services are then constructed using a grouping heuristic on the set of simple routes, based on a set partitioning formulation. The service structure is not limited to simple or butterfly services (where a single port is visited twice in the service), but to a general service structure where the hub port can be visited several times. Next, the *second stage* solves the container flow problem and evaluates the resulting network. As we forbid transshipment operations, we can efficiently formulate this problem as a *Linear Programming* (LP) model. The decision variables denote the amount of demand loaded or discharged at the specific ports of the simple routes, the constraints ensure that the capacity of the vessels is respected throughout the services, and the objective function maximises the total revenue of flowing the demand.

We develop a tabu-GRASP based heuristic (Feo and Resende 1989) to solve the FNDP, where the two-layer structure is embedded in an iterative heuristic framework. At each iteration, we construct a new solution using a randomized greedy algorithm, which is further improved by a local search algorithm. During the construction phase, we randomly select a port from a restricted candidate list. The ports in the list are sorted by the current potential revenue, which indicates how much revenue may be gained by adding a port into the current network. To control the randomness in the selection process, the ports are selected according to some probabilities based on the value of the current potential revenue. Next, the candidate port is inserted in the current solution through a best insertion algorithm. We either insert the port in the best position of an existing simple route or we open a new single simple route for the port. At each insertion attempt, the service network is constructed (First Stage), and the resulting network is evaluated by solving the container flow problem (Second Stage). This process is repeated until no more ports can be added in the current solution. Furthermore, to promote diversification in the search, we provide the heuristic with a tabu mechanism for not replicating the same solution several times at each iteration. Finally, in a post-processing phase, we adapt the operating speed of a service to the lowest allowable speed while

maintaining the same weekly frequency and respecting the transit time limit of all transported cargo.

4. Computational Results.

To test the performance of the tabu-GRASP based heuristic, we consider the benchmark suite *Liner-Lib*, presented by Brouer et al. (2013). The instances are based on real-life data and contains relevant data information for shipping network design problems. We consider the two single hub instances (*Baltic* and *WAF*), and some adapted instances from the multi-hub instances from the benchmark suite (*MedTangier*, *MedTauro* and *MedAlg*). Table 1 summarises the results and reports the weekly profit of the obtained solutions (**Z**) in k\$, the transported demand (**F**) in percentage, and the CPU time (**T**) in seconds. The heuristic provides a robust average performance, returning overall profitable solutions with high values of transported demand. Furthermore, we consider three solution approaches that have studied the same problem under similar assumptions: Karsten, Brouer, and Pisinger (2017), Karsten et al. (2017) and Koza, Desaulniers, and Ropke (2020). Although all instances present different size scenarios, we only compare the results for the *base scenario*, since it is the only scenario considered by the current methods in the literature. Table 2 summarises the main assumptions and reports the results from the comparison. From the results, we can see that the tabu-GRASP based heuristic is competitive, both in time and solution quality with respect to the results from the current state-of-the-art methods. The heuristic approach reports the best results from the instances within reasonable CPU times. In particular, we can see that even though some assumptions have been simplified (such as constant speed in services and forbidding the transshipment of cargo), the heuristic approach finds better quality solutions in short times.

5. Conclusions.

During the recent years, a number of decision support tools for liner shipping network design have been presented in the literature. However, these results are difficult to use for feeder lines. As the size of the service network for feeder lines is often much smaller, different specialised algorithms can be developed to design this type of shipping networks. Due to the intrinsic interaction between the liner and feeder lines, a well-working feeder network is paramount. The overall shipping network can benefit from the potential advantages of the feeder network. Hence, feeder networks need fast solutions times, since the routes are frequently changed to adapt to the schedule/demands from the larger vessels. We investigate the shipping network design under a feeder line structure, and propose an efficient tabu-GRASP based heuristic to solve the FNDP. The heuristic is able to generate high profitable shipping networks in relatively short times. To compare the performance of the proposed approach, the heuristic was tested on the single hub instances from the *Liner-Lib* benchmark suite.

Instance		Baltic			WAF			MedTangier			MedTauro			MedAlg		
Scenario		Low	Base	High	Low	Base	High	Low	Base	High	Low	Base	High	Low	Base	High
Z(k\$)	Best	-159	293	381	5,063	6,134	6,547	30,319	32,507	32,745	13,649	15,353	15,558	-4,018	-3,143	-2,647
	Average	-159	293	381	4,953	6,111	6,547	29,566	32,367	32,648	13,503	15,305	15,531	-4,074	-3,189	-2,746
F(%)	Best	83.3	92.1	94.7	95.1	97.0	97.0	94.3	99.4	99.4	92.0	99.7	99.7	65.5	77.6	85.6
	Average	83.3	92.1	94.7	94.5	96.8	96.9	92.1	99.3	99.4	91.2	99.7	99.7	64.5	77.2	82.62
T(s)	Best	32.2	39.5	45.6	294.3	347.9	353.1	200.2	267.0	316.6	325.5	357.7	411.6	350.6	522.3	876.3
	Average	31.2	36.7	43.4	293.2	354.7	353.3	200.2	268.5	330.4	318.1	363.7	423.4	348.2	508.1	888.9

Table 1 Comparison results for the single hub instances from the Liner-Lib benchmark suite.

Assumptions	Tabu-GRASP heuristic			Karsten, Brouer, and Pisinger (2017)			Karsten et al. (2017)			Koza, Desaulniers, and Ropke (2020)		
Transshipment times	No			48h			48h			48h		
Service leg speed	Constant			Variable			Constant			Variable		
Service structure	General			Butterfly			Butterfly			General		
Instance	**Z**(k\$)	**F**(%)	**T**(s)	**Z**(k\$)	**F**(%)	**T**(s)	**Z**(k\$)	**F**(%)	**T**(s)	**Z**(k\$)	**F**(%)	**T**(s)
Baltic												
Best	293	92.1	39.5	5	87.9	144	14	87.4	101	284	92.1	900
Average	293	92.1	36.7	-17	85.1	115	-74	86.7	108	159	90.5	900
WAF												
Best	6,134	97.0	347.9	5,480	97.6	362	5,590	97.0	255	6,000	96.7	3,600
Average	6,111	96.8	354.7	4,890	91.7	396	4,870	94.3	354	5,780	96.2	3,600

Table 2 Comparison results for the single hub instances from the Liner-Lib benchmark suite.

The results reported competitive results with the current state-of-the-art methods for shipping network design problems, outperforming the methods on both solution quality and computational times. Furthermore, one interesting insights from the results is that better solutions can be obtained by simplifying some assumptions. The heuristic approach can return overall best known solutions when transshipment operations are omitted, as opposed to other methods from the literature.

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