THE CONTAINERSHIP FEEDER NETWORK DESIGN PROBLEM: THE NEW IZMIR PORT AS HUB IN THE BLACK SEA

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ABSTRACT

Global containership liners design their transportation service as hub-and-spoke networks to increase the market linkages and reduce the average operational costs by using indirect connections. These indirect connections from the hub ports to the feeder ports called feeder networks are serviced by feeder ships. The feeder network design (FND) problem determines the smallest feeder ship fleet size with routes to minimize operational costs. Therefore, this problem could be described as capacitated vehicle routing problem with simultaneous pick-ups and deliveries with time limit. In our investigation, a perturbation based variable neighborhood search (PVNS) approach is developed to solve the FND problem which determines the fleet mix and sequence of port calls. The proposed model implementation has been tested using a case study from the Black Sea region with the new Izmir port (Candarli port) as hub. Moreover, a range of scenarios and parameter values are used in order to test the robustness of the approach through sensitivity analyses. Numerical results show that the new Izmir port has great potential as hub port in the Black Sea region.

Keywords: Maritime transport, feeder network design, variable neighborhood search

1 INTRODUCTION

The construction and introduction of mega containerships on the main international sea routes connecting major seaports gave rise to the need for containers to be stored up and distributed in a specific region. In conceptual terms, the feeder service is meant to collect containers from specific regions with feeder ships and feed large trunk container ships as to avoid their calling at too many ports (Multi Port Calling - MPC). It was the containership feeder shipping line that made the entire container service economically rational, efficient and more profitable, consequently cheaper and timely for the end users (Rudic and Hlaca 2005).

Regional feeder shipping lines have critical positions on the global hub-and-spoke (H&S) networks of shipping lines. Figure 1 shows two main feeder shipping systems: direct feeder shipping between hub and feeder port and indirect feeder shipping via line-bundling loops including more than one feeder port (Wijnolst et al. 2000). The first strategy has the lowest transit time but typically requires more feeders and smaller feeder containerships. Alternatively, indirect feeder shipping benefits from economies of feeder containership size, but incur longer distances and longer transit times. The feeder network comprises ships visiting a number of ports along the predefined lines of feeder ports in the region. The container feeder network design depends on the characteristics of feeder ships, characteristics of feeder ships ports, container demand and supply volumes of the ports and bunker costs as well as the operating/chartering/administration costs of the ships.

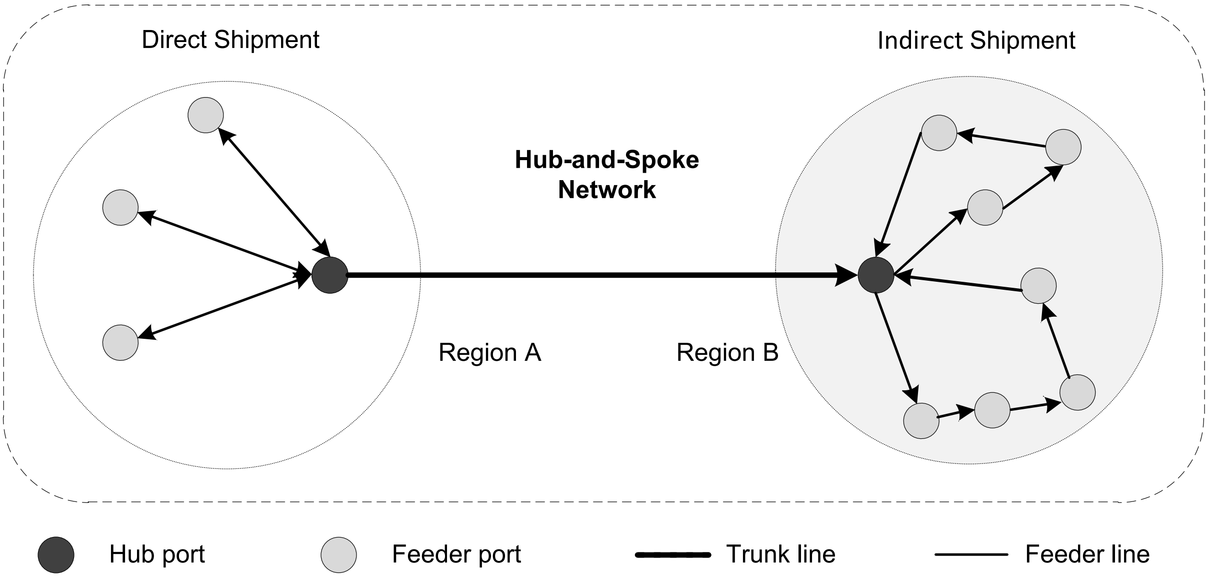

Figure 1. Feeder shipping networks as part of Hub-and-Spoke network

The problem considered is that of designing the network of indirect feeder containerships for feeder lines. In this problem assuming that a fleet of feeder capacitated container ships starting from the hub port would perform simultaneous container pickups and deliveries between hub and feeder ports under ship due date constraints for returning to the hub port at minimum cost for feeder containership liners.

Since container shipping involves considerable capital investments and huge daily operating costs, the appropriate containership feeder network design will affect the development of feeder containership liners. In this study, we focus on the potential hub role of a new port (Candarli) in the East Mediterranean and Black Sea region and develop an approach that deals with the feeder network design problem. The results are compared with current transshipment hub ports in the region. Due to the complexity of the problem, a perturbation based variable neighborhood search approach is proposed.

The remainder of this study is structured as follows. In the next section, a brief review of the relevant literature with a focus on liner network design is given. In Section 3, we present a model formulation for feeder network design problems. Next, a heuristic solution procedure is proposed. Section 5 summarizes the case study and service scenarios. Detailed numerical results are presented in Section 6. Finally, conclusions are drawn and suggestions for further research are given in Section 7.

2 LITERATURE REVIEW

Planning of container liner shipping operations has become a popular topic of academic research worldwide. Hence, a huge amount of papers has been published focusing on different planning aspects of container liner shipping (see Christiansen (2004), Notteboom (2004) and Kjeldsen (2008) for comprehensive reviews).

Only a few researches have been published which consider H&S operations with origin to destination (O-D) transportation processes as a whole. Takano and Arai (2009), Gelareh (2010), Gelareh and Nickel (2011) and Gelareh and Pisinger (2011) presented an approach for a H&S network with direct feeder services for container transportation. For a fixed number of hubs, their model determines the best network configuration of hub locations and direct shipment allocations for feeder ports that minimize the total costs of the system. In addition, Yang and Chen (2010) and Zacharioudakis et al. (2011) presented a genetic algorithm approach to optimize the combination of trunk and indirect feeder line networks for a shipping company. In the papers by Jin et al. (2005), Sun and Li (2006), Wang (2008), and Lu and Meng (2011), the authors proposed heuristic approaches to solve the containership routing problem with H&S operations by minimizing total costs.

For direct feeder shipping, Baird (2006) presented a methodology for evaluating and comparing hub ports in Northern Europe. Direct feeder shipping costs for current hub locations and a new proposed hub port in the Orkney Islands are compared. Ng and Kee (2008) evaluated optimal containership sizes of direct feeder services by using simulation models in Southeast Asia from the perspective of carriers.

Only a few researches have been published which consider the indirect feeder network design. Mourao et al. (2001) proposed an integer linear programming model for the assignment of ships to current indirect feeder routes. Catalani (2009) proposed a cost-minimization based expert system model for sequencing and scheduling of feeder ports for just one containership route in the Mediterranean area. Andersen (2010) proposed a mathematical model for service frequency requirements of predefined solid indirect liner feeder networks. The authors developed decomposition based heuristic approaches in order to solve the problem. Sambracos et al. (2004) presented a case study to dispatch small containers via coastal freight liners from a hub port to Greek island ports. Authors tried to minimize total operating cost including fuel consumption and port charges with a homogeneous ship fleet by meeting container shipment demand. Karlaftis et al. (2009) generalized a small container dispatching problem by minimizing total travel distance with simultaneous container pick-up and delivery operations and time deadlines constraints. They proposed a genetic algorithm (GA) based solution heuristic in order to solve the problem with soft time limits which tolerates violations of certain constraints.

3 THE FEEDER NETWORK DESIGN PROBLEM

The FND problem is given as follows. A set of feeder ports is located on a distribution network where feeder ports require both delivery and pickup operations. Each feeder port has to be served once for both operations with a given fleet of identical capacitated feeder ships. Each ship leaves the hub port carrying the total amount of containers it has to deliver and returns to the hub port carrying the total amount of containers it must pick-up. Each port (feeder/hub) also has a specified operation efficiency for loading and unloading containers to ships at the ports. The service time of the ports depends on port operation efficiency, ship sizes, the amount of loading and unloading containers and pilotage time for entering/exiting the port. Therefore, the total voyage duration of a ship is the sum of total travel time of the route and total service time of the hub and feeder ports. In order to determine the ship schedules and the staffing balance, each vessel has to finish its voyage before the maximal allowed duration is reached (the voyage starts in the hub port with commencing the loading operations to ships and completing the unloading operations from ships at eh hub port). Before starting a new voyage, each ship needs a lay-up interval for repair, cleaning, waste disposal etc. Total ship travel duration includes total voyage, lay-up and idle times. According to these considerations the FND has similarities with the *"vehicle routing problem with simultaneous pick-up and delivery with time limit"* (VRPSPDTL).

The FND problem aims to serve all contracted feeder ports by minimizing total operational costs in the planning period. For a feeder network provider, operational costs for the planning period include containership related fixed costs for the necessary number of ships (chartering/capital, operating, administration) and total service related variable costs (on sea bunker cost, on port bunker cost, port charges). Table 1 shows the related basic cost calculations.

Table 1. Basic calculations of total costs during the planning period

Parameter	Basic formulation
Total cost	Fix cost + Variable cost
Fix cost	Number of necessary ship ∗ (Chartering + Operating + Administration costs)
Variable cost	Number of service ∗ (Bunker (sea) + Bunker (port) + Port charges)
Number of necessary ship	ceil ((Voyage duration +Lay-up duration) / service frequency)
Number of service	Planning period / Service frequency
Voyage duration	On sea duration + On port duration (feeder) + On port duration (hub)
Idle duration	Number of necessary ship ∗ Service frequency − (Voyage + Lay-up duration)
Ship total duration	Voyage duration + Lay-up duration + Idle duration

Since our investigation is concerned with the design of a real world container feeder network, some assumptions have to be made in order to exclude elements of minor relevance and to focus on those aspects that are of paramount interest. Major assumptions of our model are the following: all parameter values are deterministic (no weather and seasonal effects), no direct delivery between feeder ports, queue time at ports is not considered, feeders' demand as well as feeders' container supply amounts cannot be divided, ship types are identical according to their carrying capacity, unlimited number of ships from each type, port handling and bunker costs are the same in all ports, there are no owned ships, fixed schedules and sailing frequencies for containerships are assumed. Vessel speed/fuel cost effect as well as straight/canal durations and costs are not considered. Container related costs are not included, since they have a given effect on the total cost.

4 THE PROPOSED METHODOLOGY

Exact methods for solving the FND problem are not practical for large problem instances because of the problem complexity. In this study, we therefore propose a perturbation based variable neighborhood search (PVNS) approach which applies the Savings Algorithm (SA) in order to gain a fast and effective initial solution. The PVNS is embedded with variable neighborhood search (VNS) to improve the initial solution by searching neighborhoods. In order to escape from local optima, an adaptive perturbation mechanism (APM) is developed.

The initial solution is constructed by means of the Savings Algorithm of Clarke and Wright (1964). This classic heuristic aims at merging sub-tours based on costs savings which can be achieved by combining two sub-tours to be served by one vehicle. In the literature, some enhancements of the Clarke and Wright savings algorithm have been suggested by adding new terms and parameterizing the savings formula. In this study, we use the savings formula proposed for the capacitated vehicle routing problems by Altinel and Öncan (2005).

Afterwards the initial solution is evaluated with a VNS improvement algorithm. The VNS, which is based on the idea of systematically changing the neighborhoods in order to improve the current situation, was introduced by Mladenović and Hansen (1997). VNS aims to explore the solution space which cannot be searched by local search. *Shaking*, *local search* and *move or not* operators are used in the implementation of the VNS. The shaking operator defines the search direction of the VNS by using the set of neighborhoods. The chance of reaching a global solution improves when combining the shaking operator with local search rather than using a single shaking operator. Therefore, each solution obtained through the shaking operator is used in the local search operator in order to explore promising new neighborhoods of the current solution. In this study we implemented the variable neighborhood descent (VND) algorithm as the local search operator. The VND aims to combine the set of neighborhoods in a deterministic way, since using more than one neighborhood structure could obtain a better solution (Hansen and Mladenović 2001).

In this study, a set of N [N1: 3-opt, N2: swap, N3: insertion, N4: 2-opt, N5: Exchange (m,n), N6: Cross, N7: Shift (0,1), N8: Replace (1,1)] neighborhood structures is employed in a deterministic order as shaking and local search operators. To avoid unnecessary movements, only feasible movements are admitted, i.e. those that do not violate the ship capacity and total duration limit of the route. Also, a reversed version of the routes which violate the vehicle capacity is applied, if the total delivery and pick-up amounts of the route are feasible.

The temporary solution which is obtained after the shaking and local search operators are applied is compared with the current solution in order to decide whether to *move or not.* In the proposed VNS and VND, the acceptance criterion of the temporary solution accepts only improvements. This procedure, however, could simply stick the search to a local optimum. Therefore, it is necessary to employ a strategy of accepting non-improving solutions. Perturbation is an effective strategy used to jump out of the local optimum and to search a new promising region. In this study, a novel perturbation method called adaptive perturbation mechanism (APM) is developed. This perturbation mechanism runs after a number of non-improving iterations counted from the last improving solution. In the APM, a set P_x [P_1: *double replace*, P_2: *double cross*, P_3: *triple shift,* P_4: *triple replace*, P_5: *triple cross*] perturbation structures is randomly run whenever the perturbation is called. In addition to the perturbation move, a local search with five previously defined intra-route neighborhood structures is applied in order to improve the perturbed solution quality, which is essential since a perturbation move satisfying the vehicle capacity and total route duration limits is always accepted. Moreover, violating moves are accepted only if the total route duration and ship capacity are below an acceptance limit (α). However, just one of the routes is allowed to use this violation and the travel duration of this route is punished with a very big penalty cost. This rule gives routes a potential improvement chance in the shaking and local search phase. The new developed perturbation structures for the APM are defined as follows:

Double Replace (P_1) is a combination of two times sequential *Replace (1,1). Double Cross* (P_2) is a combination of two times sequential *Cross* exchange. *Triple Shift* (P_3 is a combination of two times sequential *Shift (0,1)* movement between three routes. *Triple Replace* (P_4) is similar to *Triple Shift* by using the *Replace (1,1)* movement. *Triple Cross* (P_5) is similar to *Triple Shift* by using the *Cross* exchange structure.

5 CASE STUDY

The fact that the region is surrounded by several seas – the Black Sea, Mediterranean Sea, Adriatic Sea, Ionian Sea, Aegean Sea, and Marmara Sea – makes maritime shipping a prime area for growth going forward (see Figure 2). Container feeder shipping lines offer critical transport connections between the hinterland of this region and global trunk shipping lines. The feeder shipping dynamics of the region are mainly related to container transportation volumes of the trunk shipping lines between Far East and Europe. In recent years, parallel to the increase of container transportation volumes between Far East and Europe, an increase on the total container handling volume is observed in the regional feeder ports. The hub ports in the East Mediterranean area have a direct effect on the increasing importance of feeder lines in the region by serving as direct link to trunk lines. Thus feeder lines enhance the opportunity to attract more cargos in the region and ensure high capacity utilization (Varbanova 2011).

Turkey's ideal location between Asia and Europe gives its ports a competitive advantage and opportunity to develop into major transshipment hub ports. In this regard, Turkey has significant potential and several projects for the development of intermodal transport. One of these projects is the construction of a hub port in Izmir's Candarli district, in order to improve Turkey's hub port potential. In this region, the potential market areas of Candarli as a hub port could be categorized into four sub-regions: the Black Sea, the Sea of Marmara, the East Mediterranean sea and, the Aegean Sea.

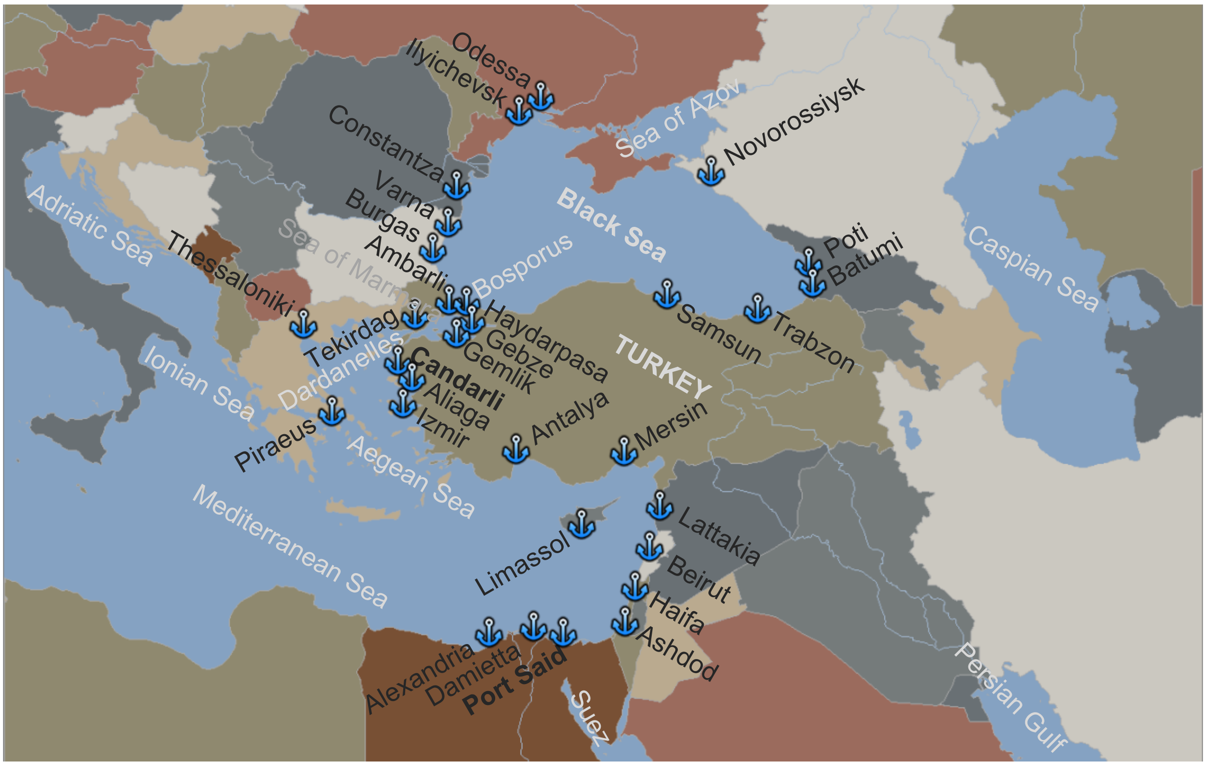

Figure 2. Regional feeder and hub ports

In this region, 38 container terminals at 28 feeder ports are served via a hub port for a feeder liner shipping company with 3680 TEU total daily demand and 2440 TEU total daily supply amount. The feeder liner currently designs its existing feeder network with a hub port of Port Said in North Egypt. However, after establishing Candarli as a new hub port alternative, feeder liner should reconsider its current feeder network. Therefore, in this study two different service scenarios are defined for the region. *The first scenario* is the current situation. Port Said serves as trunk hub port to feeder ports of the region. In *the second scenario* Candarli serves as trunk hub port to all feeder ports of the region for feeder liners. The scenarios are also tested under different time deadline and service frequency conditions for a 52 week planning period. The major cost items and ship costs for three ship types are shown in Table 2.

Table 2. Model costs and parameters

Parameter	Unit	Ship1	Ship 2	Ship 3
Capacity	TEU	4300	2600	1200
Operating speed	(knots)	22.60	19.90	17.40
Fuel consumption (on sea)	(tons/hour)	5.26	2.82	1.51
IFO 180 price (on sea)	($/ton)	647.50	647.50	647.50
Fuel consumption (on port)	(tons/hour)	0.26	0.14	0.08
MGO price (on port)	($/ton)	890.00	890.00	890.00
Charter cost	($/day)	12772.00	7579.00	5866.00
Operating costs	($/day)	6000.00	5707.00	4643.00
Administration cost	($/day)	552.00	3180.00	1380.00
Port charges	($/call)	35000.00	29000.00	22000.00
Handling cost (feeder port)	($/llift)	120.00	120.00	120.00
Handling cost (hub port)	($/llift)	120.00	120.00	120.00
Lay-up time (hub port)	(hour/call)	28.80	24.00	16.80
Pilotage time (all ports)	(hour/call)	2.00	1.80	1.50
Planning period	Days	364	364	364

Sources: Stopford (2009), VHSS (2012), BunkerIndex (2012)

6 NUMERICAL RESULTS

The proposed PVNS algorithm is coded using Matlab R2010b/Visual C# 4.0 and executed on an Intel Core 2 Duo T5750 2.0 GHz processor with 3 Gb RAM. As part of preliminary studies, experiments on the sequence of the shaking operators of the PVNS algorithm were conducted in order to determine the most effective sequence of the local neighborhood search set. The results demonstrated the effectiveness of the [N1: 3-opt, N2: Swap, N3: Insertion, N4: 2-opt, N5: Exchange (m,n), N6: Cross, N7: Shift (0,1), N8: Replace (1,1)] sequence. The same sequence is also used in the local search (VND) part of the VNS algorithm.

The perturbation mechanism is called after $1 * feeder\ port\ number$, i.e. 38, iterations counted from the last accepted move. The total route duration and the vehicle capacity violation acceptance limit (α) are used as 10%. This rule aims to allow customers to join another route for possible future improvements. The termination condition of the PVNS algorithm is used as maximum number of iterations between two improvements of the best solution. The termination condition is set to $100 * feeder\ port\ number$ iterations without improvement. The proposed PVNS algorithm is run ten times with different random seeds in order to measure its robustness. Table 3 shows the total costs for the current and alternate hub port under various service frequency and time deadline scenarios in the region.

Table 3. Scenario results for alternative hub port locations

Scenario	Hub	Frequency	Deadline	Total costs	Time
1	Port Said	7	2.5x7	286604.59	96.25
2	Port Said	7	3x7	288057.59	40.10
3	Port Said	7	3.5x7	286704.60	70.57
4	Port Said	7	4x7	**285125.22**	43.77
5	Port Said	7	4.5x7	288392.52	29.82
6	Port Said	3.5	2.5x7	332509.15	90.24
7	Port Said	3.5	3x7	332509.15	41.85
8	Port Said	3.5	3.5x7	330814.43	61.16
9	Port Said	3.5	4x7	331503.51	48.57
10	Port Said	3.5	4.5x7	333496.76	32.70
11	Candarli	7	2.5x7	259138.68	67.82
12	Candarli	7	3x7	**254338.80**	49.24
13	Candarli	7	3.5x7	257990.19	51.65
14	Candarli	7	4x7	257990.19	95.80
15	Candarli	7	4.5x7	258338.07	67.75
16	Candarli	3.5	2.5x7	300493.20	50.64
17	Candarli	3.5	3x7	299458.83	37.72
18	Candarli	3.5	3.5x7	299452.99	51.61
19	Candarli	3.5	4x7	296796.83	74.03
20	Candarli	3.5	4.5x7	299458.83	32.86

In Table 3, total costs include chartering costs, operating costs, administration costs, on-sea bunker costs, on-port bunker cost and port charges for a 52 week planning period. In the scenarios, the existing hub port (Port Said) presents minimum total operational costs of $285.125.220 with 7 days service frequency and 28 (4x7) days deadline for returning to the hub and finishing the unloading operations. The new proposed hub port (Candarli) presents minimum total operational cost of $254.338.800 with 7 days service frequency and 21 (3x7) days deadline. The network routes for the best scenarios for both hub port alternatives are shown in Figure 3. The proposed Candarli port shows around 12% cost advantage compared to the existing hub port of the network. Feeder and trunk shipping lines could transfer their transshipment operations to Candarli, as long as Candarli port authorities keep their container handling costs and relevant service quality at a favourable level.

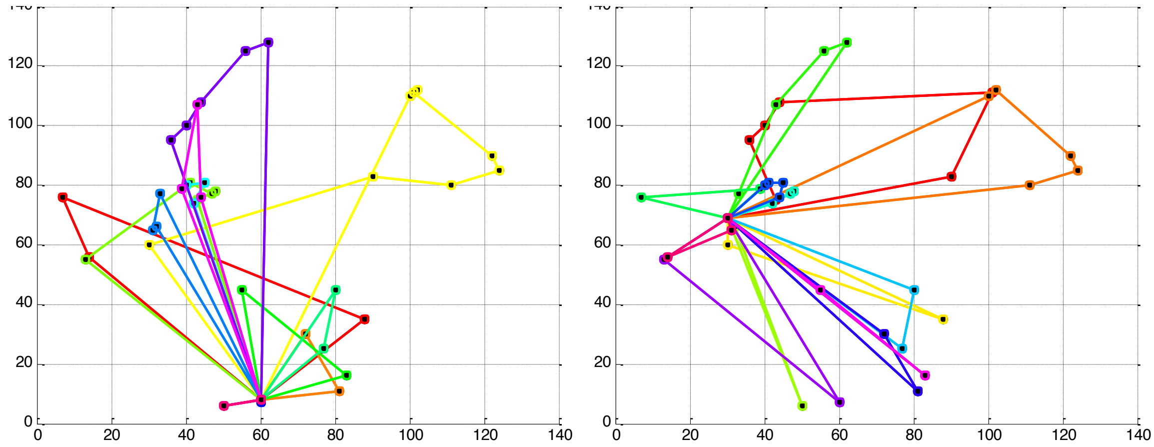

Figure 3. Feeder routing networks for Port Said and Candarli port

Table 4 presents a comparison between costs, service and duration rates of alternative hub ports. As in trunk shipping, feeder shipment is highly sensitive to bunker fuel costs as they represent between 24.98 and 27.96% of total operational cost. However bunker costs contain almost 40-45% of total operational costs for trunk shipping lines. Since total voyage distances of feeder networks are less than those of trunk networks, total network costs contain more ship based fixed costs such as chartering, operating and administration. Therefore ship type selection of the feeder networks are more fixed cost oriented. Since Candarli port has shorter distance to feeder ports, this port based feeder network selects relatively small containerships. On the other hand, the Port Said based feeder network creates its routing network with mid-sized containerships. 4600 TEU containerships are not appropriate for both hub alternatives because of its relatively high fixed costs. Still, from a comparative perspective feeder shipping liners' ship selection is sensitive to fuel price and network distance.

Table 4. Cost rates for Port Said and Candarli

	Parameter	Port Said	Candarli
Model Cost	Total cost ($1000)	285164.07	254407.03
	Chartering cost	21.81%	23.22%
	Operating cost	16.48%	17.72%
	Administration cost	8.89%	8.66%
	Bunker cost (on sea)	27.96%	24.98%
	Bunker cost (on port)	5.41%	5.46%
	Port charges	19.45%	19.96%
Ship	Number of routes	12	13
	Total necassary ship	23	23
	1200 TEU	8.70%	30.43%
	2600 TEU	91.30%	69.57%
	4300 TEU	0.00%	0.00%
Avg. Duration	Total duration (Hour)	322.00	297.23
	On sea duration	23.39%	21.23%
	Port duration (feeder)	40.28%	40.18%
	Port duration (hub)	22.75%	22.77%
	Lay-up duration	7.27%	7.14%
	Idle duration	6.31%	8.69%

It could be expected that as long as the network distance is enlarged, the selected ship capacities will increase in order to meet the balance between fixed and variable costs. Average ship duration for the Candarli related feeder network is about 297.23 hours. The most significant durations are related to feeder port service (40.18%) and hub port service (22.77%). As it expected, the basic duration variance between the alternative hub ports are on the see voyage durations (23.39% and 21.23%), which is the natural effect of geographical difference between the ports.

7 CONCLUSION

In this study, we focus on the potential hub role of a new port (Candarli) in the East Mediterranean and Black Sea region and develop an approach that deals with the feeder network design problem. According to the demand distribution, this study is to determine the feeder network, fleet mix, time deadlines and service frequencies by obtaining the minimum operational costs. Therefore, we proposed a novel hybrid search method called perturbation based variable neighborhood search (PVNS) to solve the feeder containership network design (FND) problem. PVNS is based on the Savings Algorithm (SA), variable neighborhood search (VNS) and adaptive perturbation mechanism (APM). We used eight local neighborhood search structures as shaking and local search operators of the VNS algorithm. A variable neighborhood descent (VND) procedure is used to perform the local search. We use five adaptive perturbation structures in order to escape from local optima. The total operational costs of the optimal feeder networks of existing and alternate hubs are calculated and compared. From the numerical results it can be concluded that Candarli has great market advantage as long as port authorities keep their container handling costs and relevant service quality at a favourable level. The study could be extended by considering cost and durations differences between feeder and trunk shipping networks.

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