An Optimal Design of a Transportation Network for Offshore Port Services

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***Abstract*— This paper introduces a type of offshore port services in which the ship operation is performed offshore instead of seashore and introduces a method of optimally designing an integrated network for sea and inland transportation (intermodal transportation) for the offshore services. In the offshore port service system in this study, shuttle ships are used for discharging/loading containers from/to container vessels at an offshore port and for delivering containers between container vessels offshore and small ports (depots) at seashore. In order to design the transportation network, it is necessary to determine the set of seashore ports to be used for the shuttle ships, the routes of shuttle ships, the number of shuttle ships to be deployed to each route, and the service frequency by shuttle ships on each route. The objective of the problem is to minimize the total transportation cost consisting of the overhead and operation cost for shuttle ships, the handling cost at seashore ports, port construction and maintenance cost, and inland transportation cost. A genetic algorithm (GA) is used to determine the set of seashore ports to open. The insertion algorithm is used for designing shuttle routes. The method in this study is applied to reengineer the design of the transportation network in East Java, Indonesia.**

***Index Terms*— transportation network design, offshore port services, shuttle ships, location and routing, genetic algorithm**

I. Introduction

MARITHIME industry plays an important role in international freight transportation. Recent trends in marine cargo transportation market show a continued increase in global container shipping, volume and the introduction of mega-sized containerships. Data from many transportation research organizations indicate the global container volume is expected to increase by approximately 8% a year [1]. Economy of scale in cargo transport, especially in inter-continental transport, leads to the larger containerships in the marine cargo transportation market. As the size of containerships becomes larger, many areas in the world could not accommodate the large sized containerships in their sea shore ports because of their shallow waters and narrow channels.

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This study proposes one of the solutions to the problem which is to discharge or load containers at an offshore port by letting shuttle ships deliver containers between container vessels and sea-shore ports. Then, seashore ports may have opportunities to attract larger vessels which cannot call at small seashore ports otherwise. The new conceptual transportation system with the name of “mobile harbor,” which is called a “shuttle ship” has been introduced [2]. They are designed for directly loading or unloading containers onto and from a containership in high wave conditions at an open sea and transporting containers to a port or pier (i.e., lacks any infrastructure or is located in shallow waters as indicated in Fig. 1). Playing a bridging role between the marine transport and the inland freight transport, shuttle ships perform basic functions for the offshore port services. The transportation network assumed in this study is partitioned into two parts: the transportation between an offshore port and seashore ports; the transportation between seashore ports and in-land industrial areas.

Fig. 1. A shuttle ship docking at a containership.

Rigorous research on the design of integrated transportation networks or intermodal freight transportation only began from the 1990s [3-13]. Intermodal transportation refers to the integrated use of two or more modes of transportation for delivering goods from origin to destination [3]. Ship routing problem has been studied for many years. Ronen (1983) provided the first survey of ship routing and scheduling, where various modes of operation of cargo ships (such as shipping, tramp shipping, and industrial place shipping) were described, and a classification scheme for shipping routing was introduced [4]. Rana and Vickson (1988, 1991) discussed the optimal routing of containerships operating on a trade route, which maximizes the profit. They suggested a method to determine the optimal sequence of calling port. In the method, the optimal sets of calling port sequences and the number of trips each ship made in planning horizon were also provided [5]. Perakis and Jaramillo (1991) used Linear Programming to assign an existing fleet of containerships to a given set of routes based on detailed realistic model of operating costs [6]. Cho and Perakis (1996) presented a method to determine the optimal fleet size and design of liner routes [7].

This study has the contributions in the following aspects: (1) this is the first study addressing the design of the transportation network for offshore port services; (2) the method in this study is applied to reengineer the design of transportation network in East Java, Indonesia, which proved the applicability of the approach in this study; (3)this study also provided a method integrating all the related decision-making problems for the design of the transportation network such as allocation of in-land transportation depots to ports, routing of shuttles for short sea transportation, port construction, and determination shuttle requirement; (4) all the detail cost terms related to the transportation network design are defined and used in the evaluation of alternatives; (5) a genetic algorithm for the design of the network is proposed.

The next section defines the problem in this study, provides the formulations of various cost terms, and suggests a method for determining the number of shuttles for a given route of offshore services, which satisfies various requirements for the transportation. Section 3 provides a method for finding the optimal seashore ports to open and the routes of shuttles, Section 4 introduces the results of numerical experiments and the final section provides some concluding remarks

II. PROBLEM DEFINITION

The objective of this study is to minimize the total cost of an integrated transportation network. The total cost consists of the overhead and operation cost for shuttle ships, the handling cost at sea-shore ports, port construction and maintenance cost, and inland transportation cost. A modeling framework is presented which accommodates the operational structure of individual modes of transportation, the effect of shipment consolidation at hubs on transportation costs, the interactions between modes, and the service time requirements at the offshore and sea-shore ports. It also considers the tradeoff relation between the cost for locating additional intermodal ports and the reduction in the in-land transportation cost.

We consider transportation requirements for both inbound and outbound containers to/from in-land industrial areas, simultaneously. Fig. 2 illustrates five routes of shuttles: 0-1-0, 0-2-0, 0-3-0, 0-6-0 and 0-4-5-0. Port "0" indicates the offshore port where other vessels are anchored in an open sea. The example in Fig. 2 shows that four ports with port numbers 2, 3, 4, 5 and 6 should be constructed. Gray rectangles with port numbers 7, 8, 9 and 10 indicate ports not to be constructed. The industrial places are assigned to the nearest port for the transportation of containers. For example, in-land industrial places B, H, and I are assigned to port number 2. In-land industrial places A and J are assigned to port number 1 which represents Surabaya port already constructed. In-land industrial places C is assigned to port number 3 and so on.

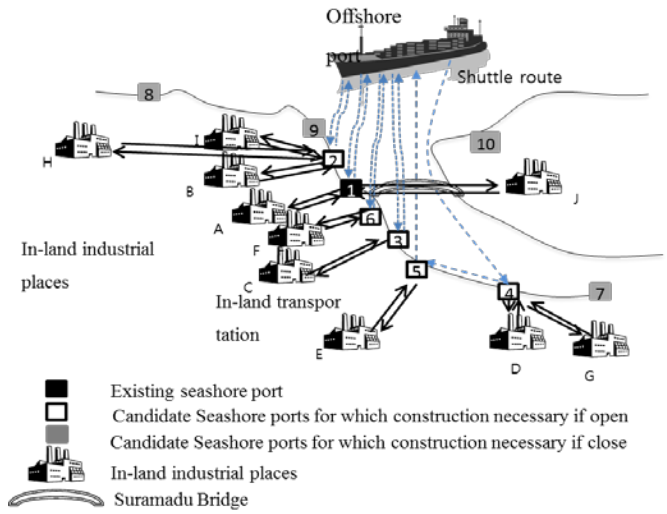


Fig. 2. Illustration of a small example problem.

A. *Problem formulation*

For the construction of transportation network, the following should be determined: (1) the set of seashore ports to open for the shuttle services; (2) the routes for shuttles. Thus, the problem in this study can be said to be a location and routing problem. The objective is to minimize the total transportation cost consisting of the following cost terms: the port construction cost, the shipping cost, and the inland transportation cost.

The following notation will be used for the formulation (input parameters): l *is* Number of candidate seashore ports; m *is* Number of routes of shuttles; n is Number of in-land industrial areas; v_k^I is Number of containers per day moved from industrial area k to the offshore port (TEUs); w_k^I is Number of containers per day moved from the offshore port to industrial area k (TEUs); c^T is Truck cost per distance travel (US$/km); f^{TEU} is Factor for converting the number of containers to TEU units during trucking; f^{dual} is Factor representing the number of round trips to the number of containers moved during trucking. This factor was estimated optimistically under the assumption that all the possible inbound and outbound containers are joined for reducing the empty travels. Thus, this factor was evaluated by1 +[min (,) / *max* (,)]; a_{ij} is 1, if seashore port i is included in route j; 0, otherwise; p_i^c is sea shore port construction and maintenance cost per day at candidate location i (US$/day); c^{OD} is Shuttle overhead cost per shuttle per day(US$/day); c^M Crew cost per shuttle per (US$/day); c^D is Shuttle's depreciation cost per shuttle per day

(US$/day); c^I is Interest and insurance cost per shuttle per day (US$/day); c^R is Repair, docking and maintenance cost per shuttle per day (US$/day); n^C is Number of crews on a shuttle; s^C is Average salary per month of a crew on a shuttle (US$/month); p^s is Purchasing price of a shuttle (US$/shuttle); l^s is Length of life cycle of a shuttle (years); is Interest and insurance rate for maintaining a shuttle per year (%); r^s is Ratio of repair cost to purchasing cost per year (%); r^{Fuel} is fuel consumption per hour by a shuttle (g/hour); r^{Lub} is lubricant consumption per hour by a shuttle (g/hour); c^{Fuel} is fuel cost per metric ton (US$/ton); c^{Lub} is lubricant cost per metric ton (US$/ton); v is an average speed of shuttles (knots); d_{st} is distance between ports s and t (nautical miles); h_i is container handling charge per container at seashore port i (US$/container); q_i is port entry cost at seashore port i (US$/entry);

Decision variables: X_i : 1, if seashore port i is open; 0, otherwise; X : $(X_i,\ i=1,\ \ldots,\ l)$; Y_j : 1, if route j is used; 0, otherwise. Functions of decision variables: $d(k,X)$: Distance between industrial area k and the nearest seashore port in X(km); C^I (k,X): In-land transportation cost per day between industrial area k and the nearest seashore port in X(US$/day); $C^S(Y_j)$: Total shipping cost between the offshore port and seashore ports per day for serving route Y_j (US$/day); $C^{Sh}(Y_j)$: Shuttle-related cost per day per shuttle for serving route Y_j(US$/day/shuttle); $C^P(Y_j)$: Port-related cost of a shuttle per day for serving route Y_j(US$/day/shuttle); $C^O(Y_j)$: Shuttle's overhead cost per day per shuttle for serving route Y_j. This cost term is not incurred in proportion to the cruse distance but in proportion to the time (US$/day/shuttle); $C^F(Y_j)$: Fuel related cost per shuttle per day for serving route Y_j(US$/day/shuttle); $C^E(Y_j)$: Seashore port entry cost by shuttles per day for serving route Y_j(US$/day); $C^H(Y_j)$: Container handling cost at seashore ports per day for serving route Yj(US$/day); $Vr(Y_j)$: Number of shuttles to be deployed for serving route Yj; $T^c(Y_i)$: Cycle time for a shuttle for a round trip on route Yj(days). Total cycle time of shuttle includes travel time between seashore and offshore ports, standby time at ports, discharging and loading time at seashore ports, and idle time at the offshore port (port 0); $N_r(Y_j)$: Set of calling seashore ports on route Yj; $A_r(Y_j)$: Set of arcs on route Yj including arcs from/to the offshore port. Then, the problem for designing the integrated transportation network can be formulated as follows:

$$\min_{X,Y} \sum_{i=1}^{l} p_i^c X_i + \sum_{k=1}^{n} C^I(k,X) + \sum_{j=1}^{m} C^S(Y_j) \quad (1)$$

such that

$$\sum_{j=1}^{m} a_{ij} Y_j \leq X_i \ \text{for} \ \forall\, all\, i \quad (2)$$

$$X_i, Y_j = 0 \text{ or } 1 \quad (3)$$

B. Cost functions

Detailed cost functions are addressed in the following. Various formulas for cost terms in this section are based on the paper by Shintani *et al*. [13].

1. Port construction cost (p_i^c)

The cost of constructing a port depends on the physical characteristics of the location selected, the design of the port, and the facilities for hinterland connections. The maintenance cost for the facilities in the port should be included. The port construction cost is the annualized construction cost plus the annual maintenance cost for the corresponding seashore port.

2. In-land transportation cost $(C^I(k,X))$

The in-land transportation cost between an in-land industrial area and the nearest seashore port can be evaluated as follows:

$$C^I(k,X) = d(k,X)\ c^T\ (w_k^I + v_k^I)/(f^{TEU}) \quad (4)$$

Note that for evaluating $d(k,X)$, it is assumed that containers are delivered from an industrial area to the nearest seashore port. Thus, once the set of seashore ports to open is determined, the evaluation of $d\ (k,X)$ is straightforward.

3. Shipping cost $(C^S(Y_j))$

Shipping costs can be divided into two main categories: shuttles related cost and port related cost. The shuttle related cost includes the shuttle overhead cost and the fuel cost. The shuttle overhead cost corresponds to the expenses paid for using the shuttles, including the cost of purchasing the shuttles, the cost for crew wages and meals, the cost for shuttle repair and maintenance, insurance, materials and supplies, and so on. The port related cost consists of the port entry cost and the container handling cost at seashore ports. The total shipping cost of routecan be expressed as

$$C^S(Y_j) = C^{Sh}(Y_j) + C^P(Y_j), \quad (5)$$

where

$$C^{Sh}(Y_j) = C^O(Y_j) + C^F(Y_j), \quad (6)$$

and

$$. \quad (7)$$

Shuttle overhead cost $(C^O(Y_j))$

Note that $C^O(Y_j) = c^{OD} \cdot V_r(Y_j)$, where

$$c^{OD} = \quad (8)$$

In the numerical experiment in the following sections, the data in Table I were used. Crew cost per day per shuttle can be calculated by $c^{M} = n^{C} \times s^{C} \times 12/365$.

TABLE I
AN ILLUSTRATIVE CALCULATION OF SHUTTLE'S OVERHEAD COST

	$ 26,000,000
	30 years
(n^C=13, s^C=US $ 1,500)	$641
	$2,374
(i^s= 5%)	$11
(=4%)	$31
c^{OD}	$ 3,057

Shuttle's depreciation cost per day per shuttle can be calculated by . Interest and insurance cost per unit time can be calculated by , and repair, docking and maintenance cost per day can be expressed by .

Shuttle fuel cost $\left(C^{F}\left(Y_j\right)\right)$

The fuel related cost per cycle per shuttle can be written as follows:
$C^{FR}(Y_j) = (r^{Fuel}c^{Fuel}+r^{Lub}c^{Lub})\cdot\sum_{(s,t)\in A_r(Y_j)}\{(DS_{st})^{2/3}\cdot v^2\cdot d_{st}\}\frac{1}{A}$, where DS_{st} represents the displacement of shuttles on the way from port *s* to port *t*, which can be evaluated by using the number of containers on the shuttle from port *s* to *t* and *A* is an admiralty coefficient which is a parameter used for the naval architecture (Tupper, 1996). Then, the total fuel related cost spent by $V_r(Y_j)$ shuttles per day becomes

$$C^{F}\left(Y_j\right)=\frac{V_r\left(Y_j\right)C^{FR}\left(Y_j\right)}{T_c\left(Y_j\right)}. \quad (9)$$

Port entering cost $(C^{E}(Y_j))$

Port entering cost term includes harbor dues, light dues, pilot, and charges for tug and mooring services. They are charged by various companies and institutions of which some are private and some have public backgrounds. In most cases, the local port agent collects and verifies all invoices and debits them to the operator as a part of its disbursement procedure. The total cost for one call (in and out) depends on the size and the type of the vessel.

$$C^{E}\left(Y_j\right)=V_r\left(Y_j\right)\sum_{i\in N_r\left(Y_j\right)} q_i / T_c\left(Y_j\right). \quad (10)$$

This study assumed that q_i = US$ 5,600 in the numerical experiment.

Container handling charge $\left(C^{H}(Y_j)\right)$

The total handling cost per day on route can be expressed by

$$C^{H}\left(Y_j\right)=\sum_{i\in N_r\left(Y_j\right)} h_i\left(w_i^S + v_i^S\right). \quad (11)$$

In the numerical experiment, it was assumed thathi = US$ 38.5/TEU for all seashore ports.

C. Determining the number of shuttles $(Vr\ (Yj\ ))$ *and the cycle time* $(Tc\ (Yj\ ))$ *for a given route* $(Yj\ )$

This subsection derives a formula for estimating the minimum number of shuttles required to satisfy the delivery requirements between the offshore port and seashore ports. The cycle time of a round trip is obtained as a bi-product. Some additional notations are introduced as follows: : Handling time (loading or unloading) per container at port *i* (min.); : Handling time (loading or unloading) per container by shuttles at the offshore port (min.); : Standby time from the arrival to the beginning of ship operation at port *i* (min.); : Standby time from the completion of the ship operation to the departure from port *i* (min.); : Standby time from the arrival to the beginning of ship operation at the offshore port (min.); ': Standby time from the completion of the ship operation to the departure from the offshore port (min.); : Number of containers per day moved from the offshore port to sea-shore port *i* (boxes); : Number of containers per day moved from sea-shore port *i* to the offshore port (boxes); : Loading capacity of a shuttle in TEU; (): Minimum loading capacity (TEUs) required per day for moving containers between the offshore port and sea-shore ports. Note that the cargo amount changes on the way for a shuttle to move on a route. Thus, () can be evaluated by finding the maximum of the cumulative cargo on a shuttle following route, which can be expressed by where $w_{(0)}^{S} = 0$ and,

$$v_{(0)}^{S} = \sum_{i\in N_r\left(Y_j\right)} w_i^S , \quad (12)$$

where and represents the number of discharging containers (TEU) and the number of loading containers (TEU) per day at the i^{th} visiting seashore port of shuttle ships. : Minimum duration of stay (min.) of shuttle ships at the offshore port which includes the loading and unloading time and the stand by time between the arrival and ship operation. Note that the idle time is not included. This can be evaluated by

$$f_{MH} + f'_{MH} + \frac{T_c\left(Y_j\right)}{V_r\left(Y_j\right)}\ e^{MH}\left\{\sum_{i\in N_r\left(Y_j\right)}\left(w_i^S + v_i^S\right)\right\}. \quad (13)$$

B_i : Duration of stay (min.) of a shuttle at sea-shore port i, which can be evaluated by $f_i + f_i' + \frac{T_c(Y_j)}{V_r(Y_j)} e_i \left(w_i^S + v_i^S\right)$). (14)

$T_r(Y_j)$: Total turnaround time (min.) of a shuttle from the departure from the offshore port to the arrival at the offshore port after visiting all the sea-shore ports. This can be represented by

$$\sum_{i \in N_r(Y_j)} B_i(Y_j) + \sum_{(s,t) \in A_r(Y_j)} d_{st} / v . \qquad (15)$$

Note that we assume that shuttles stay at the offshore port when idle. B_{MH} : Duration of stay (min.) of a shuttle at the offshore port during a cycle, which can be expressed as follows by the definition of the notation:

$$Max\left\{T_c(Y_j) - T_r(Y_j), B_{MH}^{min}\right\} . \qquad (16)$$

Because $T_c(Y_j)$ is the value of the cycle time at whichthe supply of the delivery capacity of shuttles during a cycle timebecomes equal to the demand of the delivery during a cycle, the following relationship holds: $V_r(Y_j) s_{CA} T_c(Y_j) C_v(Y_j)$, which gives the following relationship:

$$T_c(Y_j) = \frac{V_r(Y_j) s_{CA}}{C_v(Y_j)} . \qquad (17)$$

Because $T_c(Y_j)$ includes some idle time at the offshore port,

$$T_r(Y_j) + B_{MH}^{min}(Y_j) \leq T_c(Y_j). \qquad (18)$$

Replacing the left hand side of (18) with (13) and (15) and replacing $T_c(Y_j)$ with (17), we finally get the following inequality:

$$\begin{array}{l} \left\{ \frac{C_v(Y_j)}{s_{CA}} \left(f_i + f_i'\right) + e_i\left(w_i^S + v_i^S\right) \right\} + \\ \frac{C_v(Y_j)}{s_{CA}} \sum_{i \in A_r(Y_j)} d_{ij} / v + \frac{C_v(Y_j)}{s_{CA}} \left(f_{MH} + f_{MH}'\right) + \\ e^{MH} \left\{ \sum_{i \in N_r(Y_j)} \left(w_i^S + v_i^S\right) \right\} \sum_{i \in N_r(Y_j)} \end{array} \leq V_r(Y_j). \qquad (19)$$

Thus, $V_r(Y_j)$is the smallest positive integer satisfying (19). Note that $V_r(Y_j)$represents the smallest number of shuttles for satisfying only the total transportation demand on the route. Some more buffering shuttles can be added for the smoother ship operation without stopping at the offshore port.

III. FINDING THE OPTIMAL SET OF SEASHORE PORTS AND THE OPTIMAL ROUTES OF SHUTTLES

This section explains how to find the optimal set of seashore ports and the optimal routes for shuttles.

A. *Finding the optimal set of seashore ports*

A genetic algorithm (GA) is used for finding the optimal set of seashore ports. An encoded solution is represented by a string consisting of "0" and "1" where "1" indicates the corresponding seashore port is open and "0"indicates it is not open. For example, "110011"represents the 1st, the 2nd, the 5th, and the 6th seashore ports are open while the 3rd and the 4th seashore ports are not open.

Key features of the GA in this study are as follows:

(Initialization) Randomly generate an initial population of N chromosomes and evaluate the fitness valueof each chromosome.

(Selection) The fitness value of each chromosome in the current population is evaluated. From the current population, the best $(1-P_c)\times N$ chromosome are copies to the new population. By a random selection from the current population, $P_c\times N$ pairs of chromosome are selected and the crossover operation is performed on each of the selected pairs to obtain $2\times P_c\times N$ off-springs. Select $P_m\times N$ chromosomes randomly and perform the mutation operation to obtain $P_m\times N$ off-springs. Among the worst $P_c\times N$ chromosomes in the current population and $(2\times P_c\times N)+(P_m\times N)$ off-springs, the best $P_c\times N$ chromosomes are moved to the new population.

(Crossover and mutation) As the crossover operator, the single-point crossover operator is used. For the mutation, a string is selected randomly and changed from "1" to "0" or from "0" to "1."

(Fitness value) For the evaluation of the fitness value, for a given chromosome, the routes are constructed and the total cost, corresponding to (1), is calculated. The reciprocal number of the total cit is used as the fitness value of a chromosome.

B. *Determining routes* (Y) *for a given set of seashore ports* (X)

The insertion algorithm is used for constructing routes of shuttles. The algorithm starts from routes each of which includes a single seashore port, which we call an elementary route. And then, an elementary route is selected and merged with another route so that the total cost which is the last term of (1) is reduced by the largest amount. When merging, the position of the insertion of the single port is the one at which the cost reduction is maximized. Let $TC(Y) = \sum_{j=1}^{m} C^S(Y_j)$ *and* $\Delta TC(U,V)$ denotethe change in the total cost by inserting the node of elementary route U into the least cost position of route$V$.The insertion algorithm can be summarized as follows:

Step 1: Construct the initial routes each of which is *0-i-0* for all i. Let these initial routes be called "elementary routes."

Step 2: Calculate $\Delta TC(V,U)$ for all the combinations of all the routes (including elementary routes) V and all the elementary routes U. For example, if route $V$is 0-3-4-0 and elementary route $U$is 0-5-0, then $\Delta TC(V,U) = TC(V) + TC(U) -$Min $\{TC$(0-5-3-4-0),TC (0-3-5-4-0), TC(0-3-4-5-0)$\}$. Select the largest positive $\Delta TC(V,U)$. If the largest $\Delta TC(V,U)$is non-positive, then go to Step 4. Otherwise, go to Step 3.

Step 3: If there exists at least one elementary route, then go to step 2. Otherwise, go to Step 4.

Step 4: The current solution is the final solution. Stop.

IV. NUMERICAL EXPERIMENTS

A numerical example was solved by using data in Surabaya, East Java. Ten industrial places and ten candidate ports including one existing port are given. Table II shows the estimated daily traffic of inbound and outbound containers to/from in-land industrial places. Table III shows values of input parameters assumed for the example. For parameters (1) – (5), (11), and (12), data was obtained from the design of the prototype of the shuttle ship supplied KAIST. And for parameters (6) –(10),(13),and (14), data was obtained from surveys which were conducted for shipping and stevedoring companies as well as for port authorities in Surabaya, Indonesia, data in Table III are collected.

TABLE II
CONTAINER TRAFFICS TO/FROM IN-LAND INDUSTRIAL AREAS

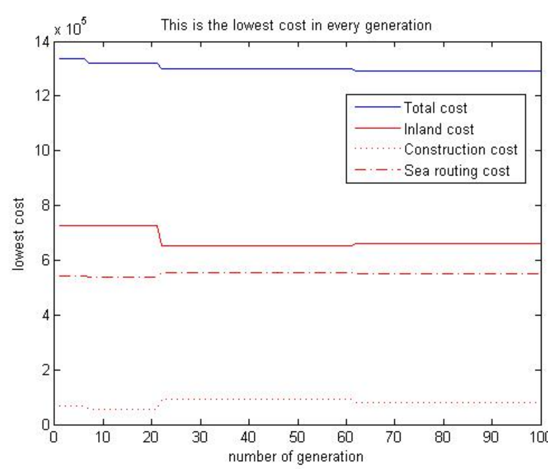
Industrial area	Inbound container (TEUs)	Outbound containers (TEUs)	f^{dual}
A	1740	1673	1.96
B	1201	1054	1.88
C	403	127	1.32
D	203	168	1.83
E	249	145	1.58
F	208	196	1.94
G	22	5	1.23
H	33	14	1.42
I	14	14	2.00
J	23	18	1.78

TABLE III
VALUE OF INPUTS PARAMETERS

Notations	Value
s_{CA}	250, 500, 1200, and 2000 TEUs
e_i, e^{MH}	2 minutes/ container
f_i, f_i' f_{MH}, f_{MH}'	10 minutes per berthing or departure
v	8 knots
r^{Fuel}	0.0011, 0.0022, 0.0066, 0.01 mt/ day for each shuttle of size 250, 500, 1200, and 2000 TEU, respectively
c^{T}	US$ 7.5
f^{TEU}	1.5
c^{Fuel}	US$ 499/ mt
r^{Lub}	0.0002 mt/day
c^{Lub}	US$ 1000/mt
DS	7469, 14938, 37345 and 59752 mtfor the shuttle of size 250, 500, 1200, and 2000 TEU , respectively
A	150, 250, 300, and 400 for each shuttle of size 250, 500, 1200, and 2000 TEU, respectively.
p_i^C	US$ 13,370/day
q_i	US$ 5600, 12000, 15000, and 20000 per entry for each shuttle of size 250, 500, 1200, and 2000 TEU, respectively.
h_i	US$ 38.5per TEU
P_c	0.8
P_m	0.1

Existing industrial places are indexed from A to J. Candidate calling ports (10 ports) are selected to be (1) Surabaya, (2) Gresik, (3) Mojokerto, (4) Pasuruan, (5) Malang, (6) Sidoarjo, (7) Probolinggo, 8) Bojonegoro, (9) Lamongan, and (10) Bangkalan. Table IV shows the distances between ports and industrial places. Table IV shows the travel distance between ports and the industrial areas and Table V shows the travel distances among seashore ports.

Fig. 3 shows the change of the total cost as the solution process proceeds. Note that the solution was not improved after the number of iterations exceeds 70. The final solution is given in Fig. 2. Fig. 4 shows that as the generation exceeds a certain level, the objective function is not improved further. The generation number 10 is the minimum for the computational time. For finding the appropriate population size, we run the algorithm for 100 generations, with input parameter of crossover probability of 0.8 and mutation probability of 0.1. Table VI shows that as the population size exceeds 10, the objective function was not improved further and found the optimal solution at the total cost US$ 1,284,528. We set the population size to be 10 in the following experiments.



(Input parameters: population size10, Iteration 100, crossover rate 0.2, mutation rate 0.1).

Fig. 3. GA performance optimal solution for the given cargo.

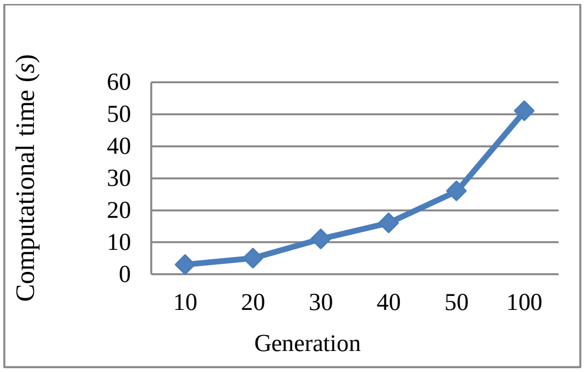


Fig. 4. Testing results number of generation in the range 10 to 100.

Fig. 5 shows the performance of optimal solution for the given cargo. Input setting parameter: population 50, number of generations 200 crossover rate 0.7, mutation rate 0.1. Note that the solution was not improved after the number of iterations exceeds 20 and found the optimal solutions at the total cost US$ 1,284,528. Fig. 6 compares CO_2 emission between the existing condition and the condition after utilizing offshore port services. It was assumed that the environment cost of truck emission per km is $ 0.2, and that of shuttle (vessel) is $1.5 per mile [1]. It was found that the total environment cost can be reduced by 28 % when utilizing offshore port services.

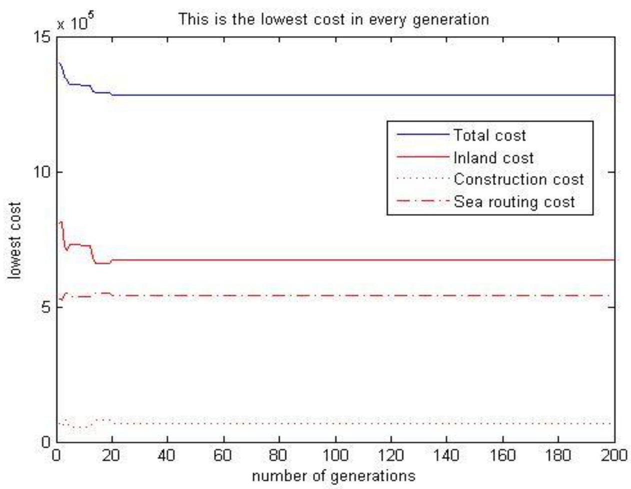


Fig. 5. GA performance global optimal solution for the given cargo (pop_size : 50, iteration : 200).

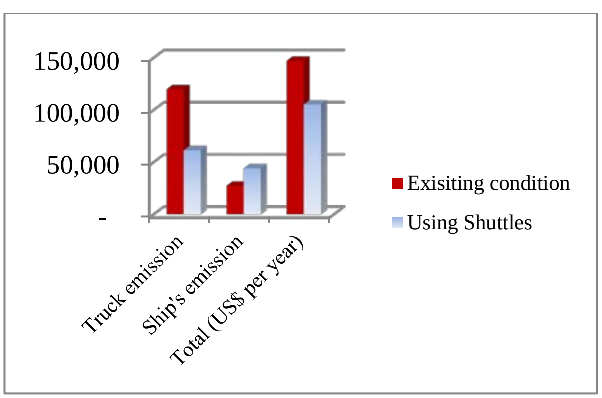


Fig. 6. The reduction of CO_2 emission by utilizing the offshore port services.

The numerical experiments were conducted with the different shuttle capacities, various speeds of shuttle ships, various port constructions costs, and various oil prices. Fig. 7 compares the total cost for various capacities of a shuttle. Note that the purchasing price of a shuttle of capacity 250, 500, 1200, and 2000 TEUs were assumed to be US$ 27,000,000, US$ 45,000,000, US$60,000,000, and US$90,000,000, respectively. The total cost was the lowest when the capacity of a shuttle is 1200 TEUs. Fig. 8 shows the change of the total cost for various speeds of shuttles and it was found that the total cost was the lowest when the speed of shuttles is 8 knots. Note that different speeds of shuttles results in different optimal numbers of shuttles to be deployed and different fuel costs. Table VII shows the computational time for various sizes of the problem. The number industrial areas and candidate ports are changed from 50 to 1000 and from 50 to 1000, respectively. It was found that the computational time was more sensitive to the number of candidate ports than the number of industrial areas. Also, it was found that the algorithm in this paper can be used to solve problems of real sizes.

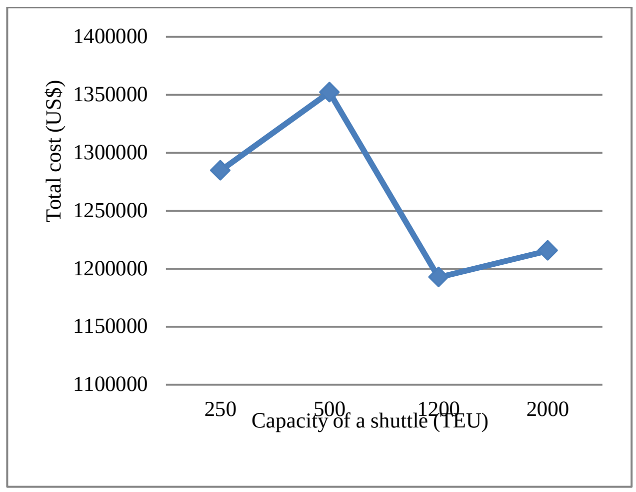


Fig. 7. The optimal shuttles capacity for the given cargo.

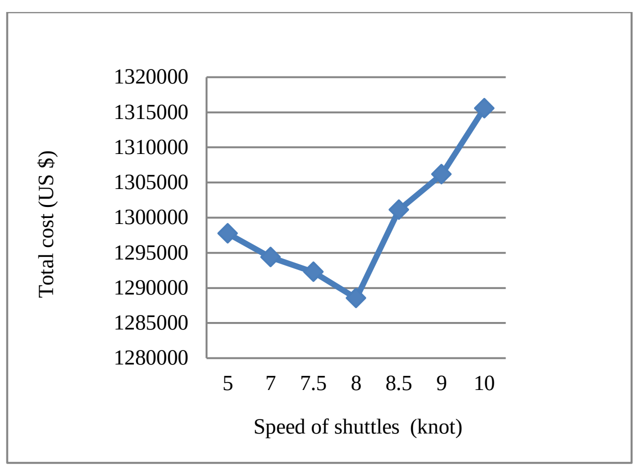


Fig. 8. The optimal speed for the given cargo

TABLE IV
DISTANCES BETWEEN PORTS AND INDUSTRIAL PLACES IN KILOMETERS

No.	Existing port and Candidate Ports	INDUSTRIAL PLACES									
		A	B	C	D	E	F	G	H	I	J
1	Surabaya*	20	44	116	120	180	72	180	216	90	56
2	Gresik	50	10	134	156	214	114	234	180	54	92
3	Mojokerto	98	134	84	122	178	54	200	344	114	154
4	Pasuruan	120	156	122	10	198	74	82	336	198	182
5	Malang	178	214	178	148	140	152	232	394	180	178
6	Sidoarjo	46	114	120	152	208	36	230	262	136	102
7	Probolinggo	180	234	200	80	224	152	10	414	262	202
8	Bojonegoro	216	160	304	336	394	262	414	102	132	272
9	Lamongan	90	54	120	142	190	136	202	158	50	90
10	Bangkalan	56	92	154	176	244	102	258	272	148	8

TABLE V
DISTANCES BETWEEN PORTS IN NAUTICAL MILES

DISTANCES	Offshore Port	Surabaya	Gresik	Mojokerto	Pasuruan	Malang	Sidoarjo	Probolinggo	Bojonegoro	Lamongan	Bangkalan
Offshore Port		25	20	49	67	50	41	82	76	18	15
Surabaya	25		6	24	41	35	18	52	77	18	32
Gresik	20	6		30	47	61	24	58	70	12	26
Mojokerto	49	24	30		25	11	10	49	100	57	73
Pasuruan	67	41	47	25		15	35	24	106	63	76
Malang	50	35	61	11	15		23	39	119	72	88
Sidoarjo	41	18	24	10	35	23		54	94	38	52
Probolinggo	82	52	58	49	24	39	54		138	100	84
Bojonegoro	76	77	70	100	106	119	94	138		93	91
Lamongan	18	18	12	57	63	72	38	100	93		28
Bangkalan	15	32	26	73	76	88	52	84	91	28	

TABLE VI
VARIOUS POP_SIZE, COMPUTATIONAL TIME AND OBJECTIVE FUNCTION

Pop-Size	Comptime (s)	Objective function
5	19	1290071
10	43	1284528
20	97	1284528
30	137	1284528
50	218	1284528

TABLE VII
THE OPTIMAL DECISION VARIABLE AND COST TERM

Route no.	0-1-0	0-2-0	0-3-0	0-6-0	0-4-5-0
No. of shuttles, $V_r(Y_j)$	9	6	2	2	3
Cycle travel time (day), $T_r(Y_j)$	1.27	1.17	1.20	1.43	1.55
Time in offshore port (days), $B_{MH}(Y_j)$	0.50	0.48	0.34	0.50	0.43
Total cycle time (days), $T^c(Y_i)$	1.77	1.65	1.54	1.93	1.98
Shipping cost (US$/day), $C^S(Y_j)$	226,237	151,798	47,889	37,944	79,670
Number of ports to be opened	0	1	1	1	2
Port construction cost (US$/day)	0	13,370	13,370	13,370	26,740
Inland cost (US$/day), C^I	180,440	93,530	169,260	41,318	189,592
Total cost (US$/day)	406,677	258,698	230,519	92,632	296,002

V. CONCLUSIONS

This paper attempts to introduce a method for optimally designing an integrated transportation network consisting of sea and inland transportation for offshore port services. It is assumed that shuttle ships are used for delivering containers between container vessels offshore and small seashore ports and discharge/load containers from/to container vessels. A genetic algorithm is developed for determining the set of ports to open for the access of shuttles to the in-land transportation network. The insertion algorithm in this paper determines the optimal routes of shuttle ships. A simple formula is suggested to determine the number of shuttle ships at each route and the service frequency for each route by shuttle ships. For the design of network, detailed cost expressions are used. Numerical experiment was conducted for finding the best set of computational parameters for the genetic algorithm. It was found that the computational time was short enough to be used in practice.

One advantage of the proposed solution method is that it is relatively easy to implement. Another advantage of the method is its flexibility to handle a large number of additional constraints that may arise in many real-life routing and scheduling applications. The result of this paper can be used for designing more general transportation networks with vessel routing.

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