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RESEARCH PAPER

Mitigating Environmental Impact Through Efficient Port Management: An Integrated Model

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Abstract

Marine transportation has become a vital element of global trade, connecting commercial hubs around the world via low-cost sea routes. Its impact is increased by the environmental concerns raised by the associated maritime traffic, which necessitates a comprehensive and efficient method to resolving these worries. A vessel follows a predefined course and departs from the home port on a scheduled basis in order to reach its destination. It carries out loading and unloading operations at the allocated berth and crane during the tour. In order to conserve schedule, the vessel needs to navigate the route at the optimal speed, which is influenced by a number of factors including fuel consumption and vessel weight. This study used a novel model to generate a vessel schedule and route map for Iran's Shahid Rajaei Port in the Persian Gulf. The data suggest that the port can manage ten vessels at a time and has two cranes for loading and unloading each vessel. In addition, we carried out a sensitivity analysis on key components of our proposed model, including fuel costs, vessel weight, load-carrying capacity, and arrival/departure delays. The keys findings are as: higher arrival/departure costs result in shorter delays; higher fuel costs have a negative impact on the objective function; lower vessel weight results in better fuel efficiency; and higher vessel load-carrying capacity is coupled with higher fuel costs.

Keywords:
Sustainable Supply Chain Management, Maritime Network, Marine Logistics, Berth Allocation, Quay-Crane Allocation.

Introduction

Logistics means the effective planning, executing, and controlling of transferring and storing goods and providing services and related information from the production origin to the consumption destination to meet consumer demand. Marine transportation - a vital mode used worldwide - plays a major role in expanding and facilitating global trade and logistics science. Recent developments in the vessel building industry, applying advanced logistics equipment in ports, using very large-volume transportation in vast geographical spans, and using containers to facilitate the transportation and storage of goods have all made marine transportation greatly popular in intercontinental and inter-country operations [1, 25-27]. Today, marine logistics is an important issue in the world not only because of the importance of such economic criteria as the timely, reliable, low-cost, large-volume delivery of goods to customers but also due to the

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seriousness of environmental crises facing the world. As 2% of the world's total CO2 emissions are by vessels and marine transportation, such emissions will pollute the environment more and make the earth warmer if the port management does not address them effectively and efficiently [2, 28-30]. Lacking accurate service planning will cause vessels to wait more for mooring and, hence, pollute the seawater more [3, 4,31-33,60,61]. The importance of marine logistics and the seriousness of trade via water borders have caused Iran to assign 11 ports for the related activities; this highlights the need to address the issue quite seriously in Iran, too.

Marine logistics mainly involves 1) marine transportation, where finding proper vessel routes is an important task, and 2) port management, where assigning ports and cranes to vessels is an important issue [34,35]. The berth allocation problem (BAP) refers to the process of assigning incoming vessels to berths at a port in a way that optimizes factors such as waiting time, service time, and overall port efficiency. The quay crane assignment problem (QCAP) involves the allocation of available quay cranes to vessels at each berth to ensure efficient loading and unloading operations, while minimizing delays and optimizing resource usage. This section aims to address assigning ports and cranes to vessels and special cranes to some vessels using the following programming algorithm.

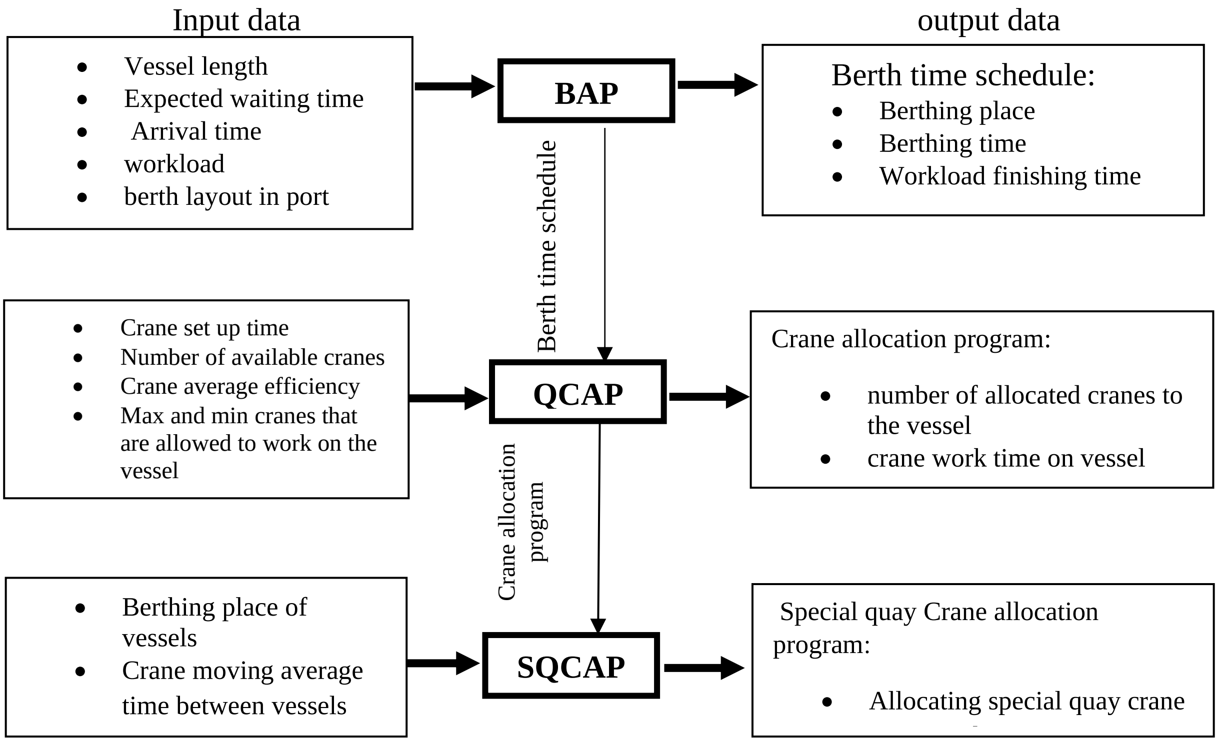

Fig. 1. Port management algorithm [8]

As shown in Figure 1, using the gathered input data and solving the berth allocation problem (BAP), quay crane assignment problem (QCAP), and special quay crane assignment problem (SQCAP) will enable a proper port-management program to be implemented. In addition, other important issues are finding proper routes, assigning vessels to them, determining the proper vessel speed and fuel/energy consumption, and preventing pollution from spreading in the environment.

This important issue has caused the present study to be aimed at not only creating integrity in such different sectors of marine logistics as port management and vessel routing but also considering the related environmental issues in the special case study. While considering routing and assigning ports and cranes to vessels simultaneously will result in a marine transportation plan with the lowest cost and the least delay, they have always been dealt with separately in related studies, and no research has addressed them together [5, 36-38,62]. Their integration is, therefore, the most important innovation of the current study, wherein sustainability in marine logistics is considered a constraint. In addition, this study will solve the proposed integrated problem with an exact approach. The problem assumptions are 1) uncertain vessel arrival to and departure from the port, which makes the plan more realistic; 2) integrated ports, which provide service to more vessels; 3) sufficient service cranes and trucks; and 4) uninterrupted on-board operations once the service has begun. Hence, the problem objectives encompass: A) Allocating ports to vessels with the goal of minimizing penalties for both due-time delays and mooring place violations, B) Allocating cranes to vessels to minimize average on-board working time and C) Determining the optimal and most efficient vessel route [6, 39-41,64]. Figure 2 shows the general vessel routes in the Persian Gulf and in the Shahid Rajaei Port, which is the proposed case study of the problem considered in the present research.

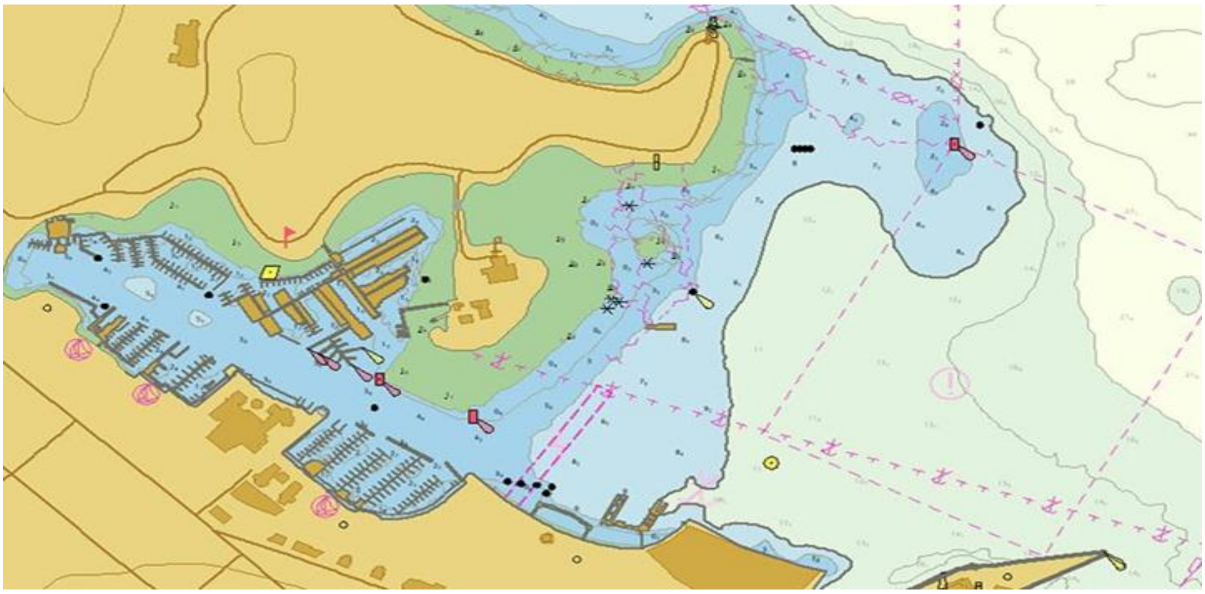

Fig. 2. Logistic view of Shahid Rajaei Port

As shown, vessels transport goods from the origin to the destination port via the route specified in the river, and then, depending on the type of the port, parts of the berth are assigned to begin serving them after they enter the port. Here, a systematic plan of the vessel's route assignment and berths-cranes assigned to the vessel in the port of destination will not only prevent wasting time and money on transporting goods through waters but also reduce the water pollution due to the vessel's reduced waiting time because when a specific route allocated to the vessel and the vessel travel through this route, its arrival time will be more precise and the destination port can plan more discreetly. Subsequently, the wasted time and cost will be reduced [7, 42-44,63]. In the following, we will explore relevant literature, building upon the context provided above and emphasizing the significance of the topic at hand.

Section 2 provides an overview of pertinent literature. In Section 3, we outline the model, its variables, and parameters. Section 4 delves into the empirical case of Rajaei Port, discusses the model's findings and presents results from the sensitivity analysis. Finally, Section 5 offers the concluding remarks for the study.

Literature Review

In this section, we delve into relevant studies covering four distinct subjects. These subjects include the classification of studies based on their modeling approach, model decisions, port types, and decision levels.

• Categorizing Papers by Modeling Approach

In general, as the problem inputs, objectives, constraints, and features of parameter indicate its solution approach, Table (1) compares the reviewed papers based on their being single-objective or multi-objective, having certain, uncertain, or fuzzy parameters, and, finally, their types of objective functions.

Table 1. Solution approach

References	Modeling	Objective Functions		Sustainability	Time Horizon		Operational Risk Consideration				
		Single-Objective	Multi-Objective		Multi-Period	single-Period	Deterministic	Uncertain Parameters	Fuzzy Programming	Robust Optimization	Stochastic Programming
[8]	Functional									✓	
[9]	MIP approach	✓					✓				
[10]	Heuristic		✓	✓				✓		✓	
[11]	Heuristic	✓		✓	✓		✓				
[12]	Integer programming		✓		✓						
[13]	Data mining	✓			✓		✓				
[14]	Metaheuristic						✓				
[15]	First search-depth							✓			
[16]	First search-depth			✓							
[17]	Data mining			✓							
[18]	Data mining		✓	✓	✓		✓				
[19]	metaheuristic		✓		✓						✓
[20]	MIP approach		✓				✓				
[21]	DSS genetic algorithm		✓				✓				
[22]	DSS genetic algorithm										
This Study	Exact methods (e.g., Queuing theory)		✓	✓	✓			✓			✓

As shown, few have considered uncertainties, whereas disruptions in vessel routes and uncertainties in parameters are, in fact, key reasons for the defective implementation of predetermined vessel plans. Solving problems that have uncertain parameters can lead to being more realistic and planning more accurately.

In addition to the mentioned studies, in recent years, Lazakis and Khan [45] introduced an optimization framework named OptiRoute, designed to enhance daily or short-term maintenance activities. Their study focuses on route planning and scheduling for offshore wind farms located far from shore, where both larger service operation vessels and smaller crew transfer vessels are utilized. Similarly, Irawan et al. [46] address a comparable issue by presenting an optimization model and proposing an innovative metaheuristic approach for efficient problem-solving. Additionally, Irawan et al. [47] develop a framework for scheduling and routing maintenance tasks at offshore wind farms on a tactical-operational level, utilizing a metaheuristic method as their solution approach.

Another issue investigated in recent years is uncertainty, particularly in weather conditions, which plays a crucial role in routing and scheduling problems related to the operation and management of offshore wind farms. This factor is addressed in various studies, such as Irawan et al. [48], which examined uncertainty in travel time, maintenance duration, and the transfer time from vessels to turbines. Schrotenboer et al. [49] also explored uncertainty, focusing on weather conditions and maintenance tasks within the context of tactical maintenance planning. Allal et al. [50] proposed a simulation optimization method to assess the impact of opportunistic maintenance. Additionally, an ant colony system is recommended for optimizing the vessel routing problem, while a multi-agent model is introduced to simulate system behavior.

Besides considering uncertainties, using exact mathematical programming methods, such as probabilistic processes (e.g., queuing), will lead to more accurate results than the heuristic and metaheuristic models; in the table, no paper has used such models to solve the problem. The mentioned innovation requires the vessel arrival/departure time to be considered as a probability, which means the need to use uncertainty in the input parameters. As such problems encounter mixed-integer, linear, or nonlinear programming models, the Benders decomposition algorithm is suggested along with other algorithms for solution and comparison purposes. This method that provides accurate solutions has not been used in any study so far; hence, its use will be the next innovation of the present research.

• Categorizing Papers by Model Decisions

Table (2) shows the decisions that different papers have tried to make; since no paper has considered the decisions related to marine logistics (transportation) and port management (e.g., assigning crane to the vessel and port to the vessel) simultaneously, the next innovation of the current research is integrating these two decisions into one model, which actually means making concurrent strategic and tactical decisions that result in an integrated credible plan for each vessel and prevents probable delays on the route when planning the intended allocations.

A proper vessel-route selection will considerably help its on-time arrival to the port; therefore, addressing routing, considered less in papers, is another innovation of the current paper needed for marine logistics. Figure (3) shows the frequency (number) of papers that have addressed various decision-making cases and their integration.

As shown, out of the 60 papers examined, none of them have concurrently tackled vessel routing, crane assignment, and port allocation.

Table 2. Decision categories

References	**Decisions Categories**						
	Routing	**Locating**	**BAP**	**QCAP**	**SQCAP**	**Marine logistics**	**Capacity**
[8]		✓					✓
[9]							
[10]							
[11]							
[12]		✓					
[13]		✓					✓
[14]		✓		✓			
[15]		✓	✓				✓
[16]						✓	
[17]		✓	✓	✓			✓
[18]						✓	
[19]			✓	✓			
[20]						✓	
[21]						✓	
[22]		✓	✓	✓			
This Study	✓	✓	✓	✓	✓	✓	

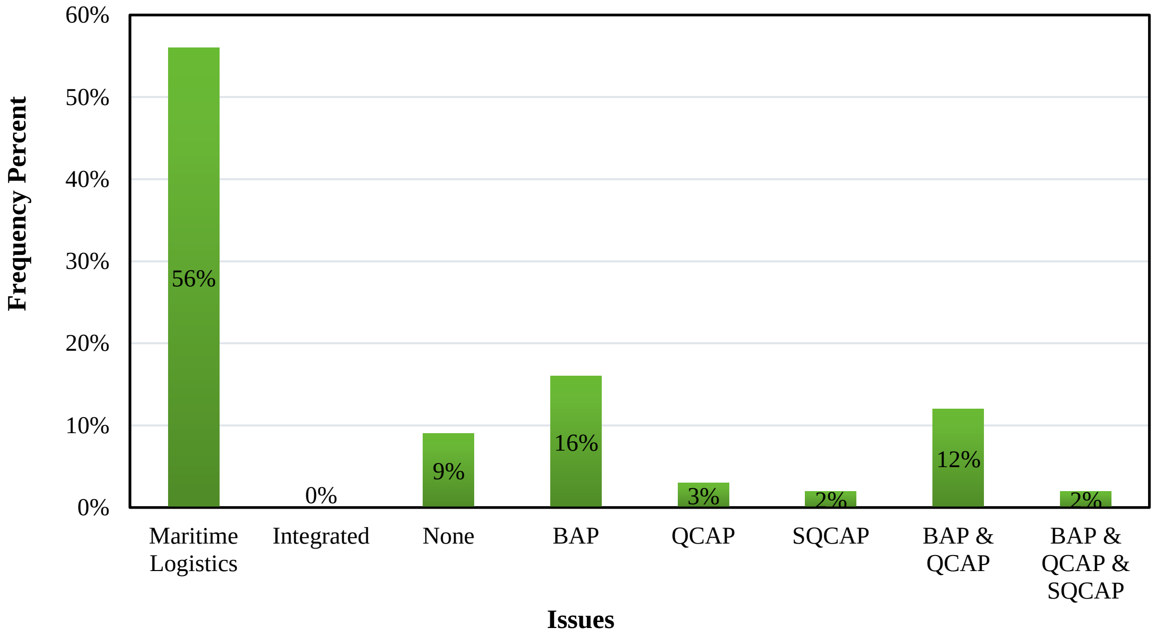

Fig. 3. Subject frequency of the reviewed papers

• Categorizing Papers by Port Types

Table (3) shows the type of ports studied in related papers. Regarding the berth design, ports are 1) discrete, 2) continuous, and 3) hybrid. In (1), the length of each beach is usually different, and the bay is divided into a limited set of sections called berths, letting only one vessel at a time. In (2), the bay is divided into equal-sized coastal sections; each vessel is assigned some sections equal to its length, and they need to consider a safe distance when adjacent to another vessel. Here, the merit is that if one section is not enough to cover the vessel length, joining different sections can solve the problem. In (3), the design is similar to (1), but some small vessels can receive service in one area while a large vessel is being served in a number of berths.

Table3. Port type

Reference	Discrete	Continuous	Hybrid
[8]		•	
[9]		•	
[10]			•
[11]			•
[12]		•	
[13]			
[14]		•	
[15]			
[16]			
[17]			
[18]			
[19]		•	
[20]		•	
[21]	•		
[22]	•		
This Study		•	

Studying research and asking questions from related officials in the Ports & Maritime Organization of Iran have revealed that although hybrid ports are very important in the world because they speed up loading/unloading processes and greatly save time and energy, they are really missing in this country. Hence, Effort has been made in this research to establish the mathematical models based on the limitations of hybrid ports so that the latter can be used properly after they have been implemented.

• Categorizing Papers by Decision Levels

Time horizon requires decisions to be made at strategic, tactical, and operational levels where none can be executed in the horizon of the other. Table (4) classifies papers based on these levels.

In addition to mentioned studies, as the environmental concern has become an increasingly important issue in identifying environmentally sustainable ways to develop transportation industries, Cammin et al. [51] examine the challenges in developing efficient Energy Infrastructures (EIs), identifying key obstacles like inadequate information systems and concerns over data confidentiality. Ampah et al. [52], in their review of alternative marine fuels, estimate that adopting cleaner fuels could reduce shipping emissions by approximately 70%. Similarly, [53] compare emissions inventories between river-sea modes and hybrid modes, concluding that river-sea vessels operating in both modes provide a more efficient way to reduce emissions. In the current era of digitization, organizations are embracing technologies such as blockchain [54] and big data analytics [55,56] to promote eco-friendly practices while meeting business demands [57,58]. Furthermore, in alignment with the Paris Agreement, the maritime freight industry and its stakeholders are encouraged to submit voluntary reports, with a focus on adhering to sustainable development policies as a primary objective [59].

Table (4) emphasizes the integration of port management and marine transport. Using facility relocation in this table can be a potentially appropriate innovation for future research. It occurs in post-planning stages, which means that if facilities are found unsuitable and not planned properly after the initial planning and implementation for a known period, they can be re-planned and help the program to be monitored.

Therefore, the literature marine logistics-related research gaps are: 1) non-integration of vessel routing and port/crane assigning to vessels despite the importance of the issue. 2) Ports studied in some papers are discrete and serve fewer vessels because they can provide service for only one vessel at a time; the present paper has considered a continuous port system as the most recent type in the world. And 3) not considering environmental issues in some papers on marine logistics despite the importance of the issue in today's world. The more optimized the vessel service plans lead to the faster service time and, hence, the less the seawater and air will be polluted. As a result, the main contributions of this work are as:

1) **Novel Approach**: The integration of vessel routing and port management is a significant contribution to the field of marine logistics.

2) **Environmental Impact**: The focus on reducing fuel consumption and pollution through speed optimization aligns with current sustainability goals.

3) **Practical Relevance**: The model is designed to be applicable to real-world port operations, considering factors like uncertain vessel arrivals and hybrid port designs.

4) **Policy Implications**: The findings can inform policy decisions regarding port infrastructure, vessel operations, and environmental regulations.

Problem definition and modeling

In the problem considered in the present study, the vessel has the problem of choosing the appropriate route immediately after it leaves the port of origin because each origin-to-destination route has its own specific length, hazards, and characteristics that affect its selection, and each vessel selects its own appropriate route based on the schedule set for it to reach the destination and the speed at which it can proceed. If it fails to meet the specified schedule and berths at the port with a delay, the system will incur delayed mooring costs. This may also cause a delayed departure due to the congestion of other vessels and, thus, impose additional costs on the system. If the vessel does not dock at a predetermined location and stays somewhere else, costs will be incurred due to this deviation from the desired location. As the vessel's speed directly affects its timely arrival to the destination port, it is very important to follow the related spatiotemporal plan, which can be affected by the speed. Here, the port consists of a number of connected berths, cranes move along them on rails, and each vessel is assigned to a part of the port with an appropriate berth according to its conditions. As mentioned earlier (on research gaps), previous studies determined vessel movement scheduling in port management plans regardless of its speed in its assigned route. However, the speed considered to solve the problem not only specifies the vessel's arrival time to the destination port but also determines the amount of consumed fuel, which is an influential water pollution factor. The less consumed fuel leads to less sea/ocean pollution, concluding that pollution control is possible through speed control. Therefore, the effort has been made in the present study to support the vessel from the origin to the destination by combining the route allocation and berth/crane allocation not considered together in any research before.

Table4. Decision levels

References	**Strategic**						**Tactical**			**Operational**
	Investing	**Locating facilities**	**Determining capacity**	**Assigning facilities**	**Relocating facilities**	**Saving time**	**Planning project**	**Routing inventory**	**Distribution**	
[8]				✓						
[9]		✓								
[10]							✓			
[11]										
[12]		✓		✓		✓	✓			
[13]		✓	✓	✓				✓	✓	
[14]		✓		✓					✓	
[15]									✓	
[16]		✓	✓	✓	✓			✓	✓	
[17]									✓	
[18]									✓	
[19]									✓	
[20]						✓			✓	
[21]		✓		✓		✓			✓	
[22]									✓	
This Study		✓		✓	✓	✓				

In short, the solution to the problem considered in the present study will provide vessels with a schedule shown in the form of a diagram with two axes where the horizontal one represents the mooring position along the shore, and the vertical one shows the mooring time. Some of the important assumptions made to solve this problem are categorized as follows:

For time:

- ✓ The vessel operation time depends on the number of cranes assigned to it.
- ✓ The planning horizon is divided into equal time intervals, and the vessel is assigned within them.

For vessels:

- ✓ After mooring, the vessel remains motionless; it does not move during operations.
- ✓ Operations do not stop after they start; they will continue until the work with the vessel is

finished.

- ✓ The loading/unloading time is a factor considered when working with the vessel.
- ✓ As vessels may have varying importance/prioritization, their cost factors are also different.
- ✓ The inter-vessel safe distance is 10% of the vessel length for those longer than 130 m and at least 10 m for small vessels.
- ✓ Vessels carry a pre-specified amount of load [23].
- ✓ The vessel's optimum speed is found as follows:

$$\hat{\upsilon}_l = \frac{(c^f . G_i . F_i (C_i + B_i)^{2/3})^{1/T_i}}{c^f . G_i (C_i + B_i)^{2/3(T_i - 1)}} \tag{1}$$

where G, F, and T are fixed fuel-consumption parameters in each vessel, and C is the weight of the empty vessel (as mentioned earlier, the vessel speed depends on various factors such as the cost and amount of the fuel consumed by the vessel based on its weight and the load it carries, transportation rate, engine size and technology used in the vessel, environmental and climate conditions, and so on, and the importance of each factor depends on the specific circumstances considered in each problem) [24].

For ports:

- ✓ Each berth, or any position in it, visits only one vessel at a time.
- ✓ Draught is suitable for all vessels.
- ✓ Vessel owners and ports are co-beneficiaries.

For cranes:

- ✓ Cranes available at each berth are similar in characteristics and fixed in number.
- ✓ All cranes can move along the port but cannot collide or interrupt one another.
- ✓ The crane motion time is ignored in plans because it is negligible compared to the vessel working time.
- ✓ Each crane is assigned to only one vessel in each time period.
- ✓ The number of cranes assigned to a vessel does not change during the time the vessel is in the port.

It is necessary to mention these assumptions create constraints explained later in the problem modeling section. In the following, the problem indices, parameters, and variables have been defined.

Indices

$T = \{1, \dots, H\}$	Time horizon (1-H hr).
τ	Another symbol for time
$P = \{1, \dots, P\}$	Vessel routes (1-p)
V= {1…, N}	Vessel sets (1-N)
i , j	Another symbol for vessel sets
Q	Crane sets
k	Berth sets

Parameters

L	Port length
l_i	Length of vessel i
a_i	Expected arrival time of vessel i
s_i	Expected departure time of vessel i
q_i^{min} , q_i^{max}	The least and most number of cranes assigned to vessel i
d_i	Expected mooring time of vessel i
u_i^q	Estimated time for q cranes to work with vessel i
c_i^w	Cost of the waiting time of vessel i mooring after its expected arrival time
c_i^p	Cost per unit length of vessel i for mooring at a place other than the assigned place

c_i^d	Delayed departure cost of vessel i after its expected departure time
c^f	Fuel cost
$G_{i,}$ F_i, T_i	Fuel consumption-related parameters of vessel i
V_i	Origin-destination speed of vessel i
B_i	Load of vessel i
C_i	Weight of vessel i
D_p	Origin-destination distance using path p
Lv , uv	Min and max allowable vessel speeds

Continuous variables

h_i	Delay time while working with vessel i
t_i	Mooring time of vessel i
e_i	Deviation from the location expected for the mooring of vessel i
p_i	Location of the mooring of vessel i

Binary Variables

m_{ik}^{pt}	1, if vessel i goes from port p to port k in period t and 0, otherwise
r_{iqt}	1, if working with vessel i starts at time t with q cranes and 0, otherwise
σ_{ij}	1, if vessel i departure time is before vessel j mooring time and 0, otherwise
δ_{ij}	1, if vessel i is fully below vessel j in the space-time diagram (i.e., looking from the berth, it lies fully on the right of vessel j) and 0, otherwise

Mathematical Model Configuration

We interpreted the problem defined in the previous section mathematically in this stage. The proposed model is a mixed integer linear programming (MILP) with an objective function and some constraints. The model objective function is of the cost type, which the model has tried to minimize.

- **Objective function**

Equation (2) shows the objective function of the present research, which consists of two parts. In the first part of the objective function, the first expression represents the cost of deviation from the expected time of arrival at the port of destination, the second expression represents the cost of deviation from the time of departure from the port, and the third expression represents the cost of deviation from the expected mooring place. In the second part of the objective function, the cost of fuel consumption is shown according to the speed of the ship if the ship crosses the p-route. Therefore, according to Equation (2), the purpose of the problem is to minimize costs both along the route and when mooring in the port.

$$z = \min \sum_{i \epsilon v} (c_i^w(t_i - a_i) + c_i^d h_i + c_i^p e_i) + \sum_i \sum_k \sum_p \sum_t \frac{D_p}{V_i} m_{ik}^{pt} (c^f G_i (F_i + V_i^{T_i})(B_i + C_i)^{2/3}) \quad (2)$$

- **Constraints**

The constraints on this issue are given below in the form of equations and inequalities (3) to (17). Constraint (3) causes each ship to be assigned to only one port and one route at a time. Constraint (4) states that when each vessel is moored at a berth and assigned to that berth, work on it shall begin once and shall not be interrupted when work on the vessel has begun, and the maximum time to work with the vessel shall be up to the end of the period is considered, and the number of cranes assigned to the vessel is between the minimum and maximum number.

$$\sum_k \sum_p m_{ik}^{pt} = 1 \qquad \forall i, t \quad (3)$$

$$\sum_{t=a_i}^{H}\sum_{q=q_i^{min}}^{q_i^{max}} r_{iqt} \leq 1 \qquad \forall i \in v \qquad (4)$$

in constraint (5), the mooring time of vessel *i* is equal to the total time spent on a vessel with q cranes in period t. In fact, this constraint correlates the variable r_iqtwith time. That is, if work on vessel i with q crane starts at time t and r_iqt is one, then the sum of the working time is equal to the time the vessel has been berth in port. This restriction also states that work with the vessel will start from the moment it anchors, and the total time of working with the vessel will be taken into account from the moment the vessel anchors.

$$t_i = \sum_{t=a_i}^{H}\sum_{q=q_i^{min}}^{q_i^{max}} r_{iqt}.t \qquad \forall i \in v \qquad (5)$$

Restriction (6) prevents vessels from overlapping at the same time. In fact, in this constraint, when σ_{ij} takes a value of one (vessel *i* leaves the port earlier than ship *j*), the limit becomes obvious because then t_j will definitely be greater than the total time that ship *i* is in port. However, if σ_{ij} does not become one and vessel *i* does not leave the port before vessel *j* arrives, then vessel mooring will be moored at a time other than when *i* is at the port.

$$t_j - t_i - \sum_{t=a_i}^{H}\sum_{q=q_i^{min}}^{q_i^{max}} (r_{iqt}.u_i^q) - (\sigma_{ij} - 1)H \geq 0 \qquad \forall i,j \in v, i \neq j \qquad (6)$$

Constraint (7) also prevents vessels from overlapping spatially so that if σ_{ij} is equal to one (vessel *i* should be in the same position as vessel *j*, and vessel *j* should completely cover it), the constraint causes the location of vessel *j* to be greater than the location of vessel *i* plus its length, and if σ_{ij} is zero, and two vessels Do not overlap spatially, this constraint will indicate that because it indicates the position of vessel *j* in a place other than the location of vessel *i*.

$$p_j - (p_i + l_i) - (\delta_{ij} - 1)L \geq 0 \qquad \forall i,j \in v, i \neq j \qquad (7)$$

In fact, it can be said that the two variables σ_{ij} and σ_{ji} work opposite each other because σ_{ij} takes the value of one when two vessels do not overlap in time but take one when two vessels overlap in space.

Constraint (8) states that vessels follow a certain order, both temporally and spatially, and that one of them is naturally placed before the other. This restriction also prevents ships from overlapping both spatially and temporally. Constraint (9) states that the location of the ship i cannot exceed the entire length of the port.

$$\sigma_{ij} + \sigma_{ji} + \delta_{ij} + \delta_{ji} \geq 1 \qquad \forall i,j \in v, i \neq j \qquad (8)$$
$$p_i + l_i \leq L + 1 \qquad \forall i \in v \qquad (9)$$

In Constraint (10), the number of cranes assigned to each ship in each time period is less than or equal to the total number of cranes available. Constraint (11) defines the delay in the departure of a vessel. Constraints (12) and (13) indicate deviations from the expected mooring position of the vessel.

$$\sum_{i \in v}\sum_{q=q_i^{min}}^{q_i^{max}}\sum_{\tau=\max(a_i, t-u_i^q+1)}^{t} r_{iq\tau}.q \leq Q \qquad \forall t \in T \qquad (10)$$

$$h_i \geq t_i - s_i + \sum_{t=a_i}^{H} \sum_{q=q_i^{min}}^{q_i^{max}} (r_{iqt} . u_i^q) - 1 \qquad \forall i \in v \qquad (11)$$

$$e_i \geq p_i - d_i \qquad \forall i \in v \qquad (12)$$

$$e_i \geq d_i - p_i \qquad \forall i \in v \qquad (13)$$

Constraints (14) to (16) control the speed of the vessel according to the optimal speed and the minimum and maximum allowable speed of the vessel. Constraint (17) expresses the relationship between the path allocation variable and the allocation for problem integration. This restriction states that the vessel will be serving at the port of destination if work has begun on route p to port k and has completed this route at the appropriate speed, resulting from the solution of the problem.

$$lv_i + max\{0, \hat{v}_i - lv_i\}. M \geq v_i \geq lv_i \qquad \forall i \in v \qquad (14)$$

$$uv_i \geq v_i \geq uv_i \ + min\{0, \hat{v}_i - uv_i\}. M \qquad \forall i \in v \qquad (15)$$

$$\hat{v}_i + max\{0, lv_i - \hat{v}_i, \hat{v}_i - uv_i\}. M \geq v_i \geq \hat{v}_i - max\{0, lv_i - \hat{v}_i, \hat{v}_i - uv_i\}. M \qquad \forall i \in v \qquad (16)$$

$$\sum_{q=q_i^{min}}^{q_i^{max}} r_{iqt} \leq \sum_{k} \sum_{p} m_{ik}^{pt} \qquad \forall i \in v, \forall t \in T \qquad (17)$$

σ_{ij},$\delta_{ij} \in \{0,1\} \forall i \in v$,$\forall t \in \{a_i, \dots, H\}$, ,$\forall q \in \left\{q_i^{min}, \dots, q_i^{max}\right\}$
h_i,$e_i \geq 0 \quad \forall i \in v$
$p_i \geq 1 \quad \forall i \in v$

To solve the problem, due to the nonlinearity of the model, first, the model is linearized, and then a complex integer linear programming model is used to solve it, the results and interpretation of which will be described in the next section.

Linearizing Proposed Mathematical Model

When a variable reaches the power of a parameter, it converts the model to a nonlinear model. In the model of this research, in addition to the existence of such a case, there is a multiplication of a bi-variable in this variable, which is linearized by making a variable change as follows:

$$uprim = V_i^{T_i} \times m_{ik}^{pt} \qquad (18)$$

By making this variable change, the following constraints need to be added to the model:

$$uprim \leq V_i^{T_i} \qquad (19)$$

$$uprim \geq V_i^{T_i} + \left(m_{ik}^{pt} - 1\right) M \qquad (20)$$

$$uprim \leq m_{ik}^{pt} M \qquad (21)$$

$$aa_s \leq V_i \leq bb_s \qquad s = 1{:}5 \qquad (22)$$

$$V_i = \gamma_s aa_s + \epsilon_s bb_s \qquad (23)$$

$$V_i^{T_i} = \sum_{s=1}^{5} \gamma_s \zeta_s + \epsilon_s \mathrm{K}_s \qquad (24)$$

$$\zeta_s = aa_s^{T_i} \qquad (25)$$

$$K_s = bb_s^{T_i} \qquad (26)$$

$$\gamma_s + \epsilon_s = \upsilon_s \qquad (27)$$

$$\sum_{s=1}^{5} \upsilon_s = 1 \qquad (28)$$

$$\upsilon_s = 0{,}1 \qquad (29)$$

The second part of the objective function of the model is due to the velocity variable at the denominator of the nonlinear fraction, and the fractional programming method has been used to linearize it. The linearization of this fraction is as follows:

$$cf \times G_i(B_i + C_i)^{2/3}\left(F_i \frac{D_p}{V_i} m_{ik}^{pt} + V_i^{T_i} \frac{D_p}{V_i} m_{ik}^{pt}\right) = cf \times G_i(B_i + C_i)^{2/3}\left(F_i \frac{D_p}{V_i} m_{ik}^{pt} + uprim \frac{D_p}{V_i}\right) = cf \times G_i(B_i + C_i)^{2/3} D_p\left(\frac{F_i m_{ik}^{pt} + uprim + ccV_i}{ffF_i m_{ik}^{pt} + hh \times uprim + V_i}\right) \tag{30}$$

$$cc = 0,\ ff = 0,\ hh = 0 \tag{31}$$

$$ff \times F_i m_{ik}^{pt} + hh \times uprim + V_i = \frac{1}{tt} \tag{32}$$

$$tt m_{ik}^{pt} = y1_{ik}^{pt} \tag{33}$$

$$tt uprim = y2 \tag{34}$$

$$tt V_i = y3_i \tag{35}$$

Therefore, to linearize the second part, the objective function will change as follows:

$$cf \times G_i(B_i + C_i)^{2/3}(F_i y1_{ik}^{pt} + y2 + ccy3_i) \tag{36}$$

And wherever we have $uprim$, $m_{ik}^{pt,}$ and V_i variables in the constraints, we have to replace them with new variables and also add the following constraints to the model:

$$y1_{ik}^{pt} - 3m_{ik}^{pt} \le 0 \tag{37}$$

$$-y1_{ik}^{pt} - m_{ik}^{pt} \le 0 \tag{38}$$

$$tt - y1_{ik}^{pt} + 3m_{ik}^{pt} \le 3 \tag{39}$$

$$y1_{ik}^{pt} + m_{ik}^{pt} - tt \le 1 \tag{40}$$

$$ff \times F_i y1_{ik}^{pt} + hhy2 + y3_i = 1 \tag{41}$$

$$y1_{ik}^{pt}, y2, y3_i \ge 0 \tag{42}$$

$$y1_{ik}^{pt} - 3m_{ik}^{pt} \le 0 \tag{43}$$

Constraints (38) to (43) due to the existence of the bi-variable m_{ik}^{pt} in the fraction will be added to the model to maintain its nature after changing the variable. If this variable is changed, it is necessary to linearize another item that has caused the model to be nonlinear:

$$x1_i = y3_i^{T_i} \tag{44}$$

$$kk_s \le y3_i \le ll_s \qquad s = 1:5 \tag{45}$$

$$y3_i = \tau_s kk_s + \chi_s ll_s \tag{46}$$

$$y3_i^{T_i} = \sum_{s=1}^{5} \tau_s \omega_s + \chi_s \mathrm{H}_s \tag{47}$$

$$\omega_s = kk_s^{T_i} \tag{48}$$

$$H_s = ll_s^{T_i} \tag{49}$$

$$\sum_{s=1}^{5} \Pi_s = 1 \tag{50}$$

$$\tau_s + \chi_s = \mathit{\Pi}_s \tag{51}$$

$$\mathit{\Pi}_s = 0,1 \tag{52}$$

In the article model, there are multiplications of two continuous variables that are changed and linearized in the following way:

$$zz_{ik}^{pt} = x1_i \times y1_{ik}^{pt} \tag{53}$$

$$lx1_i \le x1_i \le ux1_i \quad (54)$$
$$0 \le y1_{ik}^{pt} \le uy1_{ik}^{pt} \quad (55)$$
$$0 \le zz_{ik}^{pt} \le x1_i uy1_{ik}^{pt} \quad (56)$$
$$lx1_i y1_{ik}^{pt} \le zz_{ik}^{pt} \le y1_{ik}^{pt} ux1_i \quad (57)$$

Constraints (15) to (17) in the model's code cause the model to be nonlinear, which can be changed to linearize them in the following way:

The linearization of constraints (15) is as follows:

$$lv_i + \beta \times M \ge v_i \ge lv_i \qquad \forall i \in v \quad (58)$$
$$\beta \ge 0 \quad (59)$$
$$\beta \ge \hat{v}_i - lv_i \quad (60)$$

For constraint (16), as follows:

$$uv_i \ge v_i \ge uv_i + \lambda \times M \qquad \forall i \in v \quad (61)$$
$$\lambda \le 0 \quad (62)$$
$$\lambda \le \hat{v}_i - uv_i \quad (63)$$

For constraint (17), the following linearization is done:

$$\hat{v}_i + \mu \times M \ge v_i \ge \hat{v}_i - \mu \times M \quad (64)$$
$$\mu \ge 0 \quad (65)$$
$$\mu \ge lv_i - \hat{v}_i \quad (66)$$
$$\mu \ge \hat{v}_i - uv_i \quad (67)$$

Computational Results

Case Description

One of the two sections of the harbor of Bandar Abbas, southern Hormozgan Province, Iran, is the Port of Shahid Rajaee, which is situated on the north side of the Strait of Hormuz. About 14.5 kilometers (nine nautical miles) to the west-southwest of the Port of Bandar Abbas is the Shahid Rajaee harbor (worldportsource).

Shahid Rajaee Port's territory is 2400 kilometers in size. Three million TEUs (twenty-foot equivalent units) of containerized cargo are included in the port's yearly handling capability of 70 million tons of cargo. The port of Shahid Rajaee has 23 slots with a 15-meter parallel depth. Over 19 hectares of roofed buildings make up the total roofed warehouse space. There are 23.5 kilometers of local railroad lines at the port (worldportsource).

Eighty-five percent of all filling and offloading operations at Iranian ports take place at the Shahid Rajaee port. Out of 3500 major ports around the globe, Shahid Rajaee port was rated 44th in 2011. In contrast to the same period in the previous year, container loading for export from the Shahid Rajaee Port rose by 28% from 21 March to 22 August 2021, according to the director-general of Hormozgan Ports and Maritime Organization. Considering its exceptional location and situation of ports, Iran has a high potential to promote its share in the marine trade if it develops its container ports properly.

The current study focuses on Shahid Rajaei Port as a representative case to demonstrate the practical relevance of the framework. Future research could expand the scope to include comparative studies with other ports and utilize real-time data to further validate and enhance the model’s generalizability across different operational contexts.

Findings From the Proposed Problem

This problem was solved by a mixed integer linear programming model in GAMS Software (version 24.3.3) with the CPLEX Solver and resulted, as mentioned earlier, in routes that vessels take to reach the Persian Gulf Port (Fig. 4) as well as the vessel presence schedule at the port in the form of a space-time diagram (Fig. 5). We describe these figures as informative in the following discussion.

As shown, most vessels tend to use Route 1, which offers the shortest origin-to-destination distance. This highlights the significance of fuel costs, as a shorter route results in lower fuel consumption. Additionally, the reduced distance allows vessels greater flexibility in adjusting their speed to reach their destination more quickly. Assigning different routes to vessels has been based on the probabilities of Table (5).

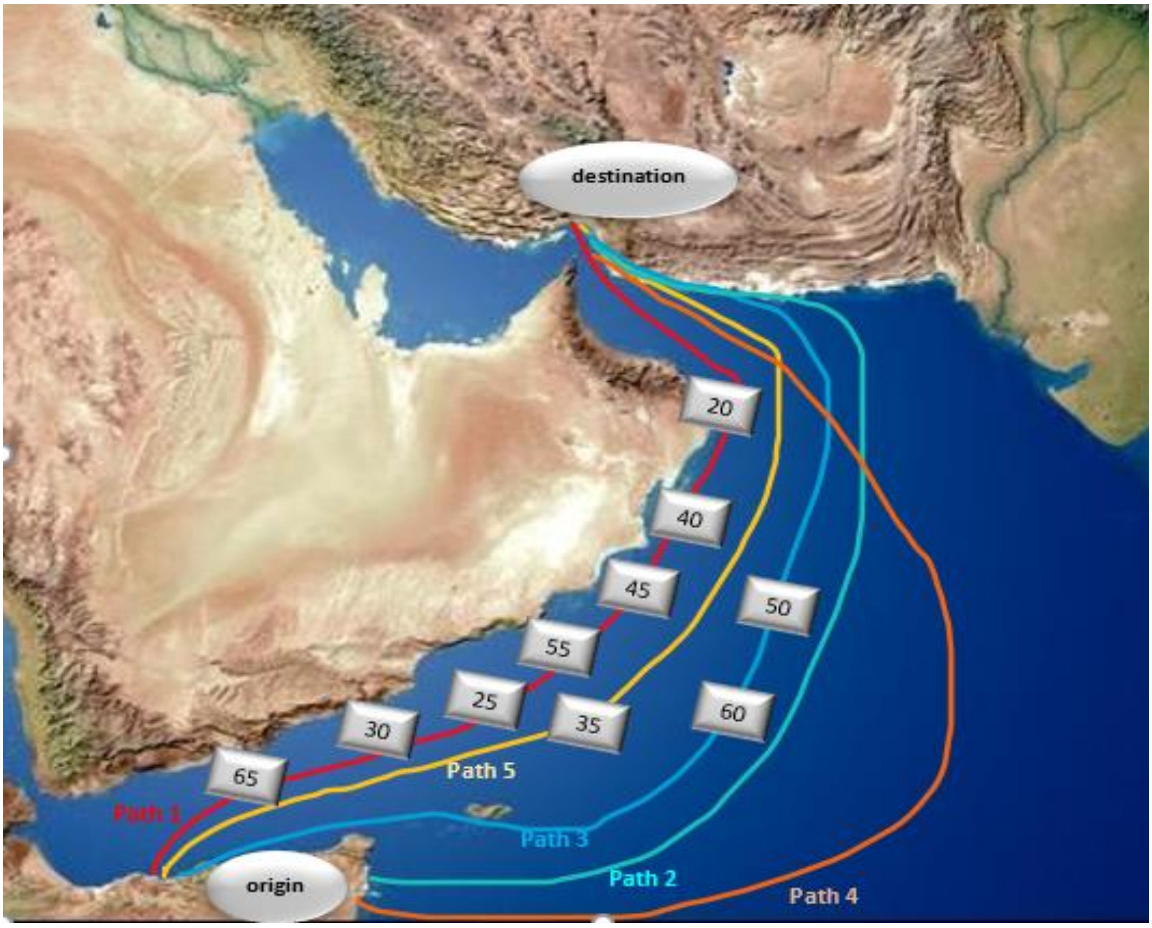

Fig. 4. Routes the problem model assigned to each vessel to pass

Table5. Vessels' route-selection probabilities

Vessel	20	25	30	35	40	45	50	55	60	65
Rout 1	0.351	0.669	0.704	0.325	0.725	0.618	0.200	0.709	0.218	0.433
Rout 2	0.149	0.083	0.074	0.084	0.069	0.095	0.199	0.073	0.127	0.110
Rout 3	0.149	0.083	0.074	0.181	0.069	0.095	0.200	0.073	0.218	0.110
Rout 4	0.149	0.083	0.074	0.084	0.069	0.095	0.200	0.073	0.218	0.110
Rout 5	0.202	0.083	0.074	0.325	0.069	0.095	0.200	0.073	0.218	0.236

When a vessel reaches the port from a certain route, it is assigned to a part of the port called "berth," with which the work begins; the model has assigned different parts of the port at different times, as shown in Figure (5). As shown, all vessels in the spatiotemporal schedule are able to berth and receive service at the port without any time or space conflicts. As previously mentioned, the Persian Gulf Port can accommodate up to 10 vessels simultaneously across its various sections. In Figure 5, the port accommodated 7 vessels during one period, 2 in the next, and 1 towards the end of the period. Each vessel was assigned two service cranes.

The deviation from the desired arrival time for all vessels was 20 hours, with no vessel arriving earlier than scheduled. This indicates that the initial plan was shifted by 20 hours to ensure all vessels could be serviced at the lowest possible cost.

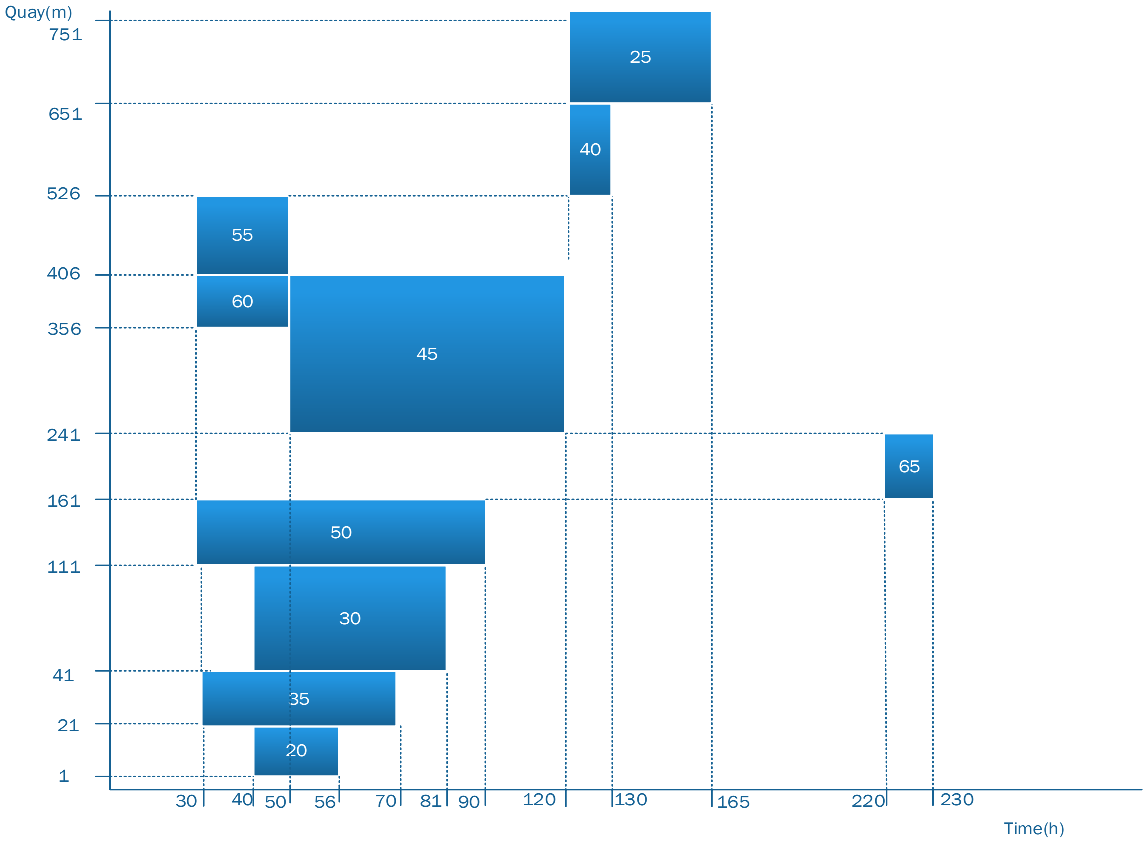

Fig. 5. Time and space assigned to vessels by the model

Table (6) presents the deviation from the vessels' desired mooring times. It provides a detailed comparison between the scheduled and actual mooring times for each vessel, highlighting any discrepancies. These deviations reflect adjustments made to accommodate port capacity, optimize resource allocation, and minimize operational delays. The information in the table is crucial for understanding how closely the port's operations align with the vessels' preferred schedules, allowing for an evaluation of the efficiency of the berth allocation process.

Table 6. Deviation from the desired mooring location

Vessel	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**
Deviation	29	551	11	9	496	211	81	186	256	131

Finally, the total cost – those of deviations from the desired spatiotemporal plan and those due to passing the route with a known speed – found for the problem objective function through a linearized model amounted to 7.94513×1015 which may be approximate because of the linearization. However, the GAMS Software has resulted in an absolute gap equal to zero and an optimal solution, which means that the linearized model itself yields exact solutions, but, in reality, it is an approximate linearization of the nonlinear model of which the result may be different from this value. The largeness of the obtained value of the objective function is because it is for ten vessels from the origin to the destination and includes the costs of fuel consumption, route passing, mooring, unloading, and loading in the port. As a large volume of petroleum products has been considered for each vessel to deliver from the origin to the destination in a 300-hr period, the total cost is quite considerable.

Sensitivity Analysis

The present study contains various operational and cost parameters that can play important roles in reducing the costs of transporting goods by vessel. The sensitivity analysis method is based on changing the values of different input parameters and examining the related effects on the variables as well as on the objective function. Applying this method to the operational and cost parameters of the problem revealed the extent to which each change affected the values of the variables and the problem's desired objectives and also showed that the changes in which parameter improved the vessel scheduling performance. Identifying the effects of important parameters revealed which parameters and parts of the proposed model had to be focused on more to reduce the costs.

To strengthen the sensitivity analysis methodology, we propose a multi-faceted approach for selecting percentage changes in fuel costs, vessel weight, and load capacity. First, historical data can be analyzed to identify typical variations, such as fluctuations in global fuel prices, guiding realistic percentage ranges. A scenario-based approach can then create optimistic, base, and pessimistic cases, reflecting potential future changes in these parameters. Additionally, a literature review of existing sensitivity studies and expert input from industry professionals can provide benchmarks and insights on expected variations. Finally, incremental testing of small percentage changes can help identify critical thresholds where operational performance is most affected. This comprehensive approach ensures that the sensitivity analysis is both realistic and robust.

Since the delayed arrival/departure costs and the deviation from the desired mooring location are among the important parameters; first, the effects of their changes by up to ±15% of the current value are examined.

Effects of the changes in the delayed mooring cost (c_i^w) on the value of the variable related to this cost ($|t2(i) - a(i)|$) are shown in Tables (7) and (8).

Table7. Effects of increased delayed mooring costs on the relevant variable

	Increased delayed mooring cost (%)				
Value of	10 times	2 times	50%	20%	5%
$\boldsymbol{|t2(i) - a(i)|}$	0	5	10	10	20

Table8. Effects of reduced delayed mooring costs on the relevant variable

	Reduced delayed mooring cost (%)				
Value of	0 CW	75% CW	50% less	20% less	5% less
$\boldsymbol{|t2(i) - a(i)|}$	94	50	25	25	20

As shown, the higher delay cost leads to a shorter delay time, causing the vessel to be in the port at the appointed time, and the lower cost result in a longer takes for the vessel to moor in the port; in other words, increased delay costs will reduce the delay (Fig. 6). As shown, delays tend to zero at high costs and increase at lower costs.

Changes in this cost have no effects on the value of the objective function because the mooring delay changes in such a way that it neutralizes the effects of the cost change. Results of the sensitivity analyses of the other two cost parameters concluded that they, too, did not have tangible effects on the total cost due to the high effects of the fuel cost on the value of the objective function explained next.

Another reason why the departure-time delay cost variations do not affect the objective function is h_i= 0 (delayed departure). When the solution yields a zero value for this variable, its related cost parameter will have no effect on the objective function, no matter how much it varies. Objective function changes relative to those in fuel costs by up to ±15% are shown in Tables (9) and (10).

As shown, fuel costs have a direct considerable effect on the objective function; a change of ±5% in it will highly change the value of the objective function (Fig. 7).

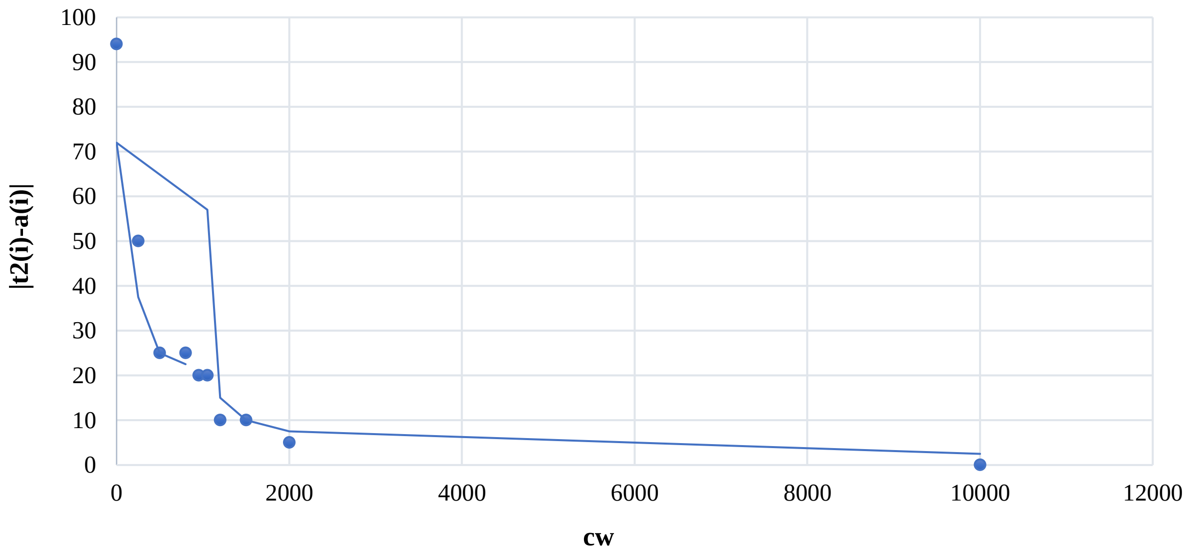

Fig. 6. Effects of varied delay costs on the delay rate

Table9. Effects of increased fuel costs on the objective function

	Increase in cf (%)		
Value of Z	15%	10%	5%
	9.13690×10^{15}	7.94513×10^{15}	8.34239×10^{15}

Table 10. Effects of reduced fuel costs on the objective function

	Decrease in cf (%)		
Value of Z	15%	10%	5%
	6.75366×10^{15}	7.15062×10^{15}	7.54787×10^{15}

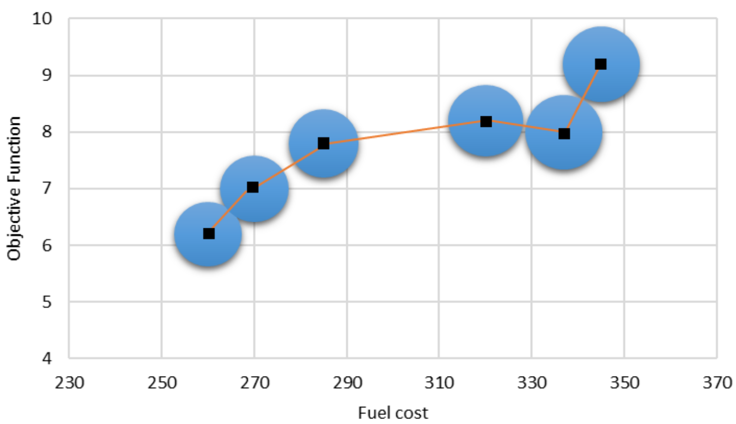

Fig. 7. Changes in the objective function relative to those in the fuel cost

As shown, since fuel costs have a direct severe effect on the total cost, they cause the effects of other cost parameters (e.g., delayed departures or deviations from the desired mooring locations) to weaken and fail to have a significant effect on the objective function.

Besides the fuel cost, there are other parameters (examined next) that affect the fuel consumption and the vessel speed and, hence, the objective function. Vessel weight is the first parameter studied for its effects on the objective function; as shown in Tables (11) and (12), up to ±15% change in the vessel weight will have a direct effect on the value of the objective function, i.e., the lighter is the vessel, the lesser is its fuel consumption and the faster it will move causing fuel costs and, hence, the total cost to reduce. Conversely, a heavier empty vessel necessitates greater fuel consumption for movement and results in slower travel, thereby extending the duration of the trip and increasing fuel consumption.

Table 11. Effects of increased vessel weight on the objective function

	Increase in vessel weight (%)		
Value of Z	15%	10%	5%
	8.16035×10^{15}	8.08893×10^{15}	8.01719×10^{15}

Table12. Effects of reduced vessel weight on the objective function

	Decrease in vessel weight (%)		
Value of Z	15%	10%	5%
	6.75841×10^{15}	7.80001×10^{15}	7.87274×10^{15}

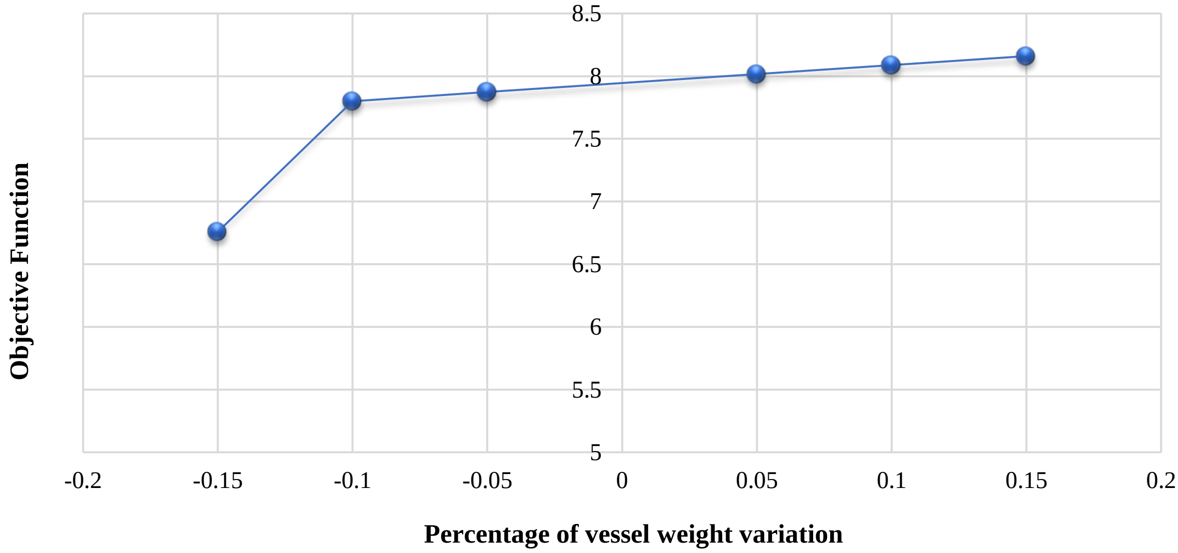

Fig. 8. Effects of vessel weight variations on the objective function

The impact of weight changes on the objective function becomes more evident in Figure (8). As depicted, an increase in vessel weight initially has a significant effect on the objective function value, and subsequently, it leads to a gradual rise in the total cost.

Besides weight, the vessel’s load-carrying capacity also has a direct significant effect on the fuel cost and, hence, on the total cost (Tables 13 and 14). As demonstrated, an increase in the mentioned capacity and the vessel's load-carrying capability results in greater vessel weight, which, in turn, demands more fuel. It is evident that this parameter exhibits similar effects on the objective function as vessel weight does. Also, Capacity change effects on the objective function are shown in Figure (9).

A comparison of Figures (8) and (9) reveals that the vessel capacity has a much greater effect on total costs than its weight because the slope of the variations of the weight effects on the objective function is much greater than that of the capacity. This, of course, makes it possible to apply necessary changes to the parameter that is more under control; weight is almost constant and cannot be changed much, while capacity can be changed (according to the costs affordable for fuel consumption) and used to control the total cost.

In summary, the findings underscore the dominant impact of fuel costs on the overall expenses associated with supporting a vessel throughout its journey. This underscores the significance of factoring in fuel costs when planning for vessel operations.

Table 13. Effects of increased vessel capacity on the objective function

	Increase in vessel capacity (%)		
Value of Z	15%	10%	5%
	8.32582×10^{15}	8.32582×10^{15}	8.13659×10^{15}

Table14. Effects of reduced vessel capacity on the objective function

	Decrease in vessel capacity (%)		
Value of Z	15%	10%	5%
	7.35623×10^{15}	7.55508×10^{15}	7.75133×10^{15}

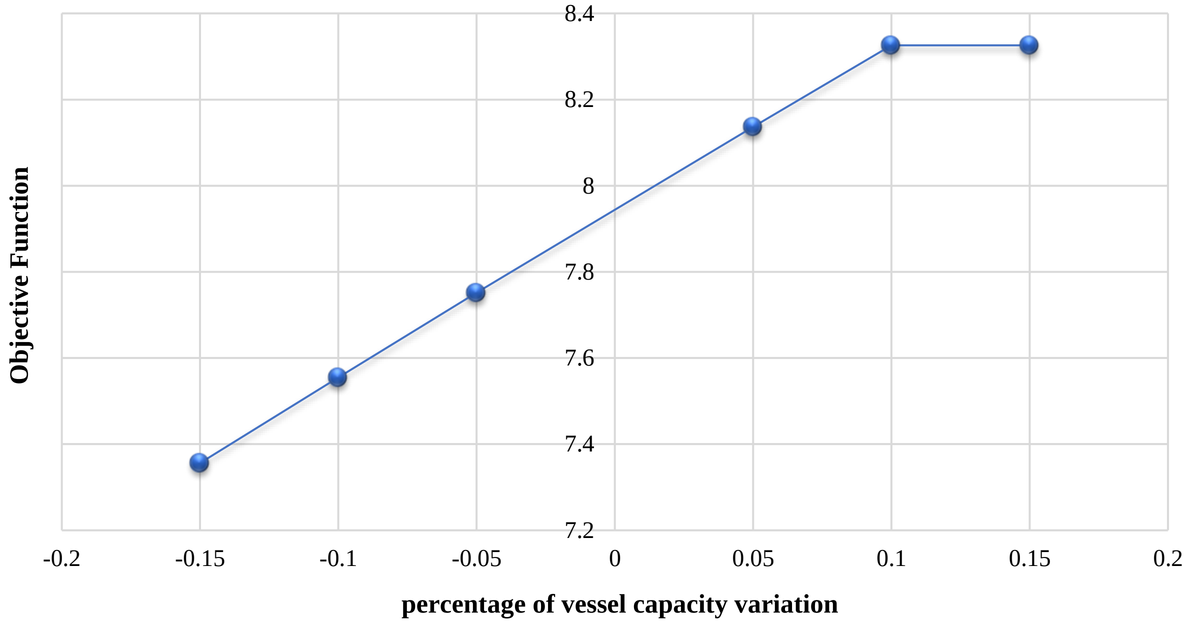

Fig. 9. Effects of vessel capacity variations on the objective function

Validation

Validation is possible by different methods, each of which can be used depending on the problem type. One method divides the problem into two parts and solves each separately. If the result is undesirable, it means that the model performs better in an integrated state and is, thus, valid. To examine the effects of integrating the route assignment and berth/crane assignment to the vessel, the model was first solved for the case where the two parts were separate. The model solution results for both the integrated and non-integrated modes are listed in Table (15).

Table15. model solution results for both the integrated and non-integrated modes

Solve the model in integrated mode	The result solves the allocation section alone	Result of solving the route allocation section alone
$7.94513*10^{15}$	$3.86*10^{5}$	$4.12714*10^{20}$

As shown, both assignment parts yield worse results in the separated mode than in the integrated mode because, in assigning routes, there is no time limit for the vessel to arrive at the destination on time; hence, it slows down its speed to reduce the fuel cost causing the voyage to take much longer and its cost to increase considerably. Therefore, if assignments are done under certain constraints imposed on the arrival time, the vessel will be forced to balance its speed and fuel costs, causing the related costs to reduce. Since this has great effects on the total cost in the integrated mode, its reduction will cause the goods transportation cost by vessel to be reduced.

In assigning cranes and berths, the related cost was better in the separated mode than in the integrated mode, but it is no longer possible to speed up the vessel's arrival time to the port by controlling its speed. In the port and loses the model of water pollution control, which depends on the length of time the vessel stays in the water and waiting for mooring, because when the vessel arrives at the port later than the scheduled time, it may have to wait a while for a mooring permit. Be on the dock. Therefore, with the integration of the model, it is possible to design a coherent and efficient plan for maritime logistics and prevent congestion in the port.

Hence, the port will encounter congestion of vessels, and the model loses control of water pollution caused by the vessels staying in the sea for a long time and waiting there for mooring. Integrating the model will enable a coherent and efficient plan to be designed for marine logistics to prevent the congestion of vessels in the port.

Conclusions

Global trade, an important and necessary step to achieve a sustainable economy, has different methods in all of which the displacement costs and amount of product to be displaced are important indicators for choosing an appropriate transportation mode. Marine transport has the lowest cost and the highest cargo handling capacity; hence, it is the best and the most effective method in global trade. Moving with the least speed and being the slowest transportation mode are among its specific features besides the mentioned merits. Since Iran has abundant water borders in the north and south, using sea routes for trade will lead to its economic growth. In this method, proper scheduling is very important for the product to reach the user on time because it increases customer reliability. As the highest CO_2 emissions are by vessels - this amount is 6-9 mg/km for only one tanker, controlling the speed of vessels for timely arrival, preventing their congestion, and reducing their waiting time for mooring in the port are quite serious issues in this regard.

This paper aimed to use the mixed integer linear programming approach to design an integrated marine route-logistics model that involved two parts: 1) assigning a suitable route to the vessel where it controlled the speed and, hence, the fuel consumption to reach the destination port and 2) assigning cranes and docks to the port. The model was aimed to minimize the costs related to delayed arrivals, moorings and departures, deviations from the desired mooring locations, and fuel consumption by controlling the vessel speed for timely arrival to the port, mooring at the right time, and preventing port traffic that elongated the vessel-stay in the port.

Achieving this goal reduced the vessel stay time in the port for either mooring or getting service in the port and, hence, reduced the water pollution. Since the proposed model was used in Shahid Rajaei Port Complex, Iran, as a case study and the analyses of the results showed that a concurrent assigning of routes to vessels and cranes/berths to ports reduced the overall marine transport costs, it is suggested that an integrated model should be used for greater productivity in ports. Using exact methods such as the Benders decomposition algorithm that yield accurate planning and cost solutions and considering uncertainty in such parameters as the vessel arrival time to the port, working time with the vessel, which is uncertain due to crane or berth failure, vessel departure time, vessel motion failure due to varied weather conditions and considering time window are other issues suggested for future researches.

As regards the management, it is suggested that 1) budgets be allocated and investments be made to improve the existing infrastructures to integrate activities and support vessels from the origin to the destination, which, according to the present study, will improve the scheduling and transportation performance and 2) experienced research teams be equipped in the “Ports and Maritime Organization of Iran” to review the past studies, eliminate weaknesses and improve the situation so that this solution method is used in Iran. Paying attention to the importance of such suggestions and using marine transportation for world trade will lead to currency inflow and an improved economy because Iran lies in the north-south corridor and connects the economic sectors in global logistics.

In this study, several simplifying assumptions were made, which present opportunities for future research. First, the assumption that operations continue uninterrupted once initiated could be relaxed to account for potential operational delays or pauses. Second, future studies could explore more complex scenarios where a berth or its positions may handle multiple vessels simultaneously or with dynamic allocation. Additionally, research could investigate varying crane characteristics and flexible crane availability, instead of assuming uniformity and a fixed number at each berth. Finally, assigning multiple cranes to a vessel during a given time period, or allowing for dynamic reassignment, could be another area of further investigation. Also, heuristic approaches could be explored to provide alternative solution methods and benchmark the performance of the integrated model, potentially enhancing computational efficiency for larger and more complex instances of the quay-crane and berth allocation problems. Furthermore, collaboration with port operators and real-time data integration could provide deeper insights into the model's operational performance and scalability.

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