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Optimizing Ship Routing to Maximize Fleet Revenue at Danaos

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In this paper we present an innovative toolkit that Danaos Corporation developed and deployed to optimize ship routing. Operations Research In Ship MAnagement (ORISMA) provides a clear answer to the conventional dilemma of least-cost voyage versus faster voyage. ORISMA maximizes revenue by using relevant information, including financial data, hydrodynamic models, weather conditions, and marketing forecasts. It considers the financial benefits after ship voyage completion to optimize the fleetwide performance instead of single-vessel performance. Using operations research and expert knowledge, we developed ORISMA to include world-class capabilities in scheduling optimization, intelligent voyage planning, ship bunkering, and chartering. In addition to maximizing Danaos' profit, it helps the company to minimize carbon emissions, reduce staff workload, and increase customer satisfaction.

Key words: voyage planning; dynamic programming; cargo transport optimization; maritime routing.

The maritime industry is responsible for transporting most of the world's commercial products. The 2011 annual report published by the European Community Shipowners' Associations (ECSA) states that the merchandise transported by ships in the European Union and European Economic Area zone represents 90 percent of its external trade (ECSA 2011).

Danaos Corporation is a leading international shipowner. It owns more than 60 containerships and is a key player in the complex and highly competitive shipping market. Each year, Danaos' vessels transport millions of containers, sail millions of miles to thousands of ports, and consume millions of tons of fuel oil. Danaos senior management, investors, and customers evaluate performance after each voyage and demand the highest level of operational quality. Accordingly, we developed an innovative tool, the Operations Research In Ship MAnagement (ORISMA) tool, which has become a key component in the provision of Danaos services. We derived our approach with guidance from our affiliate, Danaos Management Consultants (DMC). DMC developed and supports our world-class enterprise resources planning system, which holds a dominant position in the maritime industry.

ORISMA integrates financial data, hydrodynamic models, weather conditions, and marketing forecasts to determine the optimum ship voyage; accordingly, it allows the shipowner to determine the best ship-chartering option. Since its inception, ORISMA has supported Danaos' strategic goals of being innovative and creative. Its objective is to enrich, upgrade, and transform conventional maritime information systems to provide prescriptive analytics functionality. Using ORISMA, we are able to offer both data reports and intelligent, customized consultancy services using expert heuristics and in-depth operations research (OR) capabilities. Because it produces optimal solutions, it has generated millions of dollars in revenue for Danaos in the first year of its implementation. To demonstrate the full ORISMA capability in this paper, we first describe the ship-routing problem. We then describe ORISMA's development and implementation for a particular ship voyage. We demonstrate the results of the application on a micro (single-ship) and macro (fleetwide) scale. Finally, we emphasize that ORISMA is a breakthrough innovation for the maritime industry and also provides tangible benefits for the worldwide transportation sector.

Problem Description

From celestial to satellite navigation, the dilemma that sea voyage planners face centers around the trade-offs between a least-cost voyage and a faster voyage (i.e., cost savings versus time savings). By a least-cost voyage, we mean that we can significantly reduce the overall cost for a specific ship voyage if the ship sails at a lower speed than usual. That is, the ship will save on the cost of fuel by consuming less; however, it will arrive at its final port (destination) later—usually a few days later. Assuming that sufficient demand still exists for the ship's next employment, it will lose available operational time (days). By faster voyage, we mean that the ship will gain operational time; the obvious drawback is higher fuel consumption and, accordingly, higher fuel cost. For several years, we have tried to address this problem, keeping in mind the continuously changing nature of the shipping environment and of the state of the art of related theory and practice (Dimotikalis et al. 2010; Varelas et al. 2010a, b; Theodossiou and Grigoropoulos 2005). Summarizing these efforts, our objective is to maximize fleetwide net profit by optimizing ship routing over the long horizon rather than maximizing it based on one voyage. To achieve this objective, we consider in detail all the factors that may affect it by describing the ship-routing problem in a systematic way.

A ship does not necessarily optimize its fuel consumption (i.e., consume less fuel) when it sails at a constant speed along the shortest sailing path under given environmental conditions. From a scientific perspective, worldwide cargo transportation is an example of energy transformation. Chemical energy is transformed to mechanical work to overcome water resistance. However, from a business perspective, it can also be a profit-generating process, for example, by producing ton miles and consuming tons of fuel oil. Similarly, providing fuel to a ship (i.e., the ship's bunkering procedure) when the ship is along the quayside or in the anchorage area near the main port is the greatest cost factor. Although other operational costs (e.g., labor costs) contribute to the overall cost, fuel is by far the most significant factor. Hence, decreasing fuel consumption (e.g., by approximately 3 percent) can provide significant cost savings (Turan et al. 2009). Such savings are achievable by considering weather forecasts and by planning the ship's route to minimize the added resistance resulting from wind, wind waves, swells, and currents, thus minimizing nonproductive time and the resulting nonproductive costs—the costs of the additional time (days) that the ship requires to sail to a specific port because of the added resistance; nonproductive time reduces the ship's operational capacity (i.e., the available operational time that the ship has throughout the year). In recent years, various research centers have developed weather forecasting models, including wind-wave, swell, wind, and currents models, which the shipping industry has widely adopted (Journee and Meijers 1980, de Wit 1990, Spaans 1995, Kwon 2008). We can now obtain reasonably good two-week forecasts, and sophisticated interpolation techniques have improved the earth grid resolution to $0.25*0.25$ degrees, which is the latitude and longitude precision for a specific ship route; we use latitude and longitude to derive the forecasts for our optimized ship-routing process.

Conversely, the development of ship performance models enables the theoretical calculation of a vessel's performance index (measured in consumed tons of fuel per mile). In general, when a new voyage is ordered, the navigation officer, in conjunction with the ship's captain and company headquarters personnel, prepares the voyage plan. The navigation officer starts by recalling similar previous voyages, if any, and then studies the relevant terms and conditions of the commercial agreement (i.e., the charter party agreement) between the ship charterer and the shipowner and (or) manager for the specific ship route and cargo transportation. The navigation officer also uses the relevant navigation maps to draft the ship's course, splits the ship's voyage into passages, and draws them onto a ship's chart (i.e., gnomonic chart). The gnomonic map is a two-dimensional exact representation of the earth's oceans and seas, displaying all the earth's great circles as straight lines. The gnomonic maps are created by projecting the earth's surface onto a tangent plane. After consulting with the ship's captain, the navigation officer uses waypoints to plot the course the ship will follow for a particular voyage. A waypoint is a reference point that is drawn on the map and assists in specifying the exact voyage sequence. A ship voyage consists of several waypoints that are particularly useful when a ship sails long distances or in restricted areas or waters, because the ship will change its course several times before it reaches its final port. The captain transfers the selected waypoints onto the Mercator map—a map commonly used onboard ships for plotting the ship's course and navigating.

The shortest path between two points over the earth's surface is the corresponding arc of the greatest circle. We calculate its length by using the haversine formula (see the last section of the appendix). In previous times, sailors navigated along rhumb lines (i.e., lines crossing all earth meridians of longitude at the same angle). On modern ships, the captain plots the bearing of the ship's course on the map, ensuring that the ship sails along the same bearing without having to continuously change course. Following a constant compass bearing is easier than constantly adjusting the bearing, as following a great circle requires.

Consuming the least amount of fuel does not necessarily result in maximum profit for a given period and voyage between an origin-destination pair that have different positions along a ship's route; the next step in formulating the overall ship-routing problem addresses this reality. Paying more for fuel when a ship sails faster is common practice to save time when the time savings, expressed in terms of monetary values, may be higher. That is, the expected time-chartering equivalent (TCE), which is the time-saving unit expressed in US dollars, provides the potential income per day for a vessel used in predefined market boundaries. The in-house charterer is the officer who has responsibility for determining the vessel most suitable to a customer's request for container transportation from point X to point Y within a specific time horizon. To make decisions on fixing (i.e., arranging to transport a certain type and number of cargo containers) and planning a voyage, the charterer usually follows the empirical maritime common sense rule: full speed ahead whenever the ship anticipates a highly profitable next freight; economy (slower) speed whenever the result of marketing data analysis shows that profit from the next freight will be low. However, in day-to-day operations, this set of different scenarios can become much more complicated because fuel prices and market demand indexes change continuously.

Moreover, a shipowner who wants to plan a ship voyage to maximize the ship's daily revenue will try to achieve this over a horizon longer than a single-voyage duration. The charterer determines a voyage employment, which we term subject (i.e., cargo transportation from one port to another), among several alternatives; each alternative has a different path and freight (i.e., option). Accordingly, before making a decision, the charterer must evaluate each feasible next option for each subject by looking forward in time. A subject with low freight and a subsequent employment possibility of high freight might be a better option than a subject with initially high freight and relatively low next-employment freight. As an analogy, a taxi driver might prefer to go to an airport transporting low (or no) freight if the probability of transporting high freight on the way back is good. For scenarios with multiple subjects and multiple options, the problem's complexity increases, although optimum decision making is hard to achieve. Furthermore, the approach we describe is deterministic. Estimations for the succeeding options are stochastic, and their accuracy depends on the levels of expertise of the decision makers. We emphasize the importance of evaluating past decisions to determine the experts among the decision makers. We record each finalized decision and compare the corresponding voyage estimation to the actual data following the completion of a voyage. The smallest deviation implies a better decision, and we consider the associated decision maker an expert.

Additionally, fixing a vessel that is not chartered currently and that is closest to the departure port is not necessarily the optimum decision. In this case, we consider (1) the optimization of the ship fleet by minimizing the total idle time, and (2) the fleetwide long-term revenue maximization. This is a multicriteria decision-making process that considers the vessel's principal characteristics (e.g., age, capacity), position, and corresponding administrative costs. Older vessels could be fixed in low freight and vessels with high administrative costs should be fixed with high freight.

Moreover, waiting to fix a vessel while minimizing the bunkering cost does not necessarily maximize the net profit. The bunkering cost includes the costs for different types of marine fuel, such as marine gas oil, diesel, and heavier types of fuel oil, which will be consumed on board the ship. Sometimes, initiating a ship's voyage toward a potential future destination and port where it will load its cargo (e.g., a number of containers), rather than waiting to arrange or charter the cargo before sailing toward the container loading port, is a better decision. Therefore, ship management constantly seeks ways to minimize vessel idle time and maximize fleet utilization. The shipping company's operations department must often use its expertise to make a decision about a ship's route after the ship has discharged its cargo, but before its next employment, charter agreement, cargo, or port is known.

Another issue in planning ship routes is that a shipping company's objective to minimize the required ship fuel consumption (in tons) for a given ship voyage does not necessarily minimize the bunkering cost, because the company must also consider the fuel price variations per port. The bunkering operator, who is responsible for reviewing and drafting the ship's voyage bunkering plan, must consider market data (e.g., fuel prices, trends, availability), vessel attributes (e.g., fuel type, fuel storage capacity, vessel speed, fuel consumption per mile), and operational data (e.g., fuel remaining on board, fuel safety, minimum fuel quantity, distance to be covered) to compile this bunkering plan. The objective is to find the optimum bunkering cost for the specific ship voyage to conform to safety and technical constraints. In most cases, the bunkering operator empirically determines the bunkering plan, which then proves to be feasible and satisfactory only when the ship's schedule is simple and straightforward. However, in day-to-day ship operations with complicated bunkering schedules, a conventional bunkering plan is not optimum. In this situation, the bunkering operator must consider a variety of factors, including the overall marine fuel quantity needed for a specific trip or combination of trips, the specific quantities of the various types of marine fuel remaining on board, the places or ports of bunkering, and the price of these types of marine fuel at the various ports that the ship will approach. We can solve this problem using linear programming, where lower bounds ensure that enough fuel will be available to cover the next voyage leg and upper bounds prevent overfilling the fuel tank's capacity. Therefore, we must carefully and accurately formulate a process to address a problem that would otherwise be time consuming and create operational frustration.

The ORISMA Solution

ORISMA optimizes the overall fleet utilization by offering a high degree of scheduling optimization, intelligent voyage and bunkering planning, and commitment to charters. We measure fleet utilization as the total number of vessel employment days per total available vessel days. The in-house chartering department focuses on finding the proper employment for the right vessel (i.e., a vessel that is free and close to the loading port). Fleet scheduling assigns the most suitable vessel to each employment option to maximize the fleetwide revenue, rather than single-vessel voyage net profit. The objective of intelligent voyage bunkering is to minimize the cost of bunker fuel based on the spatially distributed prices of bunkering suppliers; we suggest new routes that lead to fuel cost efficiency. Intelligent voyage planning maximizes profit, while satisfying the overall chartering plan and chartering clauses. Examples of chartering clauses include payments in case of delay (demurrage) or bonuses for traveling through war zones.

We compile alternative chartering plans and then fix employments. When employment has been fixed, the voyage has been planned. The volatile and highly competitive nature of marine shipping poses many challenges to this optimization process. We overcome these challenges by using reliable information (e.g., vessel particulars, potential customer details, and financial data), which we retrieve from both external sources (e.g., the freight and bunkering market) and internal sources (e.g., Danaos' operational and administrative departments).

Our approach to ship-routing issues is to select and optimize ship routes by responding to all relevant variables by adjusting the ship's speed as a vector of the time and prevailing weather conditions of the specific sailing area and route. These variables include added resistance (e.g., because of wind, wind waves, swells, and currents), ship fuel consumption, charter party agreements, and navigation maps. Using ORISMA, we consider weather forecasts and suggest a series of actions to minimize added resistance by adjusting the ship's speed and evaluating possible deviations from the original planned route; as a result, we can save fuel costs. In Figure 1, we demonstrate an optimized ORISMA route as a series of dotted lines and compare it to the continuous plotted line of a conventional voyage from the United Kingdom to the US East Coast, as planned by a navigator.

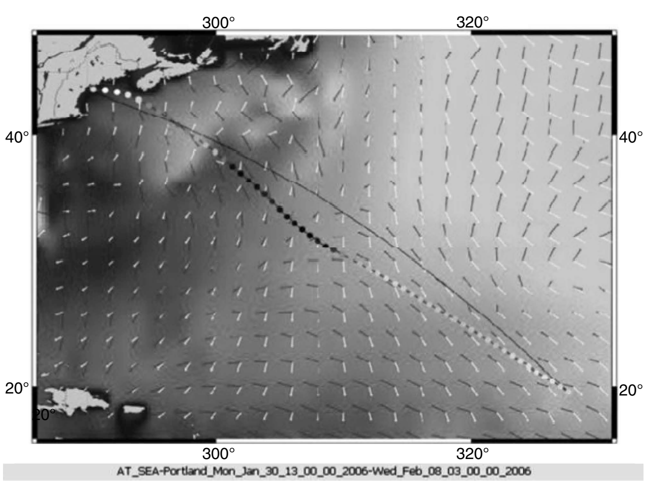

Figure 1: This screen shot shows an ORISMA-optimized ship route (dotted line) versus the conventional planned route (continuous line) for a vessel travelling from the United Kingdom to the US East Coast. The route represented by the dotted line is an optimized route because ORISMA considers the prevailing conditions in the specific ship route, thus saving tens of tons of marine fuel.

We incorporate the estimated next daily income into the objective function of ORISMA. This case is more complex when more than one chartering option and more than one alternative for subsequent vessel employment are available. Using ORISMA, we also develop and combine a number of functions, including an optimized weather routing process (i.e., the best option for a ship route considering the weather conditions at the time and place of the specific ship voyage), single-voyage efficiency, and an optimum bunkering plan, into an integrated approach to maximize the revenue over at least two consecutive voyage periods (e.g., from port X to port Y and from port Y to port Z).

We specify, implement, and appropriately integrate fleet-scheduling functions to minimize the idle time and to search for a way to optimize fleetwide revenue. We also describe this operational ship management issue by recording and evaluating existing business practices.

Initially, we addressed the geometrically formulated problem of a move from a port to two potential destinations by determining the interior point of a given triangle, where the sum of its distances from the three vertices is minimized (Varelas et al. 2010b). We transformed this triangle model to an appropriate business model to reflect real-life conditions. In particular, the various chartering alternatives are not necessarily equally likely, and the sides of the given triangle and the distances of internal points of the triangle from its vertices are not rectilinear sections, but are sets of the arcs of the largest circle. Therefore, we also satisfy spatiotemporal restrictions imposed by geography, regulations, and safety.

Relative to a ship's routes to eventual ports of call, we specify an intermediary destination that could also serve as a point of waiting. Given the time upper limit for the alternative ship routes and durations, we use dynamic programming to propose a new routing schedule that lessens idle time. Eventually, we determine that the ship should start its voyage toward the next potential port of call, sailing from one plotted point on the map to another; however, it should not wait for the company to fix a charter agreement before it sails toward a specific port. We call this model the go-and-stay model. This follows a well-known rule in the shipping industry: an unfixed vessel departs in an empirical direction to save time for its next employment.

We can further reduce the bunkering costs by minimizing the required quantity of fuel the ship consumes and by compiling an optimum bunkering plan that considers fuel price, which can vary substantially in different ports. ORISMA incorporates an advanced heuristic algorithm that optimizes the bunkering cost per voyage. We combine the weather routing process, single-voyage efficiency, and intelligent bunkering plan that we developed into an integrated approach to maximize revenues over at least two voyage periods. ORISMA transparently incorporates information from all involved company departments (i.e., chartering, bunkering, freight collection, accounting, finance) into an integrated approach based on common data, models, and knowledge, anticipating that if the maritime information system is necessary today, the need for a formal management system will be obvious tomorrow. We integrated ORISMA with the Danaos enterprise information system, and use a common database in which all data are recorded, managed, and presented to the users based on their access privileges. Using the ORISMA optimum bunkering model, Danaos achieved savings of up to 3 percent (approximately $100,000 for a 10-day voyage) using the same fuel consumption.

ORISMA Example

In this section, we discuss an example of the ORISMA routing tool to illustrate its function. A bulk carrier with a 17.0-meter draft and engine power of 25,000 horsepower sails from the United Kingdom [58° 16′ N 8° 20′ W] with its destination as the US East Coast [43° 0′ N 65° 18′ W]. The route that ORISMA suggests avoids high-resistance sailing areas, especially areas with head-of-swell and wind-wave conditions (see Figure 2).

Although the fuel oil consumption (FOC) is higher because of the additional resistance in the ship's ORISMA route, the related FOC resulting from the ship's main propulsion is much lower (see Table 1).

Considering the weather factors and the vessel's overall behavior, Table 1 shows that we reduce the optimum route distance by 10 percent and minimize the en route time by about 45 percent. Although the FOC increases by 36.5 percent as a result of the ship's main propulsion (i.e., higher ship speed), we concurrently reduce the FOC resulting from added resistance by almost 70 percent, reducing the overall ship FOC by more than 20 percent. Taking into account the price of intermediate fuel oil at $350 per metric ton (MT) and expected TCE of $66,000 per day, we can easily interpret the above figures in terms of monetary values (see Table 2).

Assuming that the fuel consumption is directly proportional to the ship's carbon emissions, the resulting environmental impact is positive and substantial, as Varelas and Archontaki (2011) quantify. In Figure 3,

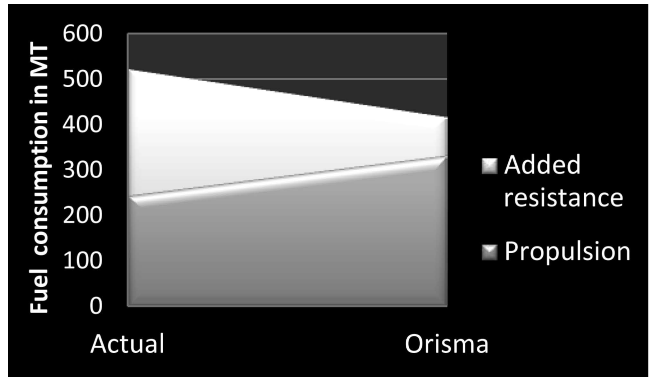

Figure 2: In this figure we compare the fuel oil consumption (FOC) in metric tons (MTs) of the route determined by conventional methods and the FOC for the route recommended by ORISMA for a ship traveling from the United Kingdom to the US East Coast. The ORISMA-recommended route consumes more fuel because of the main propulsion; however, it saves more fuel by avoiding high-resistance areas.

Variable	Actual	ORISMA	Savings	Savings %
Distance in nautical miles	2,580	2,317	263	10.2
Duration (in hours and minutes)	292 h	157 h 52 m	134 h 8 m	45.9
Propulsion in metric tons	244	333	−89	−36.5
Added forces in metric tons	280	85	195	69.4
Total consumption in metric tons	524	418	106	20.3

Table 1: The table compares the conventional (actual) and the ORISMA-suggested voyage distance, voyage duration, fuel consumption, and time required for the voyage that Figure 2 illustrates.

Cost element	Savings ($)
Bunkering cost savings	37,100
Time cost savings	368,500
Total cost savings	405,600

Table 2: The table summarizes the results of the ORISMA saving analysis for bunkering and time costs for the voyage described in Figure 2 and Table 1.

we present the wind diagrams for the same starting and finishing ports in the ship's route for both the ORISMA and conventional ship routes, and can easily observe that the ORISMA-recommended route minimizes wind resistance.

Implementation

During the ORISMA implementation, we encountered several difficulties, including an initial lack of knowledge and related training, resistance to change, and lack of motivation on the part of staff at the destination ports and on the vessels. Therefore, we developed and used several models before we determined the final ORISMA version. For example, we spent considerable time testing the method of calculus variation, which treats ship routing as a continuous optimization process. However, our initial results were imprecise; errors could reach an unacceptable level in our final calculations when we used second-order differentials in this optimization process. To avoid these inaccuracies and inconsistencies, we eventually developed a dynamic programming method based on Bellman's principle of optimality (Bellman 1957).

Before the implementation stage, we compiled a change management plan (Huse and Cummings 1989, Carnall 1995) and developed the appropriate training material to overcome significant barriers in the underutilization of our system (Banks et al. 2011, Cui et al. 2011). We highlight the importance of the change management plan, because it is fundamental to Danaos' efforts to achieve flexibility and responsiveness to adapt in the everchanging shipping business and its operational environment. The changes that may occur, particularly when introducing new technologies within a company, can be either small or radical, depending on the organizational structure, the company size, and the involvement of relevant stakeholders. However, to ensure that the transition to a new organizational structure is as smooth as possible, the company must proactively implement these changes, focusing on employee acknowledgement, participation, and eventual satisfaction. We achieved a successful transition by using continuous training, including training courses and one-to-one sessions, to support our employees and to ensure the full-scale implementation and operation of the ORISMA platform.

The difficulties we faced during ORISMA's implementation stage generally relate to portability and integrity resulting from a lack of standards in the interfaces. To overcome these difficulties, we developed gateways using commercial schemas to provide the appropriate architecture. In addition to the wind, wave, and current attributes, other factors influence

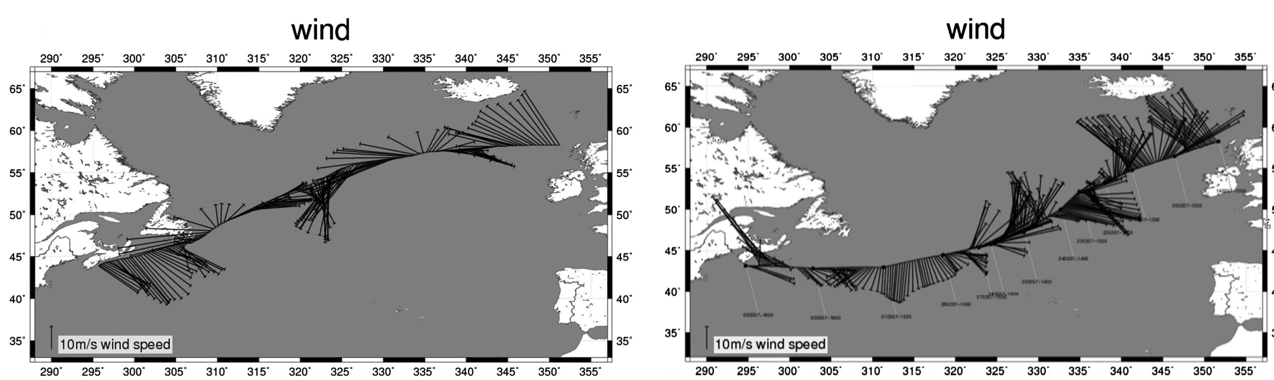

Figure 3: We compare wind diagrams for the optimal ORISMA-suggested route (left) and the actual route (right) for the example described in Figure 2 and Tables 1 and 2. The two figures in the graphic show that ORISMA recommends a route that minimizes the added wind resistance.

the voyage performance index; these include the trim, pitch, type of propeller(s), and condition of a ship's hull. Therefore, we can usually observe fluctuations between the theoretical calculated performance index and the onboard actual measurement of this index. As we expected, the actual consumption data and the calculated data from the hydrodynamic model differed by approximately a systematic deviation. To overcome this deviation, we enhanced the model with a feed-forward-back propagation artificial network. We applied the weight assignment method, a recursive procedure based on the training-the-network process (Dimotikalis et al. 2010). We initially applied a random weight function on index I attributes, such as wind, wind-wave, and swell resistance. We then introduced the first observation into the network, predicting values of output I. We next used the latter to derive the training data of I, which we used to populate the original modeling values. We then compared them to the corresponding predicted values; finally, we adjusted the optimum weighted index I function to minimize the error prediction. We used the new weighted function in the next observation and continued the repetitive training cycles until we achieved a sufficiently small prediction error.

Through the continuous research, application, and validation stages of the ORISMA toolkit, we also learned that the algorithms we used to find the best ship route for calm weather conditions between any two waypoints that avoid land, restricted areas, war zones, draft limitations, and navigation rules, were difficult to extract. Therefore, we subsequently decided that we could use ORISMA to cross-check and validate the initial ship route that the ship's captain defined initially. We then used this route, including the waypoints predetermined by the captain, as a basis to define the domain of alternative ship routes (Varelas and Archontaki 2011). We developed an artificial intelligence module that provides the shortest-path route between two waypoints. This module digitizes the map, generates parallelograms of restricted areas, and generates paths to avoid the restricted areas. We use the ORISMA-suggested route as a complementary tool to assist the ship's captain in planning the ship's actual route, taking into account the actual prevailing sea and weather conditions.

Realized Benefits

Danaos Corporation concluded that its 2011 incremental revenues from using ORISMA were \$1.3 million from time savings and \$3.2 million from fuel savings. Danaos used ORISMA for 30 vessels in 2011; as of this writing, it intends to use the tool for its entire fleet of 65 vessels in 2012. Based on Danaos' experiences so far, we believe that the full integration of ORISMA into the Danaos ship management platform will provide additional financial benefits, because it will improve operational efficiency, the quality of service offered to Danaos clients, and Danaos' profitability by 7–10 percent annually. We also believe that we can achieve additional, significant advantages that are difficult to quantify. These include lowering carbon emissions and improving safety on board ships by providing detailed forecasts that allow a ship's captain to avoid adverse weather conditions. Moreover, based on customer feedback throughout the ORISMA implementation, we achieved increasingly high levels of satisfaction and bolstered customer trust in our ability to successfully transport their goods with our vessels.

Furthermore, because ORISMA's overall concept proved to be feasible, Danaos decided to commercialize ORISMA as a product. It started by using the large repository of DMC customer vessels; customers enthusiastically welcomed the ORISMA tool. During the first year of ORISMA implementation, nearly 250 vessels belonging to DMC customers used the ORISMA platform either fully or partially.

Conclusions

Throughout the ORISMA project implementation, we considered a number of factors. These include the use of navigation expertise, combination of business knowledge with innovative and creative thinking, use of applied research, proper description of the problem statement, and use of simulation techniques for the repetitive cycle of testing, evaluation, and refinement. During the implementation stage, we used and adjusted both the existing OR models and the new models that we developed.

Our customers (i.e., the shipping companies in the DMC customer base) welcomed the ORISMA platform because of its simplicity, efficiency, and accuracy. Our novel approach provides a more optimized ship route than the conventional process. However, our process can be refined further to improve the decision-making effort. We encourage academia to do additional applied research in the transportation operations practice and to also apply ORISMA in other business areas. For example, the go-and-stay model might have applications in financial investment analysis, and the multicriteria chartering decision model might be applicable to the rental car and real estate businesses.

Many researchers have developed algorithms with the minimization of ship fuel consumption as their objective. The most popular methods include calculus of variations, and modified isochrone, isopone, and genetic algorithms. However, none considers the individual vessel behavior, the sea-keeping data, and the most important factor—the cost of time. These methods also ignore the importance of maximizing the overall fleet utilization, minimizing idle time, and considering the results of market trend analysis. We address these factors in ORISMA by using an integrated ship management platform. We also enhanced ORISMA with several modules that address intelligent crew planning, supplier appraisal and selection schemas, and risk assessment to minimize proportional and fixed operational costs (Varelas and Archontaki 2010). During the initial implementation stage, we significantly improved business administration efficiency. Decision makers are now able to use an integrated approach that enhances teamwork, improves creativity, and drastically reduces staff day-to-day workload. Moreover, universities and institutes, such as the University of Strathclyde, the Business College of Athens, the Technological University of Crete, and the Hellenic Marine Environment Protection Association (HELMEPA), have incorporated ORISMA into their academic programs as a best business practice paradigm. We are continuing to improve and refine the ORISMA solution to provide greater business value for our clients.

Appendix. Model Formulations

Routing Cost Minimization

We define each vessel route j as a voyage through n ordered x_{ij} nodes (physical points). The objective is to find the route with the minimum fuel oil consumption (FOC), as the summation of the FOC of each leg that links two consecutive nodes and the consumption resulting from any projected deviation. We calculate the FOC per leg as the product of FOC per mile (l_j) by the sum of the traveling distance and the overhead of the deviation, if any.

We formulate the weather-routing cost-minimization problem as follows.

$$\exists\, r_j \in O\{r_j = \{x_{ij} \mid i = 1:n\}\}:$$
$$\mathrm{FOC}_{\min} = \mathrm{FOC}(r_j) = \sum_{i=1}^{n} l_i * (S_i + dv_i), \tag{1}$$

with variables defined as follows:

r_j: all alternate routes;
O: the orbital set of all the alternate routes r_j;
$x_{ij} \mid (i = 1:n)$ n nodes i of route j that are linked with the shortest path;
FOC: fuel oil consumption in metric tons, subject to weather conditions and vessel particulars;
l_i: performance index (fuel oil consumption per mile) from node i to node $i+1$;
S_i: distance in miles from node i to $i+1$;
dv_i: whenever a vessel needs to deviate from the shortest path, additional miles are covered;
dv_i: definition of this deviation in miles (i.e., the additional distance traveled between node i and the next node $(i+1)$ beyond the distance of the shortest path from i to $i+1$).

Routing Cost and Time Minimization

Considering the value of time, we enhance the previous model as follows;

$$\exists\, r_j \in O\{r_j\colon \{x_{ij} \mid i = 1:n\}\}:$$
$$c_{\min} = c(r_j) = \mathrm{TCE} * t_j + \mathrm{FOC}(r_j) * p = \mathrm{TCE} * t_j + \sum_{i=1}^{n} l_i * (S_i + dv_i) * p, \tag{2}$$

with variables defined as follows:

p: fuel oil price ($/ton);
t_j: time to travel route j;
c: total cost;
TCE = Time chartering equivalent in $/day (potential daily income from chartering).

This model is further extended to cover multivoyage planning, where the evaluated potential scenarios have multiple consecutive voyages.

Optimal Bunkering

In the optimum bunkering problem, a vessel that departs from port A_1 will berth at ports A_i and will arrive at the final destination port A_n. The objective is to minimize fuel consumption:

$$\text{Minimize } f = \sum_{i=1}^{n} q_i * p_i, \tag{3}$$

with variables defined as follows:

q_i: purchased quantity of fuel oil in metric tons at port A_i;
p_i: price in $ of a fuel oil ton at port A_i.

The remaining fuel oil on board, rob_i, at port i should be sufficient to cover the required fuel to cover the distance to the next bunkering port. Also, the rob_i onboard fuel quantity at port i should be less than the vessel tanks' capacity cap. The following two constraints keep the fuel quantity purchased between its bounds and keep track of the remaining onboard fuel quantity after purchases and consumption.

$$c_i - rob_i \le q_i \le cap - rob_i, \tag{4}$$

$$rob_i = rob_{i-1} + q_i - c_i, \tag{5}$$

where

c_i: consumed fuel in tons for the (A_i to A_{i+1}) vessel route leg.

Minimize Idle Time Whenever Next Employment Is Not Fixed

Whenever a vessel is idle at node C and n eventual alternative employments nodes D_n exist, we advise the ship's captain to sail for a waiting node (G) to maximize the profit by saving time, although an additional movement cost is needed:

$$\text{maximize } f = \sum_{i=1}^{n} time \cdot saving \cdot profit_i - \text{FOC}_i, \tag{6}$$

with variables defined as follows:

$\text{FOC}_i = \text{FOC}[G - D_i] + \text{FOC}[C - G] - \text{FOC}[C - D_i]$: bunkering cost from C to destination D_i through G minus the bunkering cost of proceeding directly from C to D_i;

$time \cdot saving \cdot profit_i = \text{TCE}_i * (t[C - D_i] - t[G - D_i])$: incremental improvement in profit because of a faster route from C to D_i through G versus a direct route from C to D_i;

$\text{FOC}[A - B]$: the fuel oil consumption cost from node A to node B;

$t[A - B]$: the time in days to move from node A to B.

Haversine Formula

The shortest distance between two points on earth is calculated by the haversine formula as follows:

$$Distance = R * C,$$

where R is the earth's radius (mean radius = 6,371 km), $C = 2a\tan 2(\sqrt{a}, \sqrt{(1-a)})$, and

$a = \sin^2(\Delta\text{lat}/2) + \cos(\text{lat}_1)\cos(\text{lat}_2)\sin^2(\Delta\text{long}/2)$;

$\Delta\text{lat} = \text{lattitude}_2 - \text{latitudue}_1$: $\Delta\text{long} = \text{longitude}_2 - \text{longitude}_1$;

lat_i = latitude of point i: lon_i = longitude of point i.

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