Shipping company planners face complex problems every day. Now, thanks to O.R., help is on the way.

Today’s globalization would be impossible without modern, cost-effective merchant ships crossing the seas. World trade was 17 times as high at the end of the 20th century as it was 50 years previously. A shipping industry that has steadily lowered its costs has been a prerequisite of this development, and there are no signs that the world economy will rely any less heavily on sea transport in the future.
Nevertheless, both the current financial crisis and the global need to cut CO₂ emissions are challenging ship owners, as they are most industries. Maritime transport optimization is one important answer to both challenges. New tools to help planners solve their task more effectively are being developed and will soon emerge on the market.

In terms of energy consumption per unit transported, shipping is by far the most efficient way of transporting goods. Wherever alternative methods of transport are available, sea transport should therefore be preferred from a global warming perspective. However, like all other carriers of goods, maritime transporters need to reduce their CO₂-emissions yet further, even though they have already made considerable cuts. Ships used only 0.025 kg of fuel to transport one container one nautical mile on the voyage from Asia to Europe in 2007, compared to 0.200 kg in 1970.

Better planning of maritime operations is one of several measures that will lower emissions per transported volume further. At the same time, this measure will reduce the cost of transport and make transport more timely and efficient — valuable contributions when it comes to keeping the wheels turning in a world economy dominated by financial problems.

**Improved Fleet Utilization**

**DEVELOPED IN NORWAY,** TurboRouter is an O.R.-based decision support tool for ship routing and scheduling [1,2] that has already been implemented and tested by a number of shipping companies. One company compared plans obtained by using TurboRouter with solutions from manual planning. The
In 1939, a large ship-model towing tank was inaugurated in Trondheim. This made it possible to perform model tests to improve vessel design, which in turn made it easier to win contracts in the global shipping market.

After petroleum production started on the Norwegian continental shelf in 1971, the need for more research into maritime constructions became apparent. A new research laboratory, the Ocean Basin, was opened in 1979 in a building adjacent to the towing tank.

Until recently, the main focus of maritime research in Norway was technical construction. However, during the last 10 years research on how to operate ships more economically and efficiently has increased in Norway, as it has in the rest of the world.

**Ship Routing and Scheduling**

A planner in a shipping company has to solve a complex puzzle every single day. Vessel operation costs tens of thousands of dollars per day, and the income from carrying a single cargo can be in the hundreds of thousands. In spite of the complexity of the planning problem and the money at stake, most planners in shipping companies solve their puzzles manually, based on their experience.

In contrast with the situation in airlines and road-based goods transport, only a few shipping companies use O.R.-based decision support systems in building complete fleet schedules. Most companies have voyage calculation tools that consider one ship at a time, and evaluate the feasibility and economic consequences of assigning a given cargo to a specific vessel. However, considering only one ship at a time will clearly lead to suboptimal plans.

This is how complex the puzzle can be:

On any given day, the planner has a number of cargoes that must be transported within the planning horizon. Each cargo consists of a specific quantity of goods that have to be picked up in a given loading port and delivered in a given unloading port.

There is usually a time window that specifies when loading can begin, and sometimes also for discharge. The cargoes are usually known some time in advance, specifying the planning horizon.

To transport these cargoes, the planner controls a heterogeneous fleet of ships, each with a given service speed laden and ballast, cargo-carrying capacity, fuel consumption, loading/unloading equipment and cost structure. In contrast to most land-based vehicle routing problems, the ships in the fleet will usually have different initial positions at the time of planning, and these may be any port or point at sea.

Since planning follows a rolling horizon principle where plans are updated daily, the ships may already be carrying cargoes that must be taken into account. In some modes of operation, ships always carry only one cargo at a time, while in others they carry multiple cargoes simultaneously.

The task of the planner is to find the minimum cost or maximum profit plan for assigning cargoes to the available ships in the fleet and to existing routes and schedules, while observing a large number of complex constraints. In addition to satisfying the capacity and time windows for the cargoes, several other constraints may have to be considered, such as...
ship-port compatibility. Whether a ship can visit a port may depend on the cargo it is carrying.

The planner must also take into account the possibility that some ships in the fleet have planned dry-docking, which means that the ship will not be available within some or all of the planning horizon. Furthermore, the cost structure of a ship is quite complex; for instance, fuel consumption depends on whether the ship is sailing, waiting, loading or unloading. The ships may even use different engines with different fuel types and costs for loading/unloading and for sailing.

An excerpt from a typical ship routing and scheduling worksheet is shown in Figure 1, in which ship names and time windows have been modified to preserve confidentiality. The ports of loading are divided into four different regions: United Kingdom and Continental Europe (UK/CONT), Mediterranean Sea (MEDIT), Caribbean Sea (CARIB), and United States and Gulf of Mexico (US/GULF). The cargoes are shown in the top row of the table, based on the locations of their ports of loading. Each cargo is specified by its loading and discharge ports, the nature of the commodities, its weight and the time window during which loading can start. In the lower row, the available ships based in each region are specified in terms of times and ports.

In O.R., the ship routing and scheduling problem is a complex member of the family of **Vehicle Routing Problems (VRP)**. Even in its most basic form, the VRP is a very complex and computationally hard optimization problem. As described above, maritime routing problems have idiosyncrasies that typically increase their computational complexity and set them apart from VRPs that occur in other transport modes [3,4].

**Things Even Get Worse!**

Even though the above puzzle is complex and hard to deal with, things get even worse. In the example above, all the cargoes had to be transported by a ship in the fleet controlled by the shipping company. Planning problems with these characteristics are often classified as **industrial shipping** problems.

However, most bulk shipping companies operate in **tramp shipping**, where they usually have an amount of contract cargoes that must be transported, as in industrial shipping. In addition, however, they receive requests for optional spot cargoes. The shipping companies must evaluate these inquiries and decide which optional spot cargoes to accept and which to reject.

Sometimes, there is an opportunity to **relet a cargo**, which means that the shipping company can hire a vessel from another company on a voyage charter to carry the cargo for an agreed price. In such cases, the planner must consider both which spot cargoes to accept/reject and which cargoes to relet. These decisions are closely related to the routing and scheduling decisions.

Another typical feature of bulk shipping is the fact that cargo quantities are often somewhat flexible. For instance, instead of stating that the quantity of a certain cargo is 20,000 tons, it is not unusual that the quantity is given as 20,000 tons +/- 10 percent. The planner can sometimes use this flexibility to improve fleet utilization and even to make room for profitable spot cargoes. However, additional complexity is introduced, since the routing and scheduling problem now also includes the decision of optimal cargo quantities.

**The Birth of TurboRouter**

In 1996, researchers at MARINTEK and NTNU launched a project together with a couple of shipping companies. The aim was to develop an optimization-based decision support system for ship routing and scheduling, and the **TurboRouter** planning tool was the result.

The role of the shipping companies in this project was to provide in-depth insight into and understanding of the fleet-scheduling problems facing the shipping industry.

Some planners and shipping companies were skeptical about O.R. systems in general and about optimizing fleet scheduling in particular. They argued that it was impossible or undesirable to model all aspects needed to optimize fleet
scheduling. One of their arguments was that it could be difficult to model the compatibility between ship and port. They claimed that there might be situations in which a specific ship cannot enter or leave a given port due to draft restrictions, pointing out that if the ship is not fully loaded it may still be possible at high tide. The critics pointed out that this type of constraint would be influenced by the ship's draft, which is influenced by the cargo quantity onboard and the port's draft restrictions, which are determined by tidal conditions.

Another example of aspects or constraints that are difficult to model is port opening hours. The skeptics claimed that even though it might be possible to model these aspects, it would probably require too much user input, and that planners would not have confidence in such a system. They therefore insisted on a system with a high degree of user interaction.

The research team emphasized the importance of developing the system a small step at a time and gaining the acceptance of the shipping companies involved after each step. The first step was to develop a simple general method for automatically calculating port-to-port distances, which is essential information in maritime planning. This was initially used to develop relatively simple manual planning tools that could help planners by performing all the time-consuming calculations and feasibility checks. The team subsequently developed advanced algorithms for identifying optimal or near-optimal solutions to the ship routing and scheduling problems that were being targeted. Due to the complexity of the problem and the need for quick response, a robust, heuristic approach based on local search and metaheuristics was selected.

Figure 3 shows a form in TurboRouter for mixed-initiative planning of fleet schedules.

Combined Ship Routing and Inventory Management

In the 1990s, SINTEF and NTNU launched a research effort that targeted another challenge, in this case in collaboration with a number of maritime transport and manufacturing companies. The aim of this project was to increase the earnings of these industries and cut their emissions further through better supply chain coordination.

The new project was based on the fact that inventories often lie close to the loading and/or unloading ports of the sailing legs. Both loading operations and the transport phase itself are time-consuming and expensive. The potential for improvement is therefore great if the planning of ship schedules and inventory management at each end of the sailing leg can be coordinated.

The integration of routing and inventory management involves a new dimension in the industrial and tramp shipping problems described above, which are complex members of the VRP family. In O.R., the extended problem is called the Inventory Routing Problem (IRP). Here again, a maritime IRP normally has characteristics that make it different from, say, a typical road-based inventory routing problem, as exemplified...
below. Maritime IRPs are frequently encountered in the oil and gas industry and bulk commodity industry, as well as in process industries that transport chemicals and other heavy, high-volume bulk products [5].

Each industrial maritime inventory routing problem has its own special and complicating aspects.

The first such real maritime IRP described in the O.R. literature was the transport of ammonia [6,7]. A Norwegian company operated a fleet of five ships for transporting ammonia between production and consumption harbors with limited storage, connected to 14 of its own plants. The shipper also traded ammonia with external operators, resulting in a combined tramp scheduling and maritime inventory routing problem.

Another example comes from the cement industry. The largest producer of cement in Norway is responsible for the simultaneous inventory management of 12 production silos and 49 consumption silos and the routing of a fleet of five ships (Figure 5). The fleet capacity is limited, and occasionally the demand for cement exceeds fleet capacity. The company therefore occasionally utilizes spot charters; during periods of peak demand, additional road-based transport is also needed.

Finally, several companies in the rapidly growing liquid natural gas (LNG) sector have recently introduced decision support systems for their complex maritime inventory routing systems. Traditionally, most LNG ships have been tied to specific contracts and trades, in that they were shuttled between given liquefaction plants and regasification terminals. This is about to change. The rigidity of contracts seems to be loosening up. There is a growing spot market for LNG, which creates more business opportunities serving different markets. The spot market introduces more flexibility, which in turn means a high fleet utilization factor for LNG ships.

To the best of the authors’ knowledge, no generic commercial optimization-based decision support system for maritime IRPs is yet on the market. In the course of the past few years, SINTEF and NTNU have developed a tool called Invent, which is now in its test phase with several shipping companies. The tool is a generic software system that can model and solve a wide range of maritime routing problems, including traditional tramp and industrial shipping problems combined with inventory management. It handles tank allocation and the necessary cleaning operations between products. Invent is a pure solver, with no user interface. It must be integrated with an ERP system or a decision support system such as TurboRouter. An integrated system has been tested on several real IRP cases from industry, with very good results.

TurboRouter and Invent deal with large, complex problems in maritime transport. Significant research challenges remain to be solved before we can match the requirements of even more large, complex and wide-ranging applications in maritime transport. Through development and implementation of more powerful optimization methods, existing tools will grow more powerful and enable us to develop better plans in less time.

REFERENCES