# Ship routing and scheduling with inventory and stowage constraints

**Marielle Christiansen, Kjetil Fagerholt, Øyvind Haugen and Erik Helleberg Lund**
Department of Industrial Economics and Technology Management
Norwegian University of Science and Technology, 7491 Trondheim, Norway
fax: +47 73593603, e-mail: {marielle.christiansen}{kjetil.fagerholt}@iot.ntnu.no

## Abstract

We present a real planning problem where cement is transported by a fleet of ships from several production factories to many consumption silos along the Norwegian coast. The planners are responsible for both the ship routing and the inventory management at all production and consumption facilities. There exist several types of cement and the various types have to be allocated in separate cargo holds onboard the ships. The utilization of a ship's cargo carrying capacity depend on the stowage.

We have developed a heuristic to solve this real complex inventory ship routing and scheduling problem with stowage constraints. Computational results from the real case study will be presented. Various objective functions have also been tested, and it seems that using cost-per-ton gives best solutions for the real problem.

## Introduction

The cement industry is subject to fierce competition. Market share is considered to be top priority and the cement producers are prepared to go a long way to please their customers. Clever planning and good use of resources are therefore very important in this business where the operating margins are small.

We consider a situation within the cement industry where the cement producer is responsible for the inventories at both the cement production factories and the consumption silos. In addition, the cement producer operates a fleet of ships transporting the cement between the factories and silos, and is responsible for the routes, schedules and stowage of the different cement types on board the ships. In order to achieve an efficient supply chain, the routing and scheduling, the inventory management and the stowage onboard the ships have to be coordinated.

The planning problem is very complex from an operations research point of view and such a problem, where ship routing and scheduling must be integrated with inventory management and stowage, have not been treated in the literature yet, see the review in (Christiansen et al., 2004). We have a few contributions integrating ship routing and scheduling with stowage, but without inventory management, see for example (Fagerholt and Christiansen, 2000). There are also some contributions where the ship scheduling decisions are incorporated with the inventory decisions without the stowage planning, see for example (Christiansen, 1999), (Flatberg et al., 2000), (Ronen, 2002) and (Persson and Göthe-Lundgren, 2005).

The objective of the presentation is to describe a new and important problem within maritime transportation and to present a heuristic solution approach to the problem. Results from real planning instances will be given. In the next section we give a more detailed description of the real planning problem. Thereafter we give an overview of the heuristic solution approach and the computational study. Finally we present some concluding remarks.

## Description of the real combined ship routing, inventory management and stowage problem

The problem description given is a real problem for a major Norwegian cement producer, which has 28 consumption silos and two production facilities spread along the Norwegian coast as shown in Figure 1. There are also production facilities in Sweden, the Netherlands and Denmark that supply the Norwegian market with some types of products. These facilities are also included in the planning problem considered here.

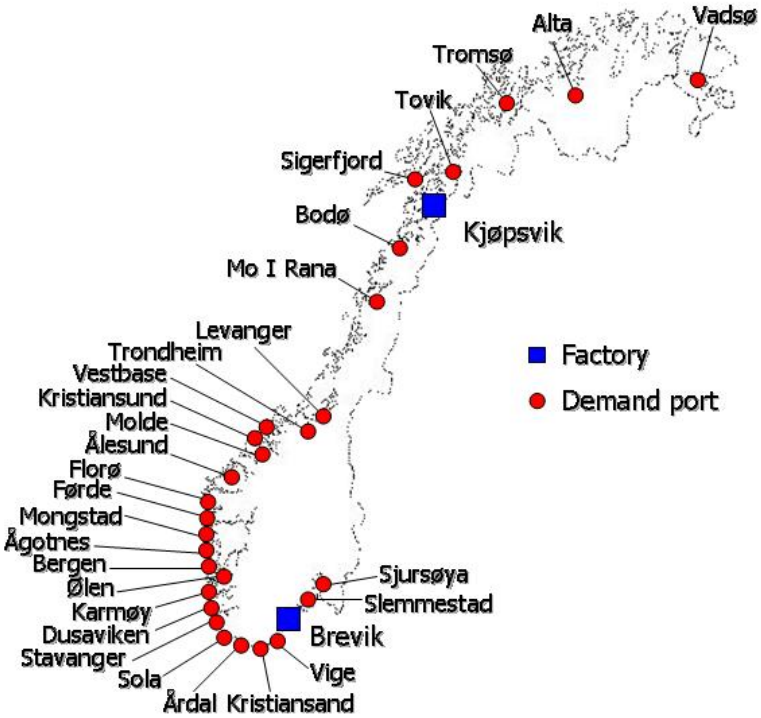


Figure 1 – Considered cement facilities in Norway

The two production facilities supply cement to all the 28 consumption silos. The cement is transported by bulk ships which can carry multiple types at the same time. The problem is to transport the different types of cement from the production facilities to the consumption silos at minimum costs subject to the following set of restrictions.

*Stock limits.* Each port is equipped with one or more *storage silos.* Different cement types cannot be stored in the same silo and we have to keep track of the level and type of cement stored in each of the tanks. Each silo has a given lower and upper stock limit. These limits include a safety stock at the consumption ports. The number of silos and their respective capacity varies greatly in the different ports. Because of this, and the fact that different ports have production/consumption rates that vary over time, each port will be visited an odd number of times. The number of visits depends on the quantities discharged or loaded in the ports. These quantities are not given in advance, but their values depend on the production/consumption rate in each port, the stock levels, and the capacity of the ships arriving at the ports. There should be no need to stop the *production at* *the factories*. This is extremely costly and is not even considered as an option. The proposed schedules should therefore be built with some slack regarding the stock levels at the factories to minimize the chance of an unexpected event creating a production shutdown.

*Loading/discharging capability.* Each port has a different capability regarding the number of types of cement that can be loaded/unloaded at the same time, and the capacity of the pipelines carrying the cement to the storage silos.

*Physical port constraints:* There are several properties regarding the physical layout of the ports. Examples are the maximum length, draft and beam of the arriving ships. This means that not all ships can visit all the ports. Some times a ship can visit the port, however not fully loaded, but with for instance up to 50 % load onboard. The production and consumption ports operate around the clock.

*Ships:* Today, 5 ships are used for the transportation of cement. The ships are operated around the clock and therefore there are no planned idle periods in the short term planning problem. Each ship has its different properties regarding cost structure and service speed. The carrying capacity of the ships ranges from 3.200 to 5.800 tons and the number of cargo holds vary from 2 to 8. The fleet is regarded as fixed for the short term planning problem.

*Stowage:* Stowage is a very important part of the planning problem, because different ways of stowing the cargo will have an impact on utilization of the ships' cargo capacities. In addition, the safe trim of the ship has to be assured during the entire voyage as no reloading is allowed on a voyage.

*Costs:* The overall objective is to distribute the cement at minimum cost. The variable costs are fuel and diesel oil costs and port tolls, which depend on the size of the ship. Inventory costs do not need to be considered in this problem because the cement producer is the owner of the product at both production and consumption silos. The actual location of the cement will therefore not influence the total costs.

*Planning horizon:* The planning horizon of the problem is typically two weeks.

Since the demand for cement in Norway has been very high for the last years, the ship fleet often has too little capacity to fulfil the inventory constraints at all silos. This means that in practice, some minor deliveries must be made by trucks. These deliveries are much more costly, and should therefore be avoided if possible, or at least only be performed between production units and consumption silos that are close to each other. In some cases, the planners at the cement producer also have no other option than to <u>not</u> satisfy the demand at some consumption silos. Selection of which consumption silos that potentially should be serviced by trucks and which should not be serviced at all is done based on a *priority list* between the silos.

## Solution approach and computational study

We have developed a heuristic to solve the problem described in the previous section. The heuristic consists of both a constructive method, which generates an initial plan, and a local search method, which tries to improve the initial plan. Before we start using the constructive method, we sort the storage silos according to *priority list* mentioned in the previous section and their *critical times*, which is the estimated time a consumption silo runs empty and a production silo gets full. The first step of the constructive heuristic is to make a pickup-delivery port (silo) pair based on the first critical silo. For instance if the first critical silo is a consumption silo, then we calculate the best production silo that can deliver the product that is needed in the consumption silo. Then, we try to insert the pickup-delivery port pair into the schedule for a given ship. This step is quite complex here compared with most insertion heuristics for routing problems described in the literature. The reason for this is that when testing an insertion of a port pair in a given ship schedule, we use a heuristic method to decide the quantities and arrival times, both for the given pickup-delivery pair and for all other pickups and deliveries already in the ship schedule.

When the constructive heuristic has inserted all port pairs corresponding to all silo critical times during the planning horizon or no more insertions are feasible, the local search heuristic will (if called) try to improve the given solution. Two local search operators are implemented; *1-resequence* that removes a port pair from a ship's schedule and tries to reinsert into the same schedule, and the *Reassign* that removes a port pair from a ship's schedule and tries to reinsert it into the schedule of another vessel. Also when performing these moves, we apply the heuristic to decide quantities for all cargoes in the schedule(s) considered. When local optimum is reached or the maximum number of iterations has been performed, the heuristic may go back to the constructive method and try to insert even more critical port pairs, in case not all yet has been inserted.

The constructive and local search heuristic will performed until the specified number of iterations is reached or no further improvements can be found. If there is still demand at one or more silos that cannot be met, the heuristic may enter a post-optimization module. This post-optimization module tries to improve the utilization of the fleet by relaxing some of the constraints in the problem, e.g. lower stock limits at the consumption silos. Here, we allow these constraints to be violated with a given amount. This may result in that even more port pairs can be inserted in the fleet schedule.

Figure 2 shows the principal flow of the heuristic developed.

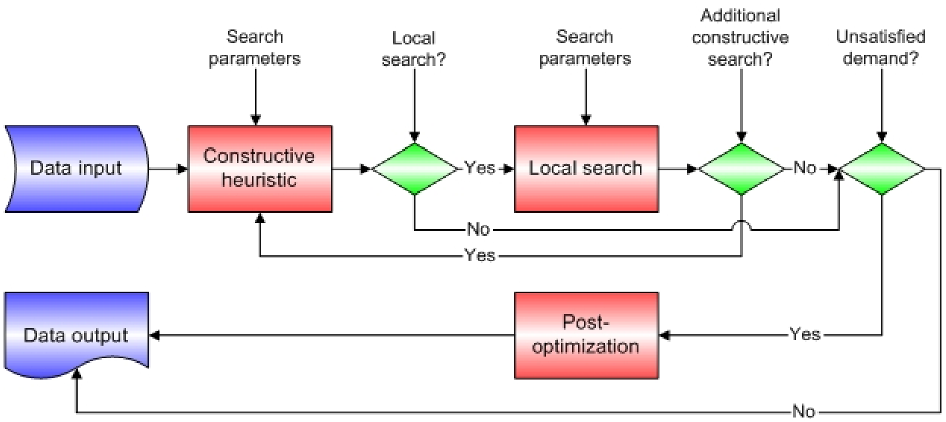


Figure 2 – Principal heuristic flow

On small test problems, we have compared results obtained by the heuristic with a MIP model. When using the heuristic, we were able to test different objective functions; total cost, cost-per-ton, and hybrids of these. However, since cost-per-ton gives non-linearities in the MIP model, we were only able to minimize total cost in the MIP model runs. When comparing results, we experienced that using the heuristic with cost-per-ton as objective gave much better results in practical planning than using the MIP model with total cost as objective. This indicates that in this problem, cost-per-ton is a much better objective than total costs. We believe that one main reason for this is that minimizing total cost is a rather myopic objective. This will tend to give results that will deliver as little as possible each time, resulting in that the silos must be visited again much sooner.

We have further tested the heuristic on real instances from the cement producer with a 14 days planning horizon. The solutions have been checked by planners at the cement producer, which state that the solutions are both feasible and better than the ones obtained by their existing manual planning procedure.

## Concluding remarks

In this extended abstract we have presented a real combined ship routing, inventory management and stowage problem from a major Norwegian cement producer. We have developed a heuristic to solve this complex planning problem. We have also developed a MIP model to solve the problem and compare with the heuristic for small test instances. The heuristic outperforms the MIP model because it can easily deal with a non-linear objective function, cost-per-ton, which seems to be a much better objective in this problem. The heuristic also solves real life instances from the cement producer and produces valid solutions that are better than the ones obtained by their existing manual planning procedure.

The heuristic has been developed into a prototype decision support system, with an Excel spreadsheet user interface. Now, we are in discussion with the cement producer in order to develop and implement a commercial decision support system based on the study presented here.

## References

Christiansen, M. (1999) “Decomposition of a combined inventory and time constrained ship routing problem”. *Transportation Science* 33(1), 3-16.

Christiansen, M., K. Fagerholt and D. Ronen (2004) “Ship routing and scheduling: Status and perspectives”. *Transportation Science* 38(1), 1-18.

Fagerholt, K. and M. Christiansen (2000) “A combined ship scheduling and allocation problem”. *Journal of the Operational Research Society* 51(7), 834-842.

Flatberg, T., H. Haavardtun, O. Kloster and A. Løkketangen. “Combining exact and heuristic methods for solving a vessel routing problem with inventory constraints and time windows”. *Ricerca Operativa* 29, 55-68 (2000).

Ronen, D. “Marine inventory routing: Shipments planning”. *Journal of Operational Research Society* 53, 108-114 (2002).

Persson, J. A. and M. Göthe-Lundgren, “Shipment planning at oil refineries using column generation and valid inequalities”. *European Journal of Operational Research* 163, 631-652 (2005).