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**AN INTEGRATED OPTIMIZATION APPROACH  
FOR CRUDE OIL DISTRIBUTION BY SHIPS**

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## **Abstract**

In this paper we consider a distribution problem where a number of commodities are produced and consumed in different bases over a given time horizon and a fleet of ships is used to distribute the goods according to demand and production rates. One such model has been designed for solving a ship scheduling problem for the distribution of different types of crude oil. The model has been integrated in a software tool that is currently used at AgipPetroli S.p.A. to produce monthly distribution plan and to optimally manage the daily disruptions that occur at the operational planning level.

*Key words:* Mixed Integer Programming, Branch & Cut, Supply Chain Management, Ship Scheduling.



## 1. Introduction

One central issue in supply chain management problems is the distribution of different products amongst a given set of production and demand points by a set of transport means. In this paper we focus on the problem of distribution of hydrocarbon products by ships. For the majority of oil companies such problem arises both in the *primary* distribution, where crude oils are transported from the extraction locations to the refineries, and in the *secondary* distribution, where refined products are moved to other refineries and to depots to be further processed or distributed to the final selling points by trains or trucks.

The transportation cost associated with the *primary* and *secondary* distribution accounts for a significant portion of the final cost; the high level of complexity and the many variables involved (product price at the production site, selling price, taxation, shipping costs) demand for a very efficient management of the shipping process in order to minimize the global transportation cost while satisfying at best the demand of each product in the different locations.

From the mathematical modeling standpoint, *primary* and *secondary* distribution differ under many aspects. First, primary distribution usually operates on a longer time horizon (one to three months) and considers shippings amongst distant countries, with travel time of several days; in secondary distribution travel times are instead much shorter and the planning time horizon usually considered ranges from one to four weeks. Second, the stocking capacity of crude oil in producing and consuming countries is large, then shipments are sized accordingly in order to benefit of more efficient cargoes. On the contrary, in secondary distribution smaller depots and smaller ships are involved, and different refined products may need to be loaded on the same ship. Last, but not least, in primary distribution the pick-up and delivery schedule needs to be fixed up front, so that the scheduler knows in advance what product must travel from an origin to a destination, in what quantity and in which time window within the time period; on the other hand, in secondary distribution such elements may be left to be decided in the most convenient way, and thus a more flexible model of the process must be used in order to identify the optimal solution amongst all the feasible ones.

Ship scheduling problems have been looked at in the literature from different angles. Early works include [3], which aims to the minimization of the number of used ships, and [6], where an LP model is proposed as an approximation for the problem of allocating a total transportation capacity for each pair of origin-destination bases, and to determine the minimum number of vessels required. In [7] it is described a mathematical model to solve the tanker scheduling model of the Defence Fuel Center and the Military Sealift Command in the worldwide distribution of bulk petroleum products; the resulting integer programming formulation appears to be intractable by the computational resources then available, and a heuristic scheme based on rounding was adopted to obtain feasible solutions.

More recently, in [8], it is described an interactive computer system addressing daily scheduling issues as well as longer range planning problems; the method utilizes a network flow model and a mixed integer programming model. The time horizon is one and a half year, during which four ships can make up to five travels. The solution method adopted is a heuristic with special features that enhance the interactions between the user and the system. In [1] a crude oil tanker scheduling problem is considered. The constraints of the problem limit the number of all feasible schedules, which can be generated off-line, and appear as columns in a set partitioning model. The contained dimensions of the application problem allow to find optimal integer solutions within a reasonable computation time. In [5] the efficient

scheduling of fleet of ships engaged in “pick-up and delivery” of bulk cargoes is presented. The system adopts off-line generation of ship schedules. According to the dimensions of the problem, it can either generate all the feasible schedules or heuristically limit the generation process. The corresponding set packing problem is efficiently solved using a Lagrangean heuristic. Finally, in [2] a variant of the multi-vehicle “pick-up and delivery” problem with time windows combined with a multi-inventory model for a real ship planning problem is described.

A complete model for secondary distribution has been presented in [4], where an optimization methodology based on the combination of Branch&Cut techniques and Column Generation is presented, which is capable of solving large instances using on the fly generation of new column and particular classes of cutting planes developed *ad hoc* for this class of problems.

In this paper we consider the problem of primary distribution of crude oil, and present an optimization model that has been developed for a company of the Eni group, AgipPetroli. The model is capable of determining a monthly schedule of ships that covers the product demand at minimum transportation cost. It has been integrated in a software system with a powerful interface that manages the interactions of the users with the proposed solutions and makes it possible to interact efficiently with the optimization model.

In Section 2 we describe the problem to be solved; Section 3 considers the modeling approach adopted, while in Section 4 the structure of the complete software system that has been developed is described. Finally, in Section 5, we describe the results obtained and the role of the system in the overall planning and distribution process in AgipPetroli.

## 2. Problem Description

The planning of primary distribution starts from the set of crude oil requirements in the refineries for the planning horizon. Such requirements have to be matched with the quantity of oil available in the production sites for the same period, in order to decide how much crude oil to buy from a given producer, and also when in the planning period that oil will be available for pick up by the ships.

Up to this point, the process does not lend itself to an effective deployment of mathematical optimization techniques; in fact, negotiations on oil contracts must take into account several strategic and political aspects that demand the involvement of sector experts and cannot be captured by rigid mathematical formulations of constraints and objective functions. Although, once the contracts have been settled, and it is known what quantity of crude oil must be transported between each pair of locations, and the related time windows, a realistic mathematical model can be used.

The problem to be solved is how to operate the transportation plan at minimum cost. The fleet of tankers of an oil company can be composed by owned ships, by ships that are rented on a long to mid term basis (one or more months) or by ships rented on the market for a specific travel. The first two categories have the same behaviour from the cost standpoint, as the company is covering the renting cost for a period that is typically longer than the time horizon; for this reason, we will refer to owned ships and to ships rented on long to mid term basis as *time-charter* ships, while ships rented for specific travels will be referred to as *spot* ships.

The identification of the optimal plan is strongly influenced by the behaviour of the shipping market. While for time-charter ships the renting cost is negotiated up front and consumption

and port taxes do not change in the mid run, several factors may affect the cost of renting a spot ship on the market. International agencies fix the reference parameters for the different types of ships that depend on the size of the ship, on the geographical area (*Worldscale*) and on the specific trip (*flat-rate*), by means of which it is possible to determine only an approximated cost of renting a specific ship on a trip from a given origin to a given destination; such approximated cost can although vary depending on many exogenous factors, and the specific negotiations may lead to final cost figures that significantly differ from the ones computed using the *Worldscale* and *Flat-rate* parameters.

Another important aspect of the problem is that time-charter or owned ships may be rented out on the market to other operators. This situation intuitively arises when such ships are not needed for covering the current transportation plan; but also it may happen that the global cost of a plan that uses several spot ships and rents out some of time-charter ships is lower than the cost of covering the plan only with the time-charter ships, depending on the current market price, on the location of the ships and on the demand that is present at the beginning of the planning period.

All these aspects have to be properly taken into account to build an optimization model. Such a model needs to be solved in reasonable time; despite the fact that the typical planning horizon is one month, many changes in the input data may occur due to weather conditions, market fluctuations, and other unforeseeable events. This situation demands the monthly schedule to be readjusted even on a daily basis, and sometimes the best solution to operate is found running several instances of the problem, exploring different strategic options that are in control of the users.

The model should have the objective of covering the given plan at a minimum cost. While we have exact information on time-charter ships, the exact cost of a spot ship on a given travel can be known with some level of approximation. This problem has been taken into account introducing proper slack variables in the model described in Section 3; the model would then *propose* some travels that:

- must be covered by *spot* ships because all time-charter ships are busy in some other transport;
- appear, on the basis of the *Worldscale* and *flat-rate* parameters, more convenient than using any of the time-charter ships available.

Such travels will then be considered to negotiate the contracts on the market.

The final solution to the problem is given by the integration of an optimization model capable of finding the optimal solution to any instance of the problem in reasonable short time (below 30 minutes) with a user interface where input data is accessed and managed, solutions can be edited and modified, and specific travels can be composed directly by the user. The interface comes also into use if one wants to manually design a specific schedule and evaluate its feasibility and cost in the most precise way.

Before ending this section we consider the input data needed to specify the model. The first aspect that we consider is the transportation plan that is to be covered. Each item of the plan has been defined a *delivery*. A delivery consists in a completely defined transportation task; the information attached to each delivery is synthesized in Table 1.

When considering *time-charter* ships, we need to consider its dimension, its speed, its consumption rates for the two types of fuel used (Fuel Oil and Marine Diesel) and the information about its position at the beginning of the planning period. Table 2 lists out such information.

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Additional information beside data on ships and deliveries is also needed to build the model:

- A distance matrix reporting actual travel distances in Nautical Miles (NM) between each pair of ports considered by the plan;
- A ship-to-port compatibility matrix, where it is specified whether a certain ship can enter a given port or not according to size constraints;
- The value of the port charges (taxes) to be paid in each port for entering and for leaving;
- Previous engagements of each ship during the planning period.

In the AgipPetroli application that is described in this paper, all data is updated in real time and organized in a relational database that is accessed by the user interface, whose structure and functioning are discussed in Section 4.

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origin port of the delivery  
destination port of the delivery  
tons of crude oil to be transported  
type of heating required by the product  
loading time (hours)  
unloading time  
starting day of loading time window  
ending day of loading time window  
starting day of unloading time window  
ending day of unloading time window  
Flat rate associated with the origin-destination travel  
World-Scale associated with the origin-destination travel

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Table 1: Information for each Delivery

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max load in tons of the ship  
speed in nautical knots when loaded (laden)  
speed in nautical knots when empty (ballast)  
port where the ship is located at the beginning of the planning period  
first day of availability at the beginning of the planning period  
laden Fuel Oil consumption without heating  
laden Fuel Oil consumption with heating 98° F  
laden Fuel Oil consumption with heating 135° F  
ballast Fuel Oil consumption  
loading Fuel Oil consumption  
unloading Fuel Oil consumption  
idling Fuel Oil consumption  
laden Marine Diesel consumption without heating  
laden Marine Diesel consumption with heating 95° F  
laden Marine Diesel consumption with heating 135° F  
ballast Marine Diesel consumption  
loading Marine Diesel consumption  
unloading Marine Diesel consumption  
idling Marine Diesel consumption

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Table 2: Information for each time-charter ship

### 3. Solution Method

In this section we outline the model that has been adopted to solve the crude oil distribution problem described in the previous section.

Scheduling problems as the one faced in this work are typically modeled and solved by integer or mixed inter programming, as already pointed out by the related references that have been considered in Section 1. The need of integer variables is motivated by the fact that the decisions to be made are mainly discrete, as they represent the assignment of a given ship to a given task. Such class of problems is known to be difficult to solve when the number of variables involved is large, although the present level of evolution of commercial integer programming solvers often enables to find optimal or quasi optimal solutions to problems of consistent size that would be impossible to solve only few years ago. Moreover, the state-of-the-art in mathematical programming research provides several techniques that can be used to develop more efficient *ad hoc* algorithms for well defined problems, where commercial solvers are used as subroutines to evaluate partial or relaxed solutions.

The mathematical model adopted is based on the explicit generation of all possible travels that each *time-charter* ship can make. Such travels are generated considering all possible assignments of each ship to each delivery.

A travel is thus defined by a ship, an origin port, a destination port, a load, a starting time, a finish time, and a cost.

We consider two types of travel: *loaded* (also referred to as *laden*) travels and *empty* (also referred to as *ballast*) travels. Loaded travels are the ones that effectively perform a transportation of material in order to cover one of the deliveries; empty travels are instead those travels that a ship performs without any load in order to reach the origin port of a loaded travel.

In order to clarify the description of the model we define  $T$  the set of all travels,  $T_l$  the set of loaded travels and  $T_e$  the set of empty travels, where  $T = T_l \cup T_e$ . We also indicate with  $D$  the set of deliveries, with  $S$  the set of available ships, with  $P$  the set of all ports, and with  $H$  the length of the planning horizon, which is divided into a finite number of time intervals, indicated by  $h \in H$ . A travel of ship  $s$  from origin port  $p_1$  to destination port  $p_2$  that leaves  $p_1$  at time  $h_1$  and arrives in  $p_2$  at time  $h_2$  is represented by the symbol  $t_{s,p_1,p_2,h_1,h_2}$ . For brevity, a travel is also indicated with  $t$  when the complete notation is not needed.

We define a loaded travel  $t_{s,p_1,p_2,h_1,h_2}$  to be *feasible* for delivery  $d \in D$  if the following conditions are satisfied:

1. Ship  $S$  can arrive to port  $p_1$  within time  $h_1$  from its position at the beginning of the planning period;
2. Port  $p_1$  is the origin port of delivery  $d$ ;
3. Port  $p_2$  is the destination port of delivery  $d$ ;
4. Time interval  $h_1$  is contained in the load window of delivery  $d$ , denoted by the interval  $[SLT(d), ELT(d)]$  (Starting/Ending day of Loading Time window);
5. Time interval  $h_2$  is contained in the arrive window of delivery  $d$ , denoted by the interval  $[SUT(d), EUT(d)]$  (Starting/Ending day of Unloading Time window);

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6. The travel time of ship  $s$  between  $p_1$  and  $p_2$  expressed in number of time intervals is less than or equal to  $h_2 - h_1$ ;
7. Ship  $s$  is of the right size and type to transport all the product associated to delivery  $d$ .

Additional notation includes:

- set  $T(d)$ : subset of loaded travels that are feasible for delivery  $d \in D$ .
- set  $T(s)$ : subset of  $T$  composed by all travels of ship  $s$ .

The dimension of set  $T$  may be very large in practical applications and affect the tractability of any associated optimization model; it is therefore important to generate only the feasible *loaded* travels that may be used by the optimal solutions. As far as *empty* travels are considered, we need take into account only those travels that connect the arriving port of a loaded travel to the starting port of any other loaded travel of the same ship.

The set  $T$  is thus generated up front using the procedure sketched below:

#### Step 1: Generation of *loaded* travels

- $\forall s \in S$ 
  - $\forall d \in D$ 
    - \* let  $p_1$  be the origin port of  $d$ ;
    - \* let  $p_2$  be the destination port of  $d$ ;
    - \* let  $z$  be the travel time, expressed in time intervals, of ship  $s$  from  $p_1$  to  $p_2$ ;
    - \*  $\forall h_1 \in H$ ,  $SLT(d) \leq h_1 \leq ELT(d)$ :
      - let  $h_2 = h_1 + z$
      - if  $SUT(d) \leq h_2 \leq EUT(d)$ , then add travel  $t_{s,p_1,p_2,h_1,h_2}$  to  $T_l$  and compute its cost.

#### Step 2: Generation of *empty* travels

- $\forall s \in S$ 
  - $\forall (t_1, t_2) \in T(s)$  such that the arriving time of  $t_1$  is smaller than the starting time of  $t_2$ :
    - \* let  $h_i$  be the arriving time of  $t_1$
    - \* let  $h_j$  be the starting time of  $t_2$
    - \* let  $p_i$  be the destination port of  $t_1$
    - \* let  $p_j$  be the origin port of  $t_2$
    - \* let  $z$  be the travel time, expressed in time intervals, of ship  $s$  from  $p_i$  to  $p_j$
    - \* if  $h_i + z \leq h_j$  create the empty travel  $t_{s,p_i,p_j,h_i,h_j}$ , compute its cost  $c_t$  and add it to  $T_e$ .

Now we turn to consider the computation of the cost for each travel. The total cost of travel  $t_{s,p_1,p_2,h_1,h_2}$  can in fact be broken into several components, each one derived from the available data:

- **rent**: obtained by the monthly rent of ship  $s$ , divided by the number of time interval in the month and multiplied by the duration of the travel  $h_2 - h_1$ ;
- **port charges**: obtained by adding the taxes to be paid at the loading and unloading ports ( $p_1$  and  $p_2$ );
- **loaded travel cost**: obtained by multiplying the consumption rates for ship  $s$  when loaded, times the cost of the different types of fuel times duration of the travel  $h_2 - h_1$ ;
- **unloaded travel cost**: obtained by multiplying the consumption rates for ship  $s$  when unloaded times the cost of the different types of fuel times duration of the travel from  $p_1$  to  $p_2$ ;
- **heating cost**: such cost occurs when the oil to be transported requires to be heated. It is obtained by multiplying the consumption rates for heating of ship  $s$  times duration of the travel from  $p_1$  to  $p_2$ ;
- **idle cost**: such cost occurs when the ship is not cruising nor loading or unloading the product. This may be the case when a ship arrives at a port before the beginning of a loading/unloading window and thus has to wait some time for the window to open; such waiting time has to be weighted with different consumption rates, that are typically lower than the consumption rates occurring when the ship is traveling.

The optimization model considers a binary variable  $x_t$  for each travel in  $T$ , with the usual interpretation of  $x_t = 1$  if travel  $t$  is picked in the optimal solution, and  $x_t = 0$  otherwise. We also consider an additional slack variable  $z_d$  for  $d \in D$ , that has value 1 if delivery  $d$  is not covered by a time-charter ship in the optimal solution, and 0 otherwise. The obvious objective function cost for variable  $z_d$  is associated with the cost of covering the delivery  $d$  with a *spot* ship, which is best approximated using the *Flat Rate* and *World Scale* parameters (later referred to as  $c'_d$ ).

The constraints of the model are derived from the following two conditions that must be obeyed for a given subset of  $T$  to represent a feasible solution to the problem:

1. each delivery must be covered exactly by one travel of a time-charter ship or by a spot ship;
2. all travels of a given time-charter ship must form a feasible path, that is, they can be sequenced.

These two conditions are modeled by a set of linear constraints on the integer variables  $x_t$  for  $t \in T$  and  $z_d$  for  $d \in D$ . Condition 1 is easily dealt with by a set of equalities where the sum of all  $x_t$  for  $t \in T(d)$  plus  $z_d$  must be equal to 1 for each  $d \in D$ . In order to impose condition 2 we need to define the space-time graph of ship  $s$ ,  $G(s) = (V(s), A(s))$ . We indicate with  $V(s)$  the vertex set of such graph, where  $V(s)$  contains a vertex  $v = (p, h)$  for each  $p \in P$  that can be reached by ship  $s$  and each time period  $h \in H$ . In addition, we include in  $V(s)$  a dummy source vertex  $d_{source}$  and a dummy sink vertex  $d_{sink}$ . The arc set of  $A(s)$  is composed of the following types of directed arcs:

- *travel arcs*, that are associated with each travel in  $T(s)$ ; for travel  $t_{s,p_1,p_2,h_1,h_2}$  the corresponding arc would have head node in  $(p_1, h_1)$  and tail node in  $(p_2, h_2)$ ;

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- *still arcs*, that connect each vertex associated with a given port  $p_i$  and a time period  $h_j$  with the vertex associated with the same port  $p_i$  and the next time period  $h_j + 1$ ;
- *ending arcs*, that connect each node associated with the port of arrival of a loaded travel with the dummy sink node;

In terms of variables involved, the travels arcs are represented by the set of  $x_t$  for  $t \in T(s)$ ; additional integer variables associated with the still, starting, and ending arcs are then added to set  $T$  resulting in an extended set of travel  $T'(s)$  that contains all the arcs contained in  $A(s)$  (in the following we also indicate with  $T'$  the union of all sets  $T'(s), s \in S$ ).

Condition 2 is then easily represented by flow conservation constraints on the node of  $G(s)$  (that is, in each node the number of incoming arcs and the number of outgoing arcs must equate), that we synthetically represent with the set of linear constraints:

$$N_s x_{T'(s)} = b_s \text{ for each } s \in S$$

where  $N_s$  is the vertex-arc incidence matrix of  $G(s)$ ,  $x_{T'(s)}$  is the vector of variables  $x_t$  for  $t \in T'(s)$ , and  $b_s$  is a vector such that  $b_s(\text{source}) = -1$ ,  $b_s(\text{sink}) = 1$ , and  $b_s(u) = 0$  otherwise.

Such condition guarantees that the travels of a ship  $s$  selected in the optimal solution form a feasible path in  $G(s)$  from source to sink, that is, they can be correctly executed in sequence.

Over the space of feasible solutions described by these two classes of constraints, we then select the optimal one minimizing an objective function composed of the sum of the costs of all selected travels plus the cost for deliveries to be performed by spot ships.

Below we give a compact description of the mathematical model adopted in terms of variables and constraints and objective function:

$$\begin{aligned} \min \quad & \sum_{s \in S} \sum_{t \in T(s)} c_t x_t + \sum_{d \in D} c'_d z_d \\ & \sum_{t \in T(d)} x_t + z_d = 1, \text{ for all } d \in D \\ & N_s x_{T'(s)} = b_s, \text{ for all } s \in S \\ & z_d \in \{0, 1\} \text{ for all } d \in D \\ & x_t \in \{0, 1\} \text{ for all } t \in T'. \end{aligned}$$

The dimension of the resulting Integer Programming model for realistic cases are considerable; in order to guarantee viable solution times for its solution we have developed a dedicated polyhedral algorithm that integrates *ad hoc* cutting planes and branching strategies in a *Branch & Cut* framework, that uses the *Xpress-MP* routines from Dash Optimization as linear solver under Windows environment. The algorithm has proved very efficient and is able to determine the optimal solution to real cases in few minutes of computation time.

#### 4. The Integrated Solution Tool

The mathematical formulation described in the previous sections and the related solution algorithm have been integrated in a complete software tool that has been made available

to the AgipPetroli team for daily deployment in the management of the ship scheduling operations. Such software is characterized by the following features:

- A direct connection to the company databases to fetch the data that are already available in the internal network; such data are read and imported into a MS Access local database;
- A number of user friendly windows that are used to input additional information, modify existing data, analyze and compare the solutions produced;
- A totally automated interface with the ILP algorithm developed, that prepares the input data files for the solver, executes the solver, imports and decodes the solutions obtained into the local database, then accessed by particular masks and windows.

The role of the software tool is not limited to the simple preparation of the data and execution of the solution algorithm; it also assists the user in building a new solution, selecting all the possible choices to cover a given travel, computing in advance the complete transport cost, and eliminating, the choices that are not feasible. These features of the software already makes it possible to produce solutions not necessarily better in quality than the ones that were produced before the introduction of the software, but indeed less costly in terms of time consumed, and far more precise.

Moreover, the interface allows to compare directly the solutions obtained by such “assisted” procedure with the ones obtained by the optimization algorithm, assessing with high precision the impact of the optimization approach in the quality of the solutions, both in terms of cost of the schedule and in terms of time needed to obtain it.

The possibility of determining an optimal solution in few minutes also led the focus of the work towards sensitivity analysis, evaluation of different scenarios, and, finally, the use of the software as a general decision support tool, used not only to determine the optimal schedule for the planning horizon and to fix this schedules on the fly during the period, but also to investigate many alternatives on the strategic level. Such type of use is supported by many additional functions in the software.

Below we report some of the windows of the visual user interface, in order to provide the reader with an idea of the level of detail of the data considered.

Below (Figure 1) a sample of a window where the information related with a specific ship is given: maximum load, speed when loaded and when empty, loading and unloading fuel consumption in the different stages of the process, and ports that cannot be accessed by that ship.

In Figure 2 it is shown the standard mask to access all the information about a travel, that is, origin and destination, products transported, admitted time windows, ship selected in the optimal solution, effective dates of operation, and disaggregated costs for each phase of the travel.

The current solution (regardless of whether it is obtained directly with the optimization algorithm or by the “assisted” procedure) is synthesized in the following windows, that provide a quick visual evaluation of the results. In Figure 3 each of the travels selected by the solution (as detailed in Figure 2) is listed with its main indicators, and a final evaluation of cost is given in the form of Time Charter Equivalent (TCE). This synthetic indicator represent a transformation of the objective function of the mathematical model that can be compared

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Figure 1: Data for Ship

Figure 2: Travel Editing Mask

with the indicators used before the introduction of this tool. TCE is thus used as the main measure of the quality of a solution.

The solution is also visualized in a graphic manner using the Zoned Time Chart depicted in Figure 4. Here the sequence of the travels of each ship are represented on a chart for the whole planning period, associating different colors to the different stages of the travels. A practical Drag&Drop facility is attached to this chart, that enables the user to move travels from one ship to the other evaluating in real time the effect of such changes on the total cost.

Finally, an economic quantification of the solutions is given in the Cashflow Chart (Figure 5), where two solutions can be compared according to the cash flow generated as the days in the planning period advance. By means of this table it is possible to quantify the effective savings determined by the solution obtained by the optimization algorithm with other solutions, and in particular with the ones obtained by manual construction (assisted procedure).

The software has been implemented on Windows PC environment using MS access to program the interface and standard C code to implement the construction of the optimization algorithm and its interface with the Dash Xpress 13.0 LP Optimization Routines. It can run

Prodotto	Quantità	Porto Caricatore	Canalzo Caricatore	Nave	Porto Scarica	Canalzo Scarica	Inizio Caricatore	Fine Operazioni Scarica	Ricavo Tempo	TCE	Note			
Alina	30.000	Rias Lenzil	01/03	03/03	Baltic Sea	Milazzo	04/03	06/03	07/03	06/03 10.49	415.800	10,5	30.121	14.250
Arabian Light	70.000	Sidi Keir	02/03	06/03	Black Sea	Livorno	08/03	14/03	02/03	09/03 16.12	505.400	11,7	36.050	15.250
Aquila	40.000	Aquila	02/03	05/03	SPOT	Taranto	04/03	08/03			616.280			
Rospo di Mare	18.000	Rospo di Mare	05/03	07/03	SPOT	Gela	07/03	11/03			568.000			
Buafiel	81.000	Zuetina	07/03	09/03	Young Lady	Saroch	10/03	14/03	07/03	13/03 3.42	453.600	9,2	35.306	19.000
Iranian Heavy	130.000	Sidi Keir	08/03	08/03	Eco Africa	Sines	15/03	20/03	08/03	19/03 1.42	896.680	16,1	46.845	26.000
Alina	30.000	Rias Lenzil	08/03	11/03	Baltic Sea	Genova	13/03	17/03	08/03	15/03 18.28	502.600	9,3	41.871	14.250
Arabian Light	70.000	Sidi Keir	12/03	12/03	Baltic Sea	Livorno	16/03	20/03	12/03	19/03 14.40	505.400	14,6	28.525	15.750
Belam	75.000	Sidi Keir	13/03	13/03	SPOT	Trieste-Gela	18/03	22/03			591.360			
Es Sider	80.000	Es Sider	13/03	16/03	Young Lady	Venezia	17/03	21/03	16/03	22/03 23.25	495.360	9,8	40.471	19.000
Sahara Blend	80.000	Bejjaja	14/03	14/03	Black Sea	Levera	16/03	20/03	14/03	19/03 4.38	481.620	9,5	29.317	15.250
Buafiel	81.000	Zuetina	18/03	20/03	Baltic Sea	Milazzo	21/03	23/03	18/03	23/03 11.22	444.960	7,7	41.805	14.250
Iranian Heavy	130.000	Sidi Keir	19/03	19/03	Eco Europa	Saroch	23/03	27/03	19/03	26/03 8.12	586.040	14,3	32.296	26.000
Arabian Light	35.000	Sidi Keir	19/03	19/03	SPOT	Livorno	23/03	27/03			482.080			
Forozan	131.000	Sidi Keir	20/03	20/03	SPOT	Taranto	23/03	27/03			435.656			
Buafiel	78.000	Zuetina	23/03	25/03	Black Sea	Prilo	25/03	29/03	23/03	28/03 8.04	397.440	9,1	29.864	15.250
Belam	75.000	Sidi Keir	23/03	24/03	Baltic Sea	Venezia	26/03	01/04	24/03	31/03 12.25	492.800	11,9	33.033	15.750
Forozan/Iran.H	130.000	Sidi Keir	25/03	26/03	Eco Africa	Milazzo-Livorno	29/03	04/04	25/03	03/04 18.08	864.435	15,7	43.940	26.000
Boun	85.000	Boun	26/03	28/03	Young Lady	Gela	28/03	01/04	26/03	30/03 14.51	308.000	7,6	28.408	19.000
Buafiel	78.000	Zuetina	28/03	30/03	Baltic Sea	Saroch	31/03	04/04	28/03	03/04 1.55	453.600	10,6	31.688	14.250
TCE													35.773	

Figure 3: Travel Chart

on any PC using Windows operating systems and requires average computational resources (i.e., Pentium IV 500 Mhz processors) with run time ranging from 15 to 25 minutes according to the size of the instances to be solved.

## 5. Ship Scheduling Optimization in AgipPetroli

The primary distribution is a central issue in Supply Chain Management for Eni (Eni is the industrial group to which AgipPetroli belongs); here crude oil is transported from the extractive location to the refineries. Being the transportation costs a significant portion of the final costs, and considering that Eni controls a fleet over a considerable number of monthly travels for the refining system, the introduction of the optimization model in the AgipPetroli ship scheduling department induced a remarkable improvement in the management of the operations.

In the past, to perform the scheduling activity of the tanker vessels and satisfy crude oil supply demand, the alternative routes were ranked in terms of TCE (time charter equivalent), in order to choose the best travels for the time-charter fleet, leaving to the spot market those with the worst TCE. This strategy was undertaken to take advantage of the current position of the ships, according to the different profitability of the routes; also, it was attempted to take into consideration the risks connected with the specific travel, in terms of type of terminal, climatic conditions, traffic condition at the ports, availability of space and tanks in the receiving installations ashore.

Such strategy was moved by the best intentions to route the ships in the most convenient way, but despite one could pretend to choose the (approximately) best vessel for the next coming delivery, the greedy approach was indeed limited in grasping the overall consequences that each single decision could bring. This shortsightedness was often evident, and in particular each time the vessels had to be rescheduled, due to occasional events such as stops in the refineries, bad weather conditions, damages of the vessels during the navigation, or particular requests received from the counterparts either in the country producers or in the refineries, delaying or advancing some operation.

In all these cases, the decision was to be made in very short time, and one was aware that such decisions could not possibly be the best one as there was not enough time to evaluate

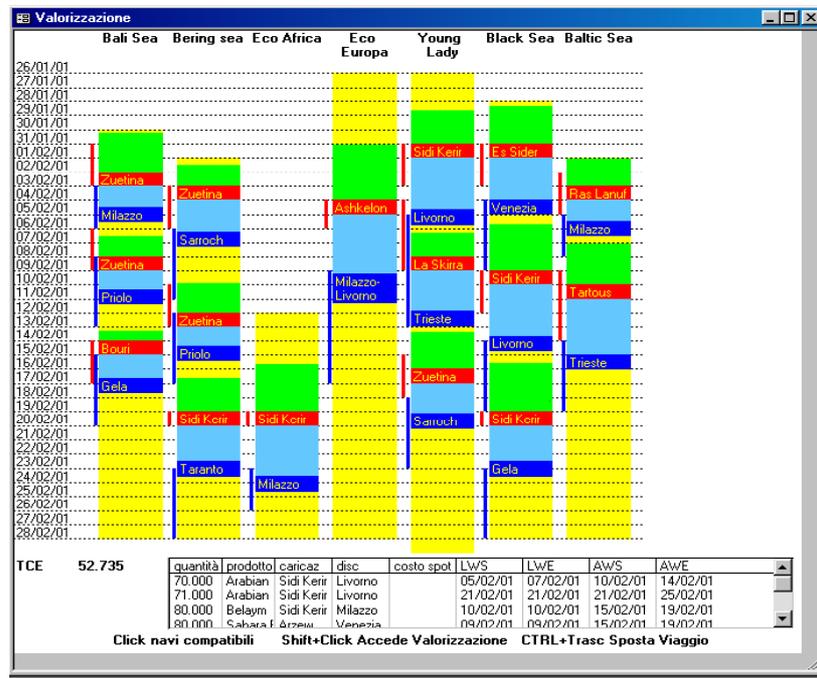


Figure 4: Zoned Time Chart

all the possible ways of turning over of vessels.

Another situation that sometimes disclosed the limits of the traditional approach was related to the opportunities that could be found in the open market selling capacity of transportation, that is, chartering out our controlled vessels.

The use of the optimization model made it possible to compute almost in real time the best solution to face each unpredicted events. Besides, the user interface allowed the scheduling team to test with great exactness manually composed solutions, and to drive the optimized solutions according to strategic considerations that are impossible to model in a mathematical framework.

The main advantage of the new procedure are then:

- short time needed to produce a solution;
- flexibility of the schedules;
- confidence in the decisions obtained;
- interactivity with the market and with the other company departments;
- consistent savings in the overall ships operational cost with respect to the previous situation.

Although it is not easy to quantify exactly the economic benefits of this approach, the experience made so far with the system showed a saving in the order of 5%- 10% in the cost of the monthly schedule plus savings in the order of tens thousand of US dollars each time the ships were rescheduled in the course of the planning period due to new events or changes in the problem's conditions due to external factors.

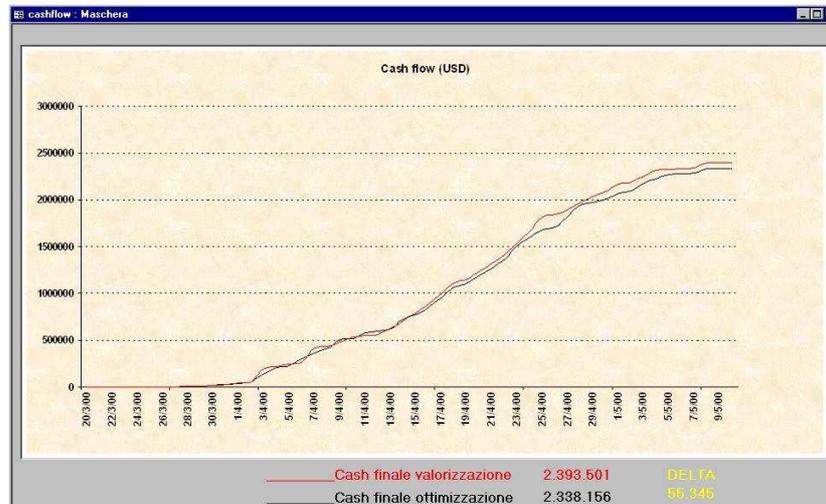


Figure 5: Cashflow

## References

- [1] G. G. Brown, G. W. Graves, and D. Ronen, "Scheduling ocean transportation of crude oil," *Management Science*, vol. 33, pp. 335–346, 1987.
- [2] M. Christiansen and B. Nygreen, "A method for solving ship routing problems with inventory constraints," *Annals of Operations Research*, vol. 81, pp. 357–378, 1998.
- [3] G. B. Dantzig and D. R. Fulkerson, "Minimizing the number of tankers to meet a fixed schedule," *Naval Research Logistics Quarterly*, vol. 1, pp. 217–222, 1954.
- [4] G. Felici, C. Gentile, and G. Rinaldi, "Solving Large MIP Models in Supply Chain Management by Branch & Cut," Tech. Rep. 522, Istituto di Analisi dei Sistemi ed Informatica del CNR, 2000.
- [5] M. L. Fisher and M. B. Rosenwein, "An interactive optimization system for bulk-cargo ship scheduling," *Naval Research Logistics*, vol. 36, pp. 27–42, 1989.
- [6] J. Laderman, L. Gleiberman, and J. F. Egan, "Vessel allocation by linear programming," *Naval Research Logistics Quarterly*, pp. 315–320, 1966.
- [7] M. D. McKay and H. O. Hartley, "Computerized scheduling of seagoing tankers," *Naval Research Logistics Quarterly*, vol. 21, pp. 255–264, 1974.
- [8] D. M. Miller, "An interactive computer-aided ship scheduling system," *European Journal of Operations Research*, vol. 32, pp. 363–379, 1987.