Scheduling short-term marine transport of bulk products

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A multinational company uses a personal computer to schedule a fleet of coastal tankers and barges transporting liquid bulk products among plants, distribution centres (tank farms), and industrial customers. A simple spreadsheet interface cloaks a sophisticated optimization-based decision support system and makes this system useable via a variety of natural languages. The dispatchers, whose native language is not English, and some of whom presumably speak no English at all, communicate via the spreadsheet, and view recommended schedules displayed in Gantt charts-both internationally familiar tools. Inside the spreadsheet, a highly detailed simulation can generate every feasible alternate vessel employment schedule, and an integer linear set partitioning model selects one schedule for each vessel so that all loads and deliveries are completed at minimal cost while satisfying all operational requirements. The optimized fleet employment schedule is displayed graphically with hourly time resolution over a planning horizon of 2-3 weeks. Each vessel will customarily make several voyages and many port calls to load and unload products during this time.

1. Introduction

Many companies manufacture liquid products and ship them to distribution centres and end customers. When quantities are large, products are shipped and stored in bulk, not packaged. For instance, oil refiners and chemical manufacturers ship most of their liquid products in bulk from their refining or manufacturing facilities to tank farms which serve as distribution centres, to industrial customers, and as feedstock to other manufacturing facilities.

Large volumes of liquids in bulk may be shipped by various modes of transport, such as tanker trucks, rail tank cars, pipelines, ships and barges. Where waterways are available, and especially if pipelines are not, marine transport by ship (or barge) turns out to be the cheapest mode of transport for these cargoes, and may be the only feasible mode. In 1993, approximately 1.7×10^9 metric tons of just oil and oil products were moved 9×10^{12} nautical ton-miles worldwide by sea [1].

This paper describes a decision support system which is used daily to optimally dispatch shipments of bulk products by ships and barges among plants, bulk distribution terminals, and industrial customers. Half a dozen organizations have recently been encountered in the US, the Far East, Australia and New Zealand, which face this type of dispatching problem [2].

The system presented here is implemented in place overseas, and is being used to schedule a diverse fleet of tankers and barges with hourly time resolution over a couple of weeks. It encompasses the richness of detail essential for an operational

system, some of which is reported here. A personal computer returns a complete fleet employment schedule within a minute or two.

2. Marine shipping operations

A multinational company ships liquid products in bulk by ship and barge among numerous port facilities used by several plants, many distribution centres (tank farms), and industrial customers. The annual volume shipped is close to 6 million tons at a cost of about $50 million (US).

The vessels used (e.g. figure 1) may be owned by the shipper, on a time charter, or spot chartered. The fleet is diverse: Each vessel has a different size (ranging from 500 to 5000 tons) and compartments (up to seven compartments per vessel), and each has its own costs and terms of employment. Each vessel is assigned an employment schedule over the next 2–3 weeks consisting of a sequence of voyages: Each voyage takes several days to load from source(s), discharge at one or more destinations, and move empty 'in ballast' for additional loading. The time horizon is limited by the ability to forecast supplies, demands, and the capability to transfer and store cargoes at the various ports of call.

A set of loads has to be conveyed by the available fleet of vessels. Each load consists of an order volume for up to five products, an earliest loading date, a loading location, a latest discharge date and location(s). A loaded leg of a vessel lasts from several hours up to several days, and a load comes from one or two sources (usually plants) and is discharged at one or more locations. A load that
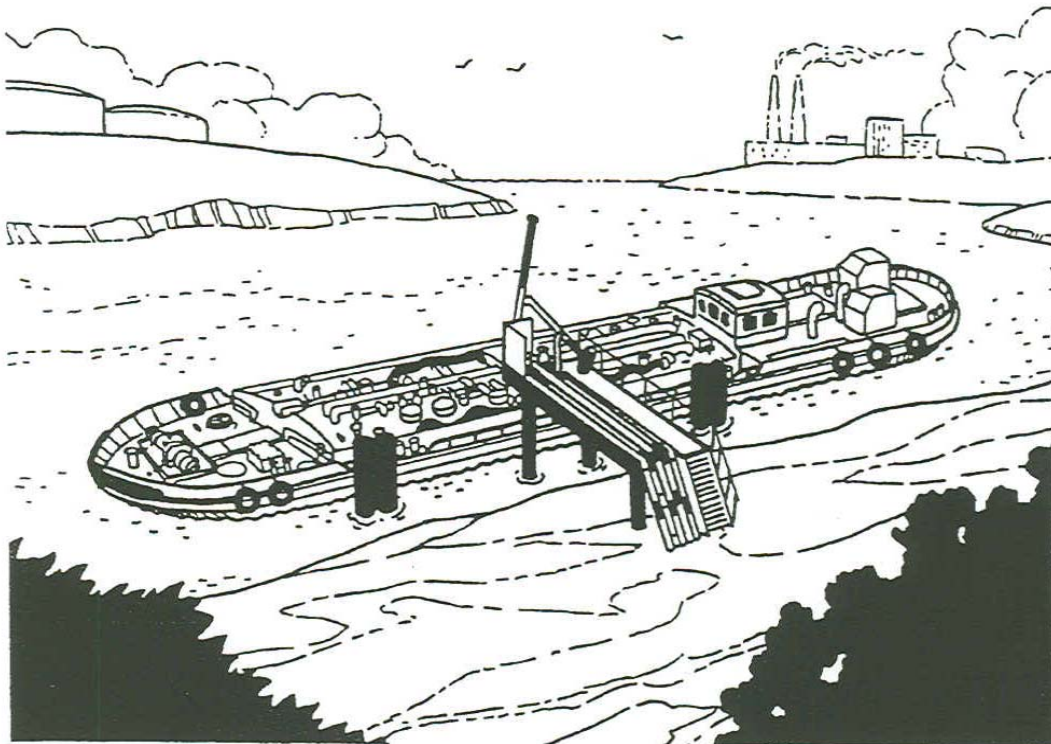

Figure 1.   The bulk liquid carriers scheduled range in size from 500 to 5000 tons, each with up to seven compartments. Vessels such as these can load and unload products from primitive berths.

cannot be accommodated by the available fleet may be assigned to spot (single voyage) charter at a known cost. The set of loads to be shipped is based on planned product availability, storage capacities at the plants (product tank topping must be avoided), and forecast product demand and safety stock requirements at the discharge locations.

In addition to the specified set of loads which must be shipped, there may be some optional back hauls available. These back hauls generate income and may be taken if they are profitable. The profitability of a back haul depends on its timing, loading and discharge locations, availability and cost of a compatible vessel to carry it, and the alternate value of the time of that vessel.

Not all vessels are compatible with all ports, due to draft and length limitations at the loading and discharging berths. The various ports have different operating hours and days. Most of the discharging ports, but not all, usually operate only during daytime and are closed during weekends and holidays. In addition, the ports have different rules regarding continuation after nightfall of product loading or discharging activities begun during daylight. Steaming at slow speed saves fuel and may avoid waiting for daylight port access.

Marine dispatching costs include the daily cost of owned and time-chartered vessels, cost of bunker fuel for steaming (which depends on the steaming speed), cost of fuel in port, port fees, and income from optional back hauls.

Marine dispatchers previously used large hand-drawn Gantt charts forecasting operations up to 2 weeks into the future. Each vessel occupies a row on the chart, with time on the horizontal axis. The complexity of dispatching, complicated by lack of relevant cost visibility and time for detailed calculations, compel the manual dispatcher to look for acceptable feasible dispatches using rules-of-thumb, without being aware of the global cost impact of his decisions.

Optimization can do better.

3. Design of a polyglot system

This study's marine dispatching system follows these principles:

- *The goal is to support the dispatcher, not replace him.* Dispatching decisions are complex. Not all future considerations can be foreseen and built into a computerized system. The system proposes optimal guidance for any problem instance and the associated minimal costs. The dispatcher should verify that the proposed dispatch meets business needs, and he should have the means to change the proposed solutions and see the cost impact of his changes.
- *The system must be user friendly,* exploit practical knowledge of the dispatchers, and accept and present data in a fashion with which dispatchers are familiar.
- *The system must operate on a personal computer.*
- *'Waiting time' for schedule advice must be kept to a minimum,* say, less than a minute, or so.

The basic components of the Computerized Marine Scheduling System (CMSS) are presented in figure 2, and some of its operational details are displayed in table 1. In the core of the system is an Elastic Set Partitioning (ESP) model (see Appendix). The ESP model accommodates transportation costs which are arbitrary nonlinear functions of extrinsic data, and almost any variety of operating rules. CMSS uses a highly specialized solver which represents ESP in a more compact form than a conventional set of partitioning model, and real business problems are reliably
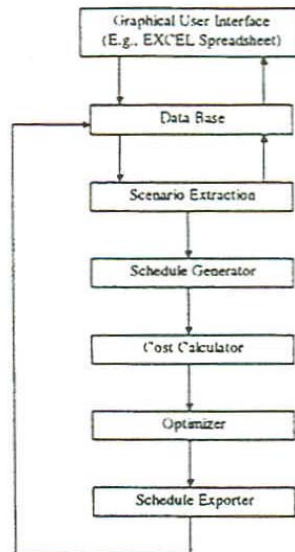
Figure 2. Components of the Computerized Marine Scheduling System (CMSS). There are a number of off-the-shelf products which can be used as a low-cost graphical user interface (GUI) shell for CMSS: Here, the ubiquitous Microsoft EXCEL is employed, principally for its worldwide availability, acceptance, and multiple language options. The CMSS internals are hidden from the user, and implemented in high-level problem-oriented computer languages.

Table 1. Sketch of Operational Details in CMSS.

Scenario Control:
  Is slow steaming permitted?
  Maximal waiting time for loading
  Maximal under-utilization of vessel volume
  Optimal sublets of owned or time-chartered vessels

Ports:
  Vessel-port compatibility
  Operating days and hours, including exceptions and holidays
  Loading and discharging rules
  Port fees
  Product-specific pumping rates

Vessels:
  Different grades (and costs) of bunker fuel
  Yard periods
  Variety of sizes, compartments, costs, and pumping line configurations
  Product pumping rate
  Fuel consumption as function of speed, both loaded and in ballast
  Safe trim on partially loaded legs
  Prevention of product cross contamination in pumping lines
  Standard spot charter rates with discounts and user override
  Voyages with multiple loading and discharging ports

Loads:
  Optional back hauls
  Pre-assignment of loads to vessels
  Multiple products in a load
  Flexible load size, controlled by product and load type
  Delivery time windows

Figure 3. CMSS view as a Microsoft EXCEL workspace. This has a look and feel which is familiar to any user with spreadsheet experience. This display is initiated by a CMSS EXCEL macro, but can be customized by each user to suit personal tastes. Thus, a user can 'drill down' or navigate among data objects in any fashion that appeals. Even the natural language can be changed to suit the user.

solved very quickly to within a small optimality tolerance (say, 0.1%). In addition to the optimizer the system has the following components; *user interface, scenario extracter, schedule generator, cost calculator*, and a *schedule exporter*.

The *user interface* is used by the dispatcher to assemble scheduling scenarios and review recommended solutions and system messages. The user interface is menu driven and written in EXCEL [3] (e.g. figure 3), which is a standard spreadsheet used by the host organization in all its operating countries and cultures. Thus both the authors and the sponsor have mitigated the expense of multilingual documentation and training. The input data, which the user can change on EXCEL spreadsheets, consists of scenario control parameters and of detailed data concerning the entities involved in the dispatch: products, ports, vessels, loads, dates, port fees, spot charter rates, and so on. Most of the data do not change very often. Conversely, the list of loads to be carried and the availability of vessels must be revised constantly. Schedule control parameters convey to the system the type of the dispatch and the proprietary policies to be used. These include, among others: type of fleet; type of products carried; dispatch beginning date; dispatch ending date; whether slow steaming should be considered; whether load-vessel pre-assignments should be honoured;

vessel maximal waiting time for loading; maximal time a load may be discharged early; maximal under-utilization of vessel volume by a load; and whether the vessels may be sublet during the planning horizon. Examples of vessel, port and load data are shown respectively in figures 4–6.

The user can also review the recommended dispatch and system messages via an EXCEL workspace. The user is provided with a detailed itinerary of each vessel, a full cost breakdown, the fitting of the assigned loads into vessel compartments, and a Gantt chart showing the proposed employment schedule which emulates the manual chart with which the dispatcher is familiar (see figures 7–10).

VESSELS										
*ID	NAME	SIZE	DRAFT	PUMP	FEE	RATE	DAVAIL	PAVAIL	TANK-1	LIN
8637	VESSEL 1	3100	5.4	1000	2	819	94030212	470	550	
8647	VESSEL 2	2650	5.35	1000	3	690	94030212	773	570	
8660	VESSEL 3	2100	4.9	1000	4	562	94030312	752	200	
8662	VESSEL 4	2100	4.95	1000	4	562	94030312	571	200	
8689	VESSEL 5	2080	5	1000	4	562	94030212	452	200	
8661	VESSEL 6	2060	5.2	1000	4	562	94030312	762	215	
8638	VESSEL 7	2050	4.95	1000	4	562	94030212	613	310	
8653	VESSEL 8	2000	5	1000	1	723	94030212	761	200	

Figure 4. Vessel descriptions. Included are vessel name, size, loaded draft, product pumping rate, port fee group, daily charter hire rate, date and hour vessel will be available for new instructions, port where vessel will be available, compartment size and pumping line connection (repeated up to seven times). Additional data (not shown) include speed-fuel consumption curve (both loaded and in ballast), type of bunker fuel used, and fuel consumption in port. For instance, Vessel 3 '8660' holds 2100 kilolitres, draws 4.9 metres, pumps 1000 kilolitres per hour, follows fee schedule 4, charters at 562 monetary units per day, and is free for scheduling at 12:00 hours (local time) on March 3, 1994, as Port '752'. Further details of this ship configuration are omitted here.

PORTS													
*ID	NAME	TYP	DRAFT	PROD	SUN		MON		TIME	PUMP		PART	NITE-1	NITE-2
100	PORT 1	L	9	W	0	0	8	17	1.5		400	T	F	F
				B	0	0	8	17	1.5		250	T	F	F
937	PORT 23	L	7	W	7	17	7	17	0.5		500	F	F	F
				B	7	17	7	17	0.5	A	500	F	F	F
										C	1000			
947	PORT 26	L	7	W	0	0	7	17	1		500	F	F	F
				B	0	0	7	17	1	A	400	F	F	F
										C	1000			
281	PORT 48	U	3.8	W	0	0	8	17	0.4		600	F	F	F
				B	0	0	0	0	99		0	F	F	F
350	PORT 49	U	6.7	W	0	0	8	17	0.7		1000	F	T	T
				B	0	0	8	17	0.7		1170	F	F	F

Figure 5. Port data. Included are port name, type, draft, product group, operating hours, fixed time for berthing, product-specific pumping rate, acceptability of partially loaded vessels, and permissibility of continuing loading and discharging operations after nightfall. For example, Port 1 '100' is 'Type L', offers a free draft of 9 metres, and has operating schedules specific to the product groups 'W' and 'B', but for both product groups the port is closed on Sundays, and open for entry from 08:00 to 17:00 hours (local time) on Monday, subject to 1.5 hour berthing delay. Although partially loaded vessels may enter, routine loading and discharging must be completed in daylight. Additional details are omitted here.

LOADS											
*NO.	FROM	DATE	TO	DATE	QTY	TYPE	SPOT	VESSEL	PROD-1	QTY-1	PROD-2(
001	931	940302	470	940304	4000	2	0	0000	D	4000	
002	960	940301	563	940302	2000	1	0	0000	R	900	K
003	905	940302	613	940304	400	1	0	0000	H	400	
004	905	940303	551	940304	2100	1	0	0000	R	700	K
005	909	940303	752	940305	2100	1	0	0000	R	700	K
006	917	940303	773	940304	2640	2	0	0000	R	1260	D
007	905	940305	760	940307	2000	1	0	0000	H	700	R
008	905	940305	763	940307	2100	1	0	0000	H	200	R
009	910	940303	470	940304	2050	1	0	0000	K	2050	
010	905	940305	479	940307	2050	1	0	0000	JA1	2050	
011	905	940307	479	940308	2050	1	0	0000	JA1	2050	
012	905	940303	451	940304	1200	1	0	0000	H	310	R
013	905	940303	470	940304	3100	1	0	0000	H	1800	R
014	905	940308	763	940310	1950	1	0	0000	J4	1500	K

Figure 6. Load data. Shown for each load are loading port, loading date, discharging port, discharging date, load size, load type, spot charter rate, pre-assigned vessel (if any), product code and product quantity (repeated for up to five products). Additional data include delivery time windows. For example, Load 008 must depart from port '905' on March 5 and discharge at port '763' 2 days later. This load consists of 2100 kilolitres, a 'Type 1' load, which may be spot chartered at the standard rate and is not pre-assigned to a vessel. Ordered volume breakdown is 200 kilolitres of product 'H', 900 'R', and so forth.

The *scenario extractor* converts all the EXCEL input to an integrated system data base which is used by the following processing steps. The extractor checks data for consistency and completeness. If any severe problems are detected which would render results meaningless, the schedule is aborted with the appropriate diagnostic message(s). Data problems which may be treated by resorting to reasonable defaults result in diagnostics which do not abort the schedule, but must be audited by the user.

The *schedule generator* produces for each vessel all (alternate) feasible schedules within the planning horizon which conform to the dispatching policy as conveyed through the input data, and conform to the operating rules of the specific vessel.

This is achieved by a detailed simulation of the potential activities of the vessel with an hourly time resolution. For example, port time consists of a fixed time for mooring plus variable pumping time which may be product specific. Product quantity adjustment tolerances (for fitting loads into vessel compartments) are specific to product and load type. The generator takes the vessel at the time and location where it is initially available for new instructions, seeds any potential first load for that vessel in a separate 'skeleton' schedule, then takes each one of these 'skeleton' schedules and tries to copy it and append a second load (repeating this process for all possible second loads). This process of copying a schedule and appending a load repeats itself until no more loads are available, or the end of the planning horizon is reached. This is performed only for loads compatible with the specific vessel (including fitting the products of the load into the vessel's compartments within the specified product quantity adjustment tolerances) and within the dispatching policy specifications. Depending on the specific problem instance, a vessel may end up with only a few, or perhaps thousands of alternate schedules.

8637 VESSEL 1	:940302 WED	:940303 THU	:940304 FRI	:940305 SAT	:940306 S/H	:940307 MON
	:AM : PM	:AM : PM	:AM : PM	:AM : PM	:AM : PM	:AM : PM
PRE-ASSIGNED						
PORT	X470	*905	*470			
STATUS	BB-----	--- LL---	---			
LOAD		*013	*013			
STATUS		PPPP	DD			
8647 VESSEL 2	:940302 WED	:940303 THU	:940304 FRI	:940305 SAT	:940306 S/H	:940307 MON
	:AM : PM	:AM : PM	:AM : PM	:AM : PM	:AM : PM	:AM : PM
PRE-ASSIGNED						
PORT	X773	*917	*773		*905	
STATUS	BBBBBBB	BBB LLLLLLL	LLL BBBBBBB	BBBBBBBS----	--- LLLLL	LLLLLLLLLS--
LOAD		*006	*006		*015	
STATUS		PP	DD		PPPP	
8660 VESSEL 3	:940302 WED	:940303 THU	:940304 FRI	:940305 SAT	:940306 S/H	:940307 MON
	:AM : PM	:AM : PM	:AM : PM	:AM : PM	:AM : PM	:AM : PM
PRE-ASSIGNED						
PORT		X752		*905		*763
STATUS		BBBBBBB	BBBBBBBBBBBBB	SS- LLLLLL	LLLLSSS----	--- BBBBBBB
LOAD				*008		*008
STATUS				PPP		DD
8662 VESSEL 4	:940302 WED	:940303 THU	:940304 FRI	:940305 SAT	:940306 S/H	:940307 MON
	:AM : PM	:AM : PM	:AM : PM	:AM : PM	:AM : PM	:AM : PM
PRE-ASSIGNED						
PORT		X571	*910*470		*905	
STATUS		B LLLL	L-- BB-----	------------	--- LLLLLL	LLLLLLLLLLLS

Figure 7(a).   Schedule proposal as a Gantt spreadsheet. Each vessel is represented by a strip showing the details of its proposed employment schedule (see legend in figure 7b). The resolution here is 2 hours per character, although the underlying model is more detailed. Pre-assigned activities are denoted by an 'X'. Balast ('B') and Loaded ('L') legs are occasionally stretched by slow steaming ('S') and are often followed by a waiting period ('–') for port operations. Pumping aboard ('P') and Discharging ('D') operations are fairly short. For example, Vessel 3 '8660' begins by (pre-assignment) a ballast (empty) leg from port '752' at 12:00 hours (local time) on Thursday, March 3, 1994. Slow steaming extends this leg by about 4 hours, but the arrival at Port '905' at 04:00 March 5 is still delayed until loading of '008' can begin at 06:00. Once begun, loading requires about 6 hours. The subsequent loaded leg is also delayed by slow steaming, but discharge at Port '763' still requires a 16-hour wait for daylight operations. This display visually conveys a great deal of information to the dispatcher, and is underlaid by the user-customized look and feel of the supporting EXCEL spreadsheets and data. The system permits even deeper customization by changing Gantt chart characters and supporting language for EXCEL (e.g. Dutch, English, Greek, Japanese,...).

At the end of each schedule (column) generation, a *cost calculator* assesses the bill. Spot charter and back haul rates are calculated by default from tariff tables unless actual rate quotes are available. Vessel fuel consumption (in case of slow steaming) is calculated by interpolation of its fuel-speed consumption curve.

Finally, the problem is converted into a standard ESP format [4] and submitted to the optimizer.

The *ESP optimizer* [5] selects at most one schedule per vessel assuring that all loads are shipped at minimal total cost. Optimal solutions (with an optimality gap of less than 0.1%) are usually achieved within a minute on a 486 based personal computer.

The *schedule exporter* converts the optimizer solution into a Gantt chart where the recommended activities of each vessel during the planning horizon are presented graphically (e.g. figure 7). In addition a detailed cost breakdown for each vessel and a cost summary by cost category and vessel type are provided (e.g. figures 8 and 9). The detailed fit of each load into the compartments of its assigned vessel is also displayed (figure 8). Finally, the recommended spot charters are listed (figure 10).

```
        G A N T T - C H A R T   L E G E N D

DATE        :  YYMMDD  YEAR MONTH DAY
               MON     MONDAY
               TUE     TUESDAY
               WED     WEDNESDAY
               THU     THURSDAY
               FRI     FRIDAY
               SAT     SATURDAY
               S/H     SUNDAY/HOLIDAY
               UNK     NOT IN CALENDAR

SHIFT       :  AM      00:00 - 11:59
               PM      12:00 - 23:59

PRE-ASSIGNED :  HOURS MARKED 'X'

       PORT :  DEPARTURE/ARRIVAL PORT ID'S; 'X' PRE-ASSIGNED

     STATUS :  'L' LOADED LEG UNDERWAY
               'B' BALLAST LEG UNDERWAY
               'S' SLOW-STEAMING DELAY
               'Y' YARD (OFF-HIRE) TIME
               'K' BACK HAUL
               '-' IDLE
               '?' UNKNOWN (MISSING DATA)

       LOAD :  LOAD ID'S; 'X' PRE-ASSIGNED

     STATUS :  'P' PUMPING ABOARD
               'D' DISCHARGING
               '-' IDLE
```

Figure 7(b).   English language Ganett chart legend.

```
VESSEL 8660 VESSEL 3
  TRIPS: 008 026
  LOADS: 008 026
COST OF TIME=      3934.00
  BUNKER FUEL=      413.11
  INPORT FUEL=       53.10
  PORT FEES  =      139.20
  BACK HAULS =         .00
    TOTAL COST=     4539.41

        V E S S E L S   L O A D O U T

VESSEL   :8660
TOTAL VOL: 2100  TANKS:      200      500      500      500      400       0        0
LOAD   :   8  TYPE:1
ORDERED VOLUMES: H      200 R      900 K      500 D      500
LOADED VOLUMES :       200        1000       500        400
PROD BY TANK   :       H   200 R   500 R   500 K   500 D   400        0        0

VESSEL   :8660
TOTAL VOL: 2100  TANKS:      200      500      500      500      400       0        0
LOAD   :  26  TYPE:1
ORDERED VOLUMES: R      830 K      500 D      720
LOADED VOLUMES :       700        500        864
PROD BY TANK   :       R   200 R   500 K   500 D   480 D   384        0        0
```

Figure 8.   Employment schedule costs and loading detail. An employment schedule may consist of several loads with partially loaded legs. A breakdown of costs incurred by each vessel provides visibility and feedback unprecedented in this industry. In order to fit the loads into the compartments on the vessel, to maintain safe trim, and to stay within product quantity adjustment tolerances, the loaded quantity is not necessarily identical to the ordered quantity, and not all vessel compartments are necessarily full: e.g. load 026 on vessel 8660 shows two such product quantity adjustments.

4.   Scheduling with CMSS

The user can pre-assign some (or all) loads to vessels based on intuition and experience, and then use the system to compare manual results with optimized scenarios. Because it is assumed the dispatcher knows what he is doing, a pre-assignment *never*

COST OF SCHEDULE

	NO.	COST OF TIME	BUNKER FUEL	IN PORT FUEL	PORT FEES	BACK HAUL INCOME	TOTAL COST
USED	9	28633.00	2072.16	428.34	2036.00	.00	33169.50
IDLE	0	.00					.00
SPOT	14						28977.20
TOTAL		28633.00	2072.16	428.34	2036.00	.00	62146.70

DISPATCH STATISTICS

	TOTAL COST	SUGGESTED VOLUME (KL)	OUTPUT (MKL*NM)	COST PER KL*NM
T/C	33169.5	36134	8099	4.096
SPOT	28977.2	22300	3766	7.694
TOTAL	62146.7	58434	11865	5.238

Figure 9. Employment schedule cost analysis. A global 'cost of schedule' is provided by cost component and type of vessel (upper). The 'dispatch statistics' analyse costs by type of vessel and per output unit. Output is measured in (delivered volume) × (direct distance). Units in this case are kilolitres (KL), Thousands of Kilolitres (MKL), and Nautical Miles (NM).

SPOT LOADS

LOAD	LOAD PORT	LOAD DATE	DISCHARGE PORT	DISCHARGE DATE	LOAD SIZE	COST OF SPOT CHARTER
001	931	940302	470	940304	4000	6360.00
002	960	940301	563	940302	2000	2260.00
003	905	940302	613	940304	400	1024.00
012	905	940303	451	940304	1200	1392.00
014	905	940308	763	940310	1950	2710.50
019	910	940308	613	940309	2100	2100.00

Figure 10. Spot-chartered loads. Recommended spot loads are listed separately, with loading, discharge and estimated cost information. These always attract close scrutiny by dispatchers.

results in an error message (which would abort the scenario). However, the system issues a warning when pre-assignment violates an operating rule or policy: *Otherwise, comparison of an optimal schedule, restricted to be legal, with a cheaper manual schedule, relaxed to ignore restrictions, might lead to confusion or even loss of faith.*

Figure 11 depicts typical navigation of CMSS. First, the dispatcher revises the set of loads to be shipped and the availability of the vessels (yard periods and other prior commitments must be pre-assigned), and reviews the scenario control parameters. Once he is satisfied with the static data, he optimizes. If the scenario is aborted due to catastrophic data errors, this must be diagnosed and corrected. Otherwise the dispatcher reviews the results and accepts them (if they meet his needs) or changes input and optimizes again (we hesitate to use the term 're-optimize', because the nature and extent of changes is not known *a prior* by the optimizer). The level of detail is at once a blessing and a curse: Detail lends credibility to results, but requires some care in preparation. Table 1 provides an outline of the variety of operational details captured by the input data, and figures 3–6 amplify some of this detail.
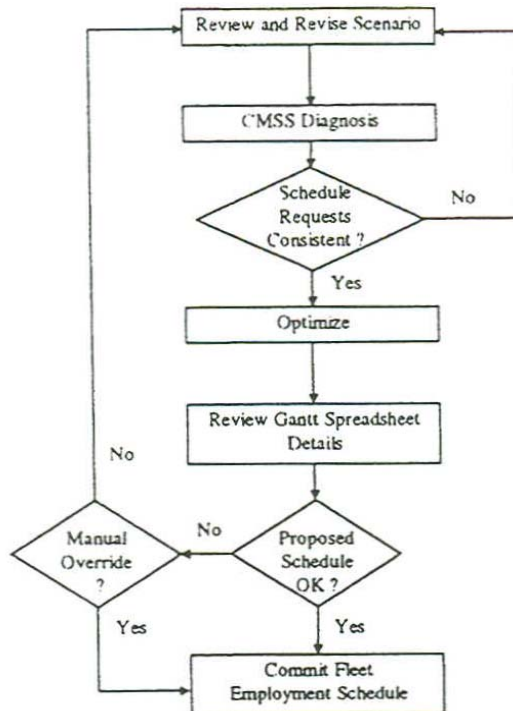
Figure 11. Functional flow of CMSS. Serious input errors in scenarios are preemptively diagnosed for dispatcher attention. Otherwise, optimization is automatic. The optimized schedule can be accepted, as is, or the dispatcher (who knows more than CMSS) can manually override any undesirable assignment. The dispatcher can also develop multiple, parallel alternate sequences of employment schedules pursuing, say, competing ideas for dealing with some upcoming contingency

Schedules with a dozen vessels and 50 loads are routine. System response time is usually less than a minute on a modest (Intel 486/33) personal computer. Importing data into and exporting schedules from EXCEL are more time consuming than the optimization.

The system was originally designed for a scheduling horizon of 2 weeks. The users have extended this to 6 weeks for tactical planning, addressing fleet size and mix decisions.

Surprisingly, an optimal schedule will often idle an owned or chartered vessel, or even two, and convey loads compatible with these idle vessels by spot charter. Naturally, the dispatchers try pre-assigning the idled vessels with compatible spot chartered loads. They discover that as long as such pre-assignments do not violate any operational rules, total costs increase. Results such as these imply that the cost data are incorrect, or that there are too many time chartered vessels, or that controlled vessels are too expensive. Whether these are frustrations, or insights, the authors are not aware of a single instance where the user has succeeded in finding a cheaper manual solution without violating some rule which CMSS cannot.

5. Summary

This study has presented a personal computer based system which is used to schedule marine transportation of liquid bulk products. A mathematical programming model

(which is hidden from the user) provides a minimal cost schedule within a minute or so. The system comprehends a rich variety of operational considerations and provides schedules which are not only efficient but are also face valid and directly usable. The users communicate with the system through EXCEL spreadsheets and Gantt charts, tools with which they are acquainted, regardless of native country or language fluency. The total cost of a host personal computer and software for CMSS is about $1000 (US): Judging from experience, the pay back for this investment may be just one optimal dispatch.

Among the distinguishing features of CMSS: slow steaming is considered explicitly, the optimal steaming speed is recommended, a variety of vessel and load sizes is accommodated, a load may consist of multiple products, safe trim is assured for partially loaded legs on voyages with multiple loading or discharging ports, cargo sizes are flexible (within a range controlled by the user), and product cross contamination in vessel pumping lines is prevented.

Hourly time resolution admits extremely detailed model fidelity. For example, although this has not been necessary yet, CMSS can easily accommodate hourly tide levels and restrict vessel port entry times, or barge passage under bridges accordingly.

The best innovation CMSS offers to this industry has nothing to do with optimization: simple global cost visibility of employment schedules is, as far as the authors know, totally new. Based on experience, cost visibility leads to immediate insights and informed improvements in scheduling.

Ship scheduling problems have received some attention in the literature (e.g. see review by Ronen [6]). The work here evolves from earlier medium-term (60–90 day) scheduling of a fleet of (about 30) large crude oil carriers [7]. Later, Bremer and Perakis [8] and Perakis and Bremer [9] suggest a hypothetical model which appears similar.

Evolution to larger fleets, longer time horizons, and more fine detail has continued with the annual employment scheduling of (about 80) combatant ships in the US Navy's Atlantic Fleet [10], daily port scheduling of US Naval Base, Norfolk, Virginia [11], and berth planning for US Submarine Base, Point Loma, California [12].

The development of CMSS began in 1990. Half a calendar year was required for finishing a prototype for evaluation. Most of this effort was spent travelling to see the marine operations and then capturing their essence in the schedule generator. Accommodating enhancements and changes arising from on-site experience overseas required another half year. With the accumulation of operational experience, some additional changes have been implemented, but these are now very infrequent.

Appendix
CMSS relies on an embedded Elastic Set Partition (ESP):

Indices:

$v = 1, \ldots, Vessels$
$l = 1, \ldots, Loads$
$s = 1, \ldots, Schedules$
  $SV(v)$ Schedules for vessel v
  $SL(l)$ Schedules delivering load l

Data:

Cost$_s$ Cost of schedule s (An arbitrary function of vessel and load attributes and exogenous data, such as load sequence)
ICost$_v$ Idle cost for vessel v
SCost$_l$ Spot Charter Cost for load l

Binary decision variables:

DISPATCH$_s$ = 1 if schedule s is selected
IDLE$_v$ = 1 if vessel v is idle
SPOT$_l$ = 1 if load l is spot chartered

(ESP) formulation:

(1) Minimize

$$\sum_s Cost_s\, DISPATCH_s + \sum_v ICost_v IDLE_v + \sum_l SCost_l SPOT_l;$$

(2) for each vessel v:

$$\sum_{s \in SV(v)} DISPATCH_s + IDLE_v = 1;$$

(3) for each load l:

$$\sum_{s \in SL(l)} DISPATCH_s + SPOT_l = 1.$$

The objective function (1) expresses total fleet employment schedule costs, including elastic penalties for idle vessels and spot charter loads. Constraint (2) ensures each vessel is assigned an employment schedule, or is idled. Constraint (3) ensures each load either appears on a selected employment schedule, or is spot chartered.

CMSS uses a solver (i.e. [5]) which represents the variable types IDLE and SPOT logically, rather than explicitly. When represented explicitly for a conventional solver, these variables will intrinsically assume binary values, so they can be expressed as continuous variables.

The fidelity of this model derives from the ability to provide it all, or at least a large number of the alternate feasible employment schedules for each vessel. The identity simulator which generates these schedules must render good-quality schedules as well as unlikely-looking or high-cost schedules which, in concert with less expensive cohorts for other vessels, provide a good global fill and fit for an entire fleet employment schedule.

The ESP cost of each alternate employment schedule is a complicated nonlinear function of exogenous data such as load delivery sequence (which is not known by ESP), speed by leg and consequent fuel consumption, and so forth. Flexibility in accommodating such costs is a hallmark of set partitions.

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