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Principles of Combinatorial Optimization Applied to Container-Ship Stowage Planning

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Abstract

In this paper, a methodology for generating automated solutions to the container stowage problem is shown. The methodology was derived by applying principles of combinatorial optimization and, in particular, the Tabu Search metaheuristic. The methodology progressively refines the placement of containers, using the Tabu search concept of neighbourhoods, within the cargo-space of a container ship until each container is specifically allocated to a stowage location. Heuristic rules are built into objective functions for each stage that enable the combinatorial tree to be explored in an intelligent way, resulting in good, if not optimal, solutions for the problem in a reasonable processing time.

Key Words: automation, container stowage, heuristic, planning, search, sea transport

Generally, difficulties associated with combinatorial problems are such that exact procedures (giving an optimal solution) may not be easily determined or are too expensive to apply. Instead, procedures that give good, but possibly not optimal, solutions are applied. These procedures are called *heuristics*. A more general class of heuristic methods has arisen, such as Genetic Algorithms, Simulated Annealing and Tabu search, which are collectively referred to as *metaheuristic* procedures. With metaheuristics, the process of finding a good (or optimal) solution involves the application of a subordinate heuristic at different stages in the procedure that is specifically designed for the particular type of problem (Glover, 1993). This paper summarises the results of the design and testing of a computerised stowage-planning system developed by applying principles associated with combinatorial optimization. In particular, it highlights how a hybrid approach incorporating metaheuristic problem solving algorithms can be employed to offer good, if not optimal, results.

1. Background

Since the 1970s, *containerisation* (the packing of cargo into large, dedicated boxes, of different dimensions, enabling multiple units of cargo to be handled simultaneously) has facilitated the transportation of cargo. This standardisation of containers has permitted the introduction of *inter-modal* transportation systems. That is, containerised cargo can be transported by rail, truck or sea due to its standard frame and dimensions having enabled the introduction of carriers dedicated to this purpose. In order to increase the benefits of economy of scale, the size of *container ships* has increased. This increase in size has seen

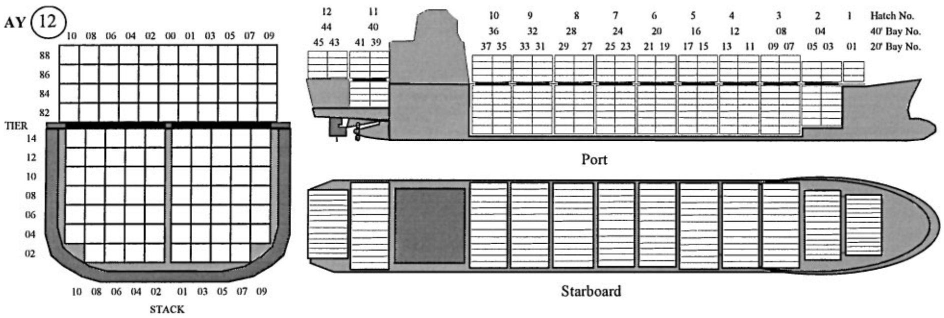

Figure 1. Stowage arrangement of a cellular container ship.

the capacity of container ships rise from the relatively small 350 Twenty Foot Equivalent Units (TEU) vessels to ships with capacities of more than 4800 TEUs.

Container ships are vessels possessing a structure that facilitates the handling of containerised cargo. At each port along the vessel's journey, containers are unloaded and additional containers destined for subsequent ports are loaded. Determining a viable configuration of containers that facilitates this process, in a cost-effective way, constitutes the container stowage problem. The work of determining a stowage configuration for a container ship is performed by human stowage planners. The large container ships of today (an example of which is illustrated in figure 1) can require thousands of container *movements* (the loading, unloading or re-positioning of each container) per port of destination (POD) to complete the discharge and load process. It is important that the process of loading and discharging container ships be carried out with a minimum of disruption. However, given this large number of container movements, reaching optimum efficiency is very difficult.

Container-ship efficiency is largely determined by the arrangement of containers both within the container-terminal and on the container ship. Determining the arrangement of these containers is an error prone process that relies upon the intuitive skills of human planners. The planner must determine the optimum placement of containers so that all constraints are satisfied and material handling costs are minimised. The complexity of stowage planning is increased by its multi-port nature. That is, a plan for a stowage configuration at one port must take into account the consequences at subsequent ports (an example of a typical voyage is given in figure 2).

As the following example of the planner's documents will show, the stowage planning task is split into two main parts—the generation of long-term (generalised) and short-term (specialised) stowage strategies. Planners must consider expected loads at subsequent ports, which often include statistical information describing loads in generic terms. (In the general cargo trade it is quite frequently the case that booking lists arrive little by little, over time, and are not completely known much in advance of loading taking place—hence the need for such statistical information.) Planners use a combination of documents (the General Arrangement, Outline Plan and Bay Plan described below) to plan stowage of cargo.

The *General Arrangement* document (illustrated in figure 3) is a simplified, small-scale, vertical longitudinal section through the centre of the vessel, viewed from the starboard side. The planner 'reserves' areas of the ship to hold groups of containers with specific

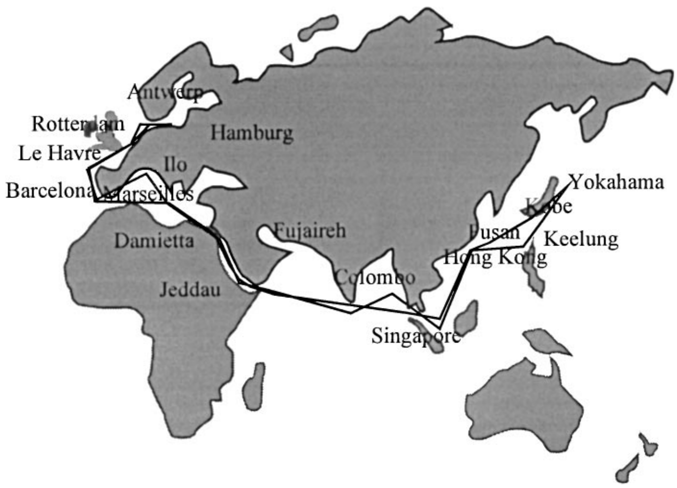

Figure 2. Example port rotation.

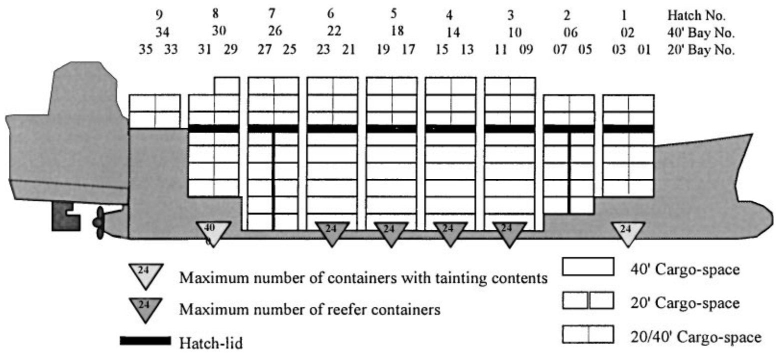

Figure 3. General Arrangement.

destinations. These destinations are usually indicated using different coloured pens. To understand this task, an awareness is required of the relationship between the cargo-space indicated by the document and the containers.

The cargo-space of a container-ship is made up of *cells* where each cell is 20′ long, 8′ wide and 4′3″ high. Cells are grouped into vertical *stacks*, which are in turn grouped into *bays* (collections of stacks across the width of a ship). Bays are either above-deck, or below-deck (enclosed within the ship beneath removable hatch-lids), and are grouped together by associated hatch number (indicated in figure 1). Below-deck bays have restrictions upon the container dimensions that can be accommodated. The relationship between a cell and a physical location (or *slot*) for a given container need not be one-to-one. Each container is labelled with its own uniquely identifying code, part of which indicates the dimensions of a container. Roach and Thomas (1994) state that the International Standards Organisation

(ISO) recommend that a container should be 8 feet wide, 8 feet 6 inches high and, most commonly, 20′ and 40′ long. Some non-standard containers do not conform to an ISO classification. In addition, some containers are frames of standard dimensions that allow cargo to protrude. As well as considering the physical dimensions of cargo and cargo-space, the planner must consider how the cargo contents can restrict placement. So-called *specials* have particular stowage requirements (perhaps needing a power supply to either cool or heat contents). Certain types of cargo are defined as *hazardous* and have specific stowage requirements that include segregation from other cargo. There are rules governing requirements to segregate hazardous cargo, at specified distances, from each other and certain cargo.

Lastly, part of the cargo stowage planner's task is to ensure, via *intact stability* calculations, that the vessel remains in a stable condition. The following serves to introduce stability and stress constraints, for a complete review of intact stability, refer to Goldberg (1980). Cargo weight should be spread evenly to avoid *heeling* (an inclination from the vertical towards port or starboard) and ensure close to zero *trim* (which reflects the angle of the vessel fore to aft). Uneven weight distributions also produce forces which can distort the physical structure of the ship, namely *bending* (acting from bow to stern) and *torsion* (port to starboard). Ballast (seawater) may be used to stabilise a vessel, but is considered additional cargo and so should be kept to a minimum.

The General Arrangement document provides information that can help when planning the ship operation, in particular: the location of each hatch (cranes may not be able operate simultaneously on bays located side-by-side); the position of the accommodation block and engine room (important when considering crane positioning and hazardous container stowage); bay restrictions on the lengths of containers which can be accommodated and on cells which can hold only empty containers. In the use of this document, the planner employs two heuristics:

- to minimise the number of cargo spaces occupied by each destination;
- to maximise the number of cranes in operation at each subsequent port.

The General Arrangement does not show how many containers can be stowed across the vessel at each level above and below deck. That information is provided in an *Outline Plan* (illustrated in figure 4). Here, the container stowage stacks of the entire ship are shown in more detail, in the form of a series of vertical transverse sections, or *bays*, viewed from aft. Each stowage location (slot) is shown as a small box. The Outline Plan shows exactly how many containers can be stowed in each bay. Slots are marked using letters and/or colours to indicate the container's port of discharge. Container slots can be marked with symbols to show the presence of over-height and over-width containers. It also allows indication of the positions of power supplies, and presence and type of any special and hazardous cargo.

The planner uses the Outline Plan to consider how best to arrange the containers latitudinally. Containers are loaded by cranes from the bottom of the ship, into vertical stacks. If a container destined for one port is positioned below containers destined for a later port, the containers above must be unloaded and reloaded at that earlier port. This is particularly costly for such containers below-deck. All containers placed on a hatch cover (above-deck) must be removed, along with the hatch cover, to access containers stowed below-deck that

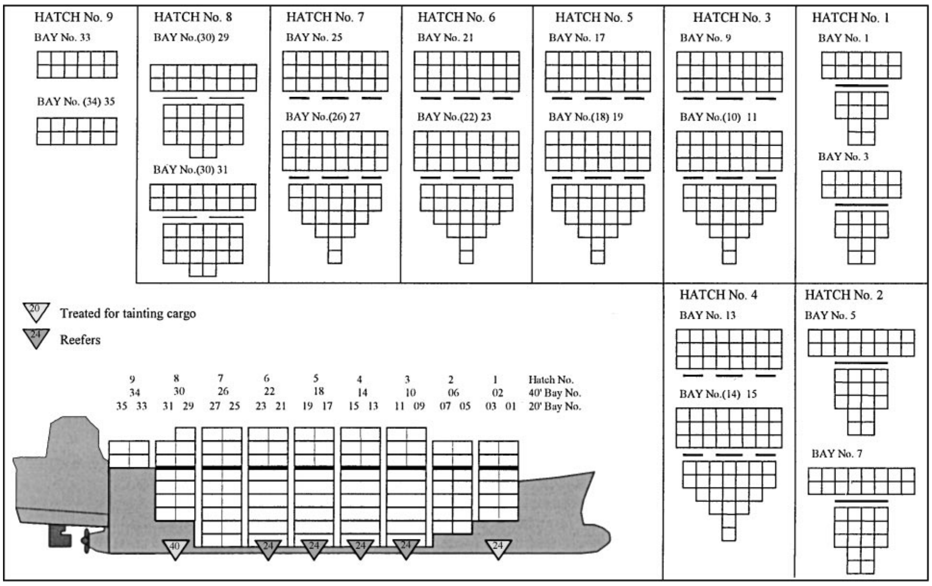

Figure 4. Outline Plan.

correspond to that hatch. Containers blocking access to others to be unloaded first are known as *over-stows*. Containers may need to be moved to allow access to ones to be unloaded or simply to improve the overall stowage pattern—such movements are called *re-handles*. Movements of containers incur additional costs in time, so cargo should be arranged so that the time spent in port is kept to a minimum. Illustrations of container re-handles can be found in Shields (1984) and Wilson (1997).

From this document, the planner can see at a glance how many hatch-covers (marked as thick black lines) will have to be removed before below-deck containers can be moved. The planner can also see how many above-deck containers will have to be removed before a hatch cover can be accessed. At this stage of planning, the planner employs three heuristics:

- minimise the number of hatch-lids moved;
- minimise the number of over-stows;
- minimise the number of cargo *blocks* occupied ('blocks' being defined in Section 4), which has the effect of reducing crane movements and hatch-lid movements.

Given the generalised information available about cargo, even a few days before docking, little attention is given to placing specific containers at this stage in the planning process. Instead, groups of containers of a general type and destination are allocated to groups of cells.

A bay plan is a detailed view of just one of the stowage bays from the Outline Plan usually showing the above-deck and below-deck parts of the bay on separate sheets. The last of the planner's documents, the complete Bay Plan for a ship, is a large document composed of

Voyage number:______ Date:______ Port:_____/______
Discharging/Loading

210814	210614	210414	210214	210014	210114	210314	210514	210714
210812	210612	210412	210212	210012	210112	210312	210512	210712
210810	210610	210410	210210	210010	210110	210310	210510	210710
210808	210608	210408	210208	210008	210108	210308	210508	210708
210804	210606	210406	210206	210006	210106	210306	210506	210706
	210604	210404	210204	210004	210104	210304	210504	
		210402	210202	210002	210102	210302		

Bay No. 21
Under deck
8' 6"

Figure 5. A Bay Plan.

many sheets, each of which will be similar to the generic example shown in figure 5. On this document, specific containers are allocated to specific positions. The heuristics employed by the planner to complete this document are outlined in Section 5.3.

The General Arrangement and Outline Plan are often used to indicate the broad allocation of groups of slots to containers of particular ports of discharge. The larger and more detailed Bay Plan is required for the planning and supervising of the actual stow for a loading operation and the detailed sequence for discharge. When planning is complete, each slot on the Bay Plan is labelled with information about the containers. This information includes the slot address, port of discharge and container identification code, type, dimensions, cargo content and weight. Non-containerised cargo and specials can also be indicated on the bay plan. In full, the bay plan contains the information required for the planners to make required intact stability, and stress calculations and to ensure that maximum stack height and weight limits are not exceeded.

2. Problem size and existing work

The container stowage problem is a combinatorial problem the size of which depends upon ship capacity (given by the number of TEU units) and the container supply and demand at each POD. The container loading problem is combinatorially explosive with the number of possible stowage configurations for a medium-sized container-ship being vast (Dillingham and Perakis (1986) state that the number of possible configurations for a 2000 TEU ship is approximately 3.3 times ten to the 5735th power). Even for the smallest vessel sizes, container stowage planning is a large-scale problem due to the large number of variables (e.g. vessel intact-stability, hazardous cargo segregation, the need to consider stowage across a number of ports) which require consideration. Generally, very many theoretically plausible solutions exist. The problem has been described as being NP-Hard (Botter and Brinati, 1992; Avriel et al., 1998). This is to say that it is not possible to guarantee that an optimal solution can be found for commercial sized ships in a reasonable processing time.

This real-world problem is one that benefits from automation through the application of Artificial Intelligence. Many decision support systems exist that assist planners with short-term stowage planning, by providing a graphical interface that enables the manipulation of stowage plans and the automatic generation of the time-consuming calculations for ship stability. However, little work has been published in the area of full automation of stowage planning. Authors proposing full automation have correctly identified the salient features of the problem, but have allowed the 'honey-combed' nature of spaces within containerised vessels to entirely dictate their approach. In addition, these authors have greatly simplified the problem by removing important features, rendering solutions commercially unworkable. By concentrating on the specific placements of containers, these authors have failed to identify abstraction processes employed by human planners which facilitate the determination of commercially viable solutions. The failure of past attempts to automate the planning procedure has, in the authors view, resulted in a drying-up of research. However, there has been some recent interest in this area: Wilson (1997), Wilson and Roach (1997), Avriel et al. (1998).

Of particular interest are the Computer Aided Pre-planning System (CAPS) due to Shields (1984) and work of Botter and Brinati (1992). In addition to providing a decision support system that augments a paper based system, Shields attempts to provide automation of the planning process. Shields uses a data structure based upon specific cells, and employs a weighted random approach to allocating containers to those cells. The weights are governed by sensible stowage criteria. CAPS is reported as reducing the number of over-stows. However, other shipping companies that have augmented or replaced paper-based stowage planning systems with computer-assisted methods also report similar improvements, without fully automating stowage planning.

Botter and Brinati (1992) provide a mathematical model for describing the entire stowage problem. This models also represents the cargo-space as cell-based data structure. Botter and Brinati (1992) report that the model can be used to find an optimal solution. However, this model incorporates too many simplifications to justify this claim. The model does demonstrate the computational complexity of the problem. As it can not be guaranteed that an optimal solution can be found for commercial ships in a reasonable processing time, Botter developed integer-programming methods, based on the mathematical model, which solve the problem only by ignoring important features. Avriel et al. (1998) use a similar approach to Botter and Brinati (1992), adding some sophisticated heuristics to their model.

Importantly, non-standard dimension containers, hazardous cargo and specials are not included in the models due to Shields, Botter and Brinati, and Avriel et al. This reduces the search space of the problem by ignoring important factors. However, Shields and Botter and Brinati group containers with the same characteristics (such as the destination port) prior to loading. Further, Shields uses general descriptions of the groups, so that generically described containers of a class, rather than precise containers, can be loaded. The authors' approach proposed in this paper, and described in Section 4, has built on this type of grouping and abstraction, to better model the processes used by human planners.

3. Tabu search

Tabu search is an iterative procedure for solving discrete combinatorial optimization problems. Tabu search was first suggested by Glover (1977) and has since become increasingly used. It has been successfully applied to obtain optimal or sub-optimal solutions to such problems as scheduling, time-tabling, travelling salesman, and layout optimization. The principal method, described by Glover, Taillard and de Werra (1993), is to explore a search space of feasible solutions by making a sequence of moves. A move from one solution to another being the best available. However, so that cycling is avoided and global optimality pursued, some moves, at a particular iteration, are categorised as illegal or tabu. A tabu status is assigned to historical moves that meet defined criteria. For example, one might classify a move as tabu if the reverse move has been made recently (within a given number of iterations) or frequently (a given number of times). It may sometimes be desirable to make an otherwise tabu move and a particular implementation may include aspiration criteria that override the tabu status of a move. A typical characterisation of the search space S for which tabu search can be applied is that there is a set of k moves $M = \{m_1, \ldots, m_k]$ and the application of the moves to a feasible solution $s \in S$ leads to k usually distinct solutions $M(s) = \{m_1(s), \ldots, m_k(s)\}$. The subset $N(s) \subseteq M(s)$ of feasible solutions is known as the neighbourhood of s. The neighbourhood of s is generally too large for it to be completely explored. This is especially true of stowage planning since an already prohibitively large search space is increased exponentially when the implications of a given solution are explored at future PODs (Wilson, 1997). In the authors' approach in this paper, the neighbourhood of s at any given POD is reduced by a number of abstraction processes that model the human planners' use of stowage documents. This led to a hybrid implementation, described below, combining Branch and Bound Search, Packing Heuristics, and Tabu Search to enable complete solutions to be generated in a short time through evaluation of a small neighbourhood.

4. Approach taken

In order that the computational difficulties associated with producing an exact solution for the stowage problem be overcome, the authors propose that the process be decomposed into two sub-processes:

1. A strategic planning process; generalised containers (containers generically described by class, rather than specific containers) are assigned to a blocked cargo-space in which slots corresponding to hatch-lids are grouped together (illustrated in figure 6). This approach models human planners' use of the General Arrangement and the Outline Plan to plan stowage, resulting in a 'generalised solution'.

   The hatch-lids are the removable separators of above-deck and below-deck cargo, and are usually composed of a number of sections that interlock latitudinally; three sections in the case of the hatch in figure 6, two for Hatch 8 in figure 4. Above-deck cargo can be placed across two sections of the lid (indicated in figure 6), creating blocks of cargo slots that have a partnership relationship with these sections of hatch-lids. This in turn has consequences for which lids and containers must be removed by cranes to allow access to other containers and slots. Blocking the cargo-space of the container-ship enables the number of options for specifying container placements available at any stage of the planning process to be reduced from, perhaps, thousands of possibilities to within a hundred, whilst retaining the inherent characteristics of the problem. Stress

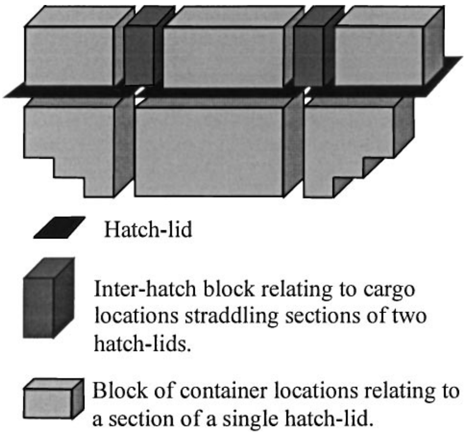

Figure 6. Example of cargo-space blocking relating to a single hatch.

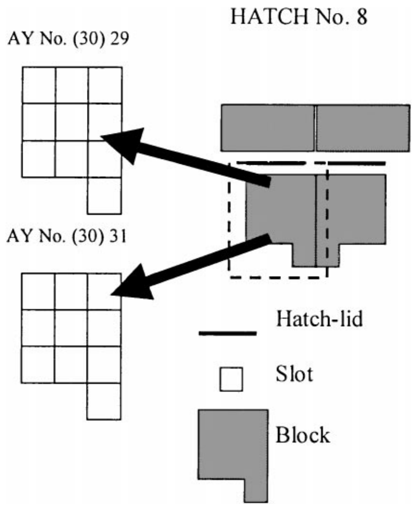

Figure 7. Relationship between blocks and slots.

and stability can then be calculated for the abstract model to an acceptable degree (using an approach based upon the work of Sato (1992)). This phase provides a picture of the cargo stowage *distribution* of the generalised containers at the end of the unloading and loading processes at each POD.

2. A tactical planning process; specific containers are assigned to specific slots within the blocks determined during the strategic planning phase, illustrated in figure 7. (Note that this hatch, also shown in figure 4, can be used as one 40′ bay—number 30—or two adjoining 20′ bays, numbered 29 and 31.)

   This phase determines the exact slot occupied by each container at the current POD. Using this model, the neighbourhood is reduced to the moves within the same *block* of the container ship. This avoids the combinatorial difficulties associated with attempting to make specific placements within the entire cargo space. This procedure models the human planner's conceptual approach in their use of the Bay Plans.

5. A worked example

The following describes an example of the application of the hybrid software to an example based upon data supplied by the then P&O Containers. Each phase in the decomposition process is explained and related to the human planner's own approach to producing stowage solutions.

5.1. Problem description

The prototype hybrid planning software was applied to a nine-hatch container ship with an above-deck capacity of 352 TEU and an under-deck capacity of 336 TEU giving a total TEU capacity of 688. The loading and unloading strategies for four ports were considered with a total of 696 containers being loaded and 312 containers being unloaded for 1008 movements. The breakdown of containers handled was typical of the general cargo trade, and was as follows:

- 54% were 20′ in length;
- 44% were 40′ in length;
- 2% were of other lengths;
- 20% required refrigeration (so-called *reefers*);
- 14% required special segregation (due to the hazardous or tainting nature of their contents);
- 66% were of a general type.

The container ship used to test the methodology had specific constraints upon where different lengths and types of containers can be stowed:

- All above-deck bays can have any length of container stowed there;
- Under-deck hatches 1 and 8 can have 40′ and 20′ containers stowed there;
- Under-deck hatches 2 and 7 can only have 20′ containers stowed there;
- Under-deck hatches 3, 4, 5 & 6 can only have 40′ containers stowed there;
- Under-deck hatches 1 and 8 are specially treated so that tainting cargo can be stowed there;
- Under-deck hatches 3, 4, 5 & 6 can have reefers stowed there.

In addition, the problem considered included other factors, namely:

- At each POD, unloading and loading occurred, but the latter did not begin until the former had finished;
- Ballast conditions were assumed to be set by the user;
- Two cranes were available for loading and unloading at each POD;

The following sections describe how stowage plans were generated.

5.2. Branch & bound used to establish the neighbourhood

The purpose of the strategic phase is to arrange cargo according to the following stowage objectives:

- the number of cargo spaces occupied by each destination is minimised;
- the number of cranes in operation at each subsequent port is maximised;
- the number of hatch-lids moved is minimised;
- the number of over-stows is minimised;
- the number of cargo blocks occupied by containers is minimised.

Branch and bound search was applied to the generalised representation so that all containers were allocated to individual blocks (not individual cells), using the following approach. The initial state is the blocked cargo-space and existing loaded cargo. The generalised containers to be loaded at the current POD (described by generic class, e.g. length and POD) are ordered with those having the fewest available legal stowage locations and furthest POD first. Partial stowage configurations are found by allocating containers from the list, and are ordered by fitness value and pruned by taking advantage of constraints such as necessary segregation of cargo and ship intact stability. A number of the best solutions generated for stowage configuration at the next POD are used as starting points at the next POD. This process is continued for a number of subsequent PODs. The number of solutions passed on to the next POD should reflect the time available and the trade route under consideration. In this example, four ports were considered and four solutions were passed on to port two, with two passed on to the third and fourth ports; the best overall solution (shown in figure 8) was selected as sub-optimal. The diminishing number of solutions passed on reflects the diminishing reliability of load data for more distant ports.

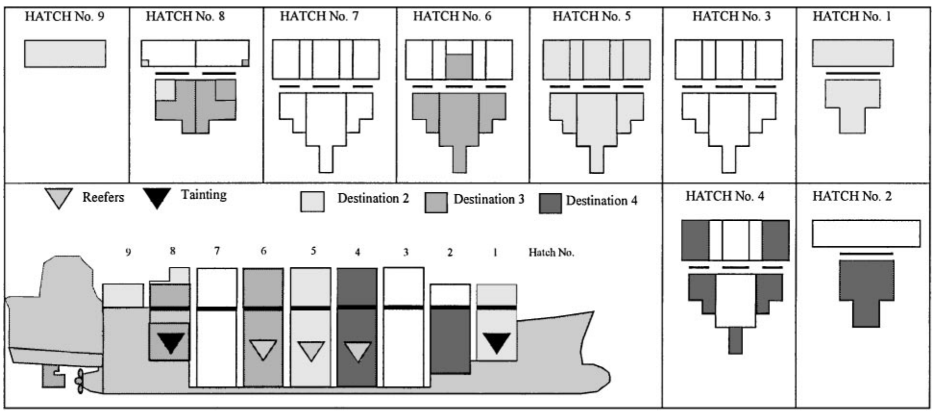

Figure 8. Generalised Outline Plan showing cargo distribution.

The objective function used to determine fitness is a weighted sum of functions that reflect the quality of a generalised solution. These functions measure: block stowage by counting the number of blocks occupied by containers of each POD and the number of PODs in each block; crane usage by counting the number of hatches occupied by containers of each POD and their spread; overstowage. The exact weighting of the functions depends on shipping operator practices, the vessel, the route, the numbers of cranes in operation at ports and the cargo. A more detailed exposition of the objective function is provided in Wilson and Roach (1998).

No attempt is made at this stage in the planning process to allocate specific containers to specific cells since the objective here is to select the best, overall, generalised solution. Note that cargo is distributed according to the stated stowage objectives and that constraints upon where cargo can be stowed and the segregation of hazardous have been met. This procedure fixes the placement of containers to specific areas of the ship, the alteration of which may have long-term consequences. This procedure has two benefits: firstly, that the combinatorial complexity of the strategic planning phase is reduced (the number of potential locations considered has been reduced from over 600 to under 50); secondly, that the neighbourhood associated with a given solution during the tactical planning phase is also reduced.

5.3. Tabu search applied to the generalised solution

The purpose of the strategic phase is to arrange cargo according to the following stowage objectives:

- the number of re-handles are to be minimised;
- container weight is to graded upwards in the cargo space, heaviest to lightest;
- stacks (vertical collections of containers) with mixed POD are to be minimised;

Before optimisation of the generalised solution (the cargo distribution of the generalised containers) can take place, each of the containers in a given block is heuristically allocated to a slot. The objective here is to prepare an initial specific loading; a starting point from which an optimum solution can subsequently be determined. A randomly generated stowage configuration would permit the application of Tabu search. However, the application of sensible heuristics to generate a starting solution facilitates the stowage-configuration optimisation process. A number of heuristics can be used to pack the cargo-space. The following describes one specific example of heuristically allocating containers to slots within a block using 3D packing theory (see Dowsland and Dowsland (1992) for a full exposition of such methods) which has been applied to this representative worked example. A comparison of a number of such heuristics can be found in Wilson (1997). However, the authors note that 3D packing approaches are generally based upon a series of heuristic rules derived by common sense, and that no single approach can be said to be superior to others (Dowsland and Dowsland, 1992).

During the strategic phase, sixteen 20′ and four 40′ containers were allocated the port block shown in figure 9 within Bay 30 of the example vessel; recall that bays 29 and 31

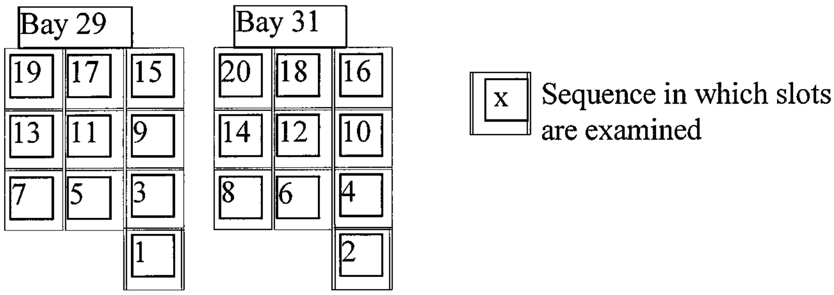

Figure 9. Order in which slots are filled.

are the 20′ bays which make up that particular 40′ bay. The following packing heuristic, designed to sequence containers into blocks, was used to generate an initial distribution of these containers. For each block:

1. The list of containers is ordered according to size (largest first, but with non-standard dimensions last), and within that ordered by destination (furthest first) and weight (heaviest first).
2. The first container is taken from the list.
3. A standard dimension container to be loaded is placed in the first available slot, searching each bay, stack and tier in the sequence shown in figure 9. (Note that for central blocks, the sequence is to stack upwards, stern to bow, and centre outwards; for starboard blocks the sequence is to stack upwards, stern to bow, left to right.) Where possible, non-standard dimension containers are swapped with containers for the same POD at the top of a stack, returning the displaced container to the list to be placed.
4. If the list of containers is empty then the placement procedure is terminated, otherwise the process begins again at point 2.

Applying this packing algorithm to each of the 'blocks' resulted in stowage configurations that were near optimal for that block giving a good starting place for the optimization by Tabu search. In particular, the algorithm tends to produce good weight gradation stacks, low mixing of PODs in stacks and non-standard dimensions located at the tops of stacks. For the container to slot allocation problem, the neighbourhood $N(s)$ was determined by the blocking procedure. That is, the neighbourhood would include only solutions in which the containers in the same block have been swapped. The initial solution s has been determined by the heuristic placement of containers within their block. Each of the heuristically filled blocks was optimized using Tabu search with the above neighbourhood. The objective function used to determined fitness is a weighted sum of functions which reflect the quality of a generalised solution. These functions measure: the number of re-handles; the number of stacks with mixed POD; stack weight distribution. Again, the exact weighting of the functions depends on shipping operator practices, the vessel, the route, the numbers of cranes in operation at ports and the cargo. A more detailed exposition of the objective function is provided in Wilson and Roach (1998).

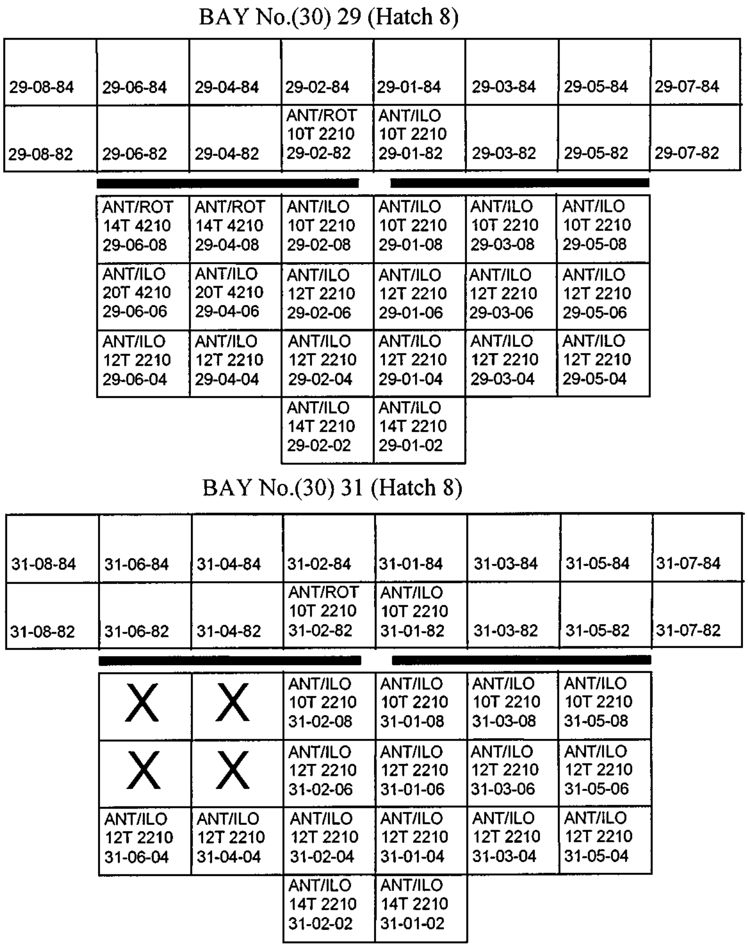

Figure 10. Departure bay plan giving container destinations, origins, types and weights.

A complete set of Bay Plans, optimised with respect to cargo allocated in the strategic phase, was generated using this procedure (an example of which is shown in figure 10) in which all constraints were met. Note that in figure 10: X marks the tail end of a 40′ container; ROT is an earlier POD than ILO; containers numbered 4210 are 40′ in length and ones labelled 2210 are 20′ in length—hence the four 40′ containers are lighter ‘per foot’ than the 20′ containers below them.

5.4. *Computational experiments*

Results were obtained on a 166 MHz Pentium with 40 megabytes of memory using Allegro Lisp to encode the blocking and GFA (a PC-based 3GL with a high degree of functionality and graphic display features) to encode the specific placement algorithm. A generalised solution to the described problem was obtained in approximately 90 minutes whereas specialised solutions for each block were produced in under an hour. The state space size for the strategic planning phase will vary with vessel capacity and number of ports considered, but the blocking of cargo-space is believed to ensure that solutions of acceptable quality can always be generated in a viable time. The packing algorithm always requires little processing time, as it involves the placement of fewer than 100 TEUs (and typically cargo blocks will hold approximately 12–60 TEUs). Optimization of stowage in individual blocks by Tabu search is also relatively simple. Below-deck blocks have restrictions on container lengths, and experimentation on typical loads generated optimum solutions in as few as 15 iterations, and a recency list (Glover, 1977) of just one move. For above-deck blocks, this number increases due partly to variations in container lengths, but mostly due to the increased likelihood of hazardous cargo segregation requirements. However, in the worst cases, no more than 200 iterations, and recency lists of up to 7 moves are required.

As was stated in Section 2, other published approaches to container-ship stowage planning have removed important factors such as hazardous cargo and non-standard container sizes. Moreover, it is important to note that there is a strong relationship between the efficient use of cargo-space and the shipping operator, container ship, route and market. These factors, and the commercially sensitive nature of real data used, preclude further meaningful quantitative analysis of the results of this approach here. However, qualitatively, and from a knowledge-engineering perspective, the authors observe that the solutions obtained in experiments meet all constraints and reflect the stowage objectives described. The heuristics used and the plans output are reported by industry experts consulted as being comparable with those of human planners. Further, the automated approach described in this paper allows consideration of more stowage plans in the time available for planning than human planners can manage.

6. Summary

The paper presented the application of heuristic procedures to the deep-sea container-ship stowage problem. Heuristics were used to quantify the effectiveness of solutions, firstly during the long-term decision making process, where the implications of decisions at one port are explored at further PODs, and then during the generation of stowage plans at an individual POD. Prototype software composed of a hybrid of traditional (Branch and Bound) and modern (Tabu Search) search techniques was used to successfully generate stowage plans that reflect human planners' expertise. The result of the long-term planning procedure was to limit the size of the neighbourhood under consideration during the stowage optimization phase. The proposed solution to the stowage planning problem is based upon an understanding of the conceptual processes employed by human planners. This approach circumvents the difficulties evident in the work of other authors, allowing commercially viable solutions to be produced in a reasonable amount of time. It is the authors' hope that the proposed hybrid approach will stimulate further work in the application of search techniques to exploit the conceptual model developed.

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References

Avriel, M., M. Penn, N. Shpirer, and S. Witteboon. (1998). "Stowage Planning for Container Ships to Reduce the Number of Shifts," *Annals of Operations Research* 76, 55–71.

Botter, R.C. and M.A. Brinati. (1992). "Stowage Container Planning: A Model for Getting an Optimal Solution," *IFIP Transactions B (Applications in Technology)* B-5, 217–29.

Dillingham, J.T. and A.N. Perakis. (1986). "Application of Artificial Intelligence in the Marine Industry," *Fleet Management Technology Conference*, Boston, Mass., April.

Dowsland, K.A. and W.B. Dowsland. (1992). "Packing Problems," *European Journal of Operational Research* 56(1), 2–14.

Glover, F. (1977). "Heuristics for Integer Programming Using Surrogate Constraints," *Decision Sciences* 8, 156–166.

Glover, F., E. Taillard, and D. de Werra. (1993). "A Users Guide to Tabu Search," *Annals of Operations Research* 41, 3–28.

Goldberg, L.L. (1980). "Chapter II: Intact Stability." In J.P. Comstock (ed.), *Principals of Naval Architecture*. New York, The Society of Naval Architecture and Marine Engineers.

Roach, D.K. and B.J. Thomas. (1994). *Portworker Development Programme Unit C.2.2, Container-ship Stowage Plans*, International Labour Organisation, ISBN 92-2-109271-2.

Sato, K., H. Itoh, and Y. Awashima. (1992). "Expert System for Oil Tanker Loading/Unloading Operation Planning." In C. Barauna Vieira, P. Martins, C. Kuo (eds.), *Computer Applications in the Automation of Shipyard Operation and Ship Design, VII—C*. North Holland.

Shields, J.J. (1984). "Container-ship Stowage: A Computer-Aided Preplanning System," *Marine Technology* 21(4), 370–383.

Wilson, I.D. (1997). The Application of Artificial Intelligence Techniques to the Deep-Sea Container-ship Cargo Stowage Problem. Ph.D. Thesis, University of Glamorgan, Division of Mathematics and Computing, Wales, UK.

Wilson, I.D. and P.A. Roach. (1997). "The Deep-Sea Container-ship Stowage Problem: Modelling and Automating the Human Planning Process," In *Proceeding of the Second International ICSC Symposium on Intelligent Industrial Automation*, Canada/Switzerland: ICSC, 129–135.

Wilson, I. D. and P.A. Roach. (1998). "Container Stowage Planning: A Methodology for Generating Computerised Solutions," submitted to *Operational Research Society*.