Journal of the Operational Research Society (2016) 67, 148–158

www.palgrave-journals.com/jors/

A heuristic approach to stowing general cargo into platform supply vessels

Michel Povlovitsch Seixas[1], André Bergsten Mendes[1]*, Marcos Ribeiro Pereira Barretto[2], Claudio Barbieri da Cunha[3], Marco Antonio Brinati[1], Roberto Edward Cruz[4], Yue Wu[5] and Philip A Wilson[6]

[1]Department of Naval Architecture and Ocean Engineering - University of Sao Paulo, São Paulo, Brazil; [2]Department of Mechatronics Engineering - University of Sao Paulo, São Paulo, Brazil; [3]Department Transportation Engineering - University of Sao Paulo, São Paulo, Brazil; [4]CENPES Petrobras, Rio de Janeiro, Brazil; [5]School of Management, University of Southampton, Southampton, UK; and [6]Faculty of Engineering and the Environment, Engineering Centre of Excellence, University of Southampton, Southampton, UK

This paper addresses a practical problem encountered in the oil industry, related to the supplying of general cargo to offshore rigs and production units. For a given route assigned to a supply vessel we seek to determine the optimal two-dimensional positioning of deck cargoes such that the overall profit is maximized, while ensuring that several safety and operational constraints are respected. In terms of mathematical modelling, the resulting problem can be seen as a rich variation of the two-dimensional knapsack problem, since some cargoes may wait for a later trip. Furthermore, given that the trip may serve many offshore units and that a substantial number of items must also return from these units, the problem becomes even more complex and can be viewed as a pickup and delivery allocation problem. We propose a probabilistic constructive procedure combined with a local search heuristic to solve this problem. We also report the results of computational experiments with randomly generated instances. These results evidence that our proposed heuristic can effectively help ship planners when dealing with such large-scale allocation problems, with many operational constraints.

Journal of the Operational Research Society (2016) **67**(1), 148–158. doi:10.1057/jors.2015.62
Published online 2 September 2015

Keywords: allocation; cutting stock problem; distribution; heuristics; logistics; sea transport

Introduction

Increasing petroleum demand, soaring costs and market competition are pressuring oil companies to search for innovative solutions. In this context, an effective response to the demand for supply items of drilling rigs and production platforms is a key issue in contemporary offshore logistics. Bassi *et al* (2012) point out that some of the most important and expensive activities during the oil field development and production phases relate to the use of rigs for drilling wells or for maintenance activities. These are expensive assets, representing daily hire rates of up to US$600 000 (Bassi *et al*, 2012; Kaiser and Snyder, 2013). Hence, oil companies cannot have their operations jeopardized because of supply delays or shortages.

Supplies requested by offshore units are commonly segregated into general cargo and bulk cargo (Ritchie, 2004). General cargo encompasses a broad range of items including food, equipment, tools, spare items, pipes and risers. Bulk cargoes consist of fresh water, diesel fuel, chemicals, drilling mud and pulverized cement, among others. While bulk cargoes are stored in underdeck tanks, general cargoes, with the exception of pipes and risers, are unitized into different types of offshore containers before being conveyed by supply vessels.

In this paper we heuristically deal with the combined process of selecting and assigning general cargoes to the deck of a given vessel while respecting many operational aspects. The proposal of this heuristic is motivated by the need to achieve maximum efficiency and utilization of a limited fleet of supply vessels, which is constantly pursued by oil companies. A brief description of the problem to be solved is as follows. It is given a list of drilling rigs and production platforms (which will be hereafter referred to as ‘offshore units’) to be served in a given tour, as well as a list of pending general cargo transportation orders per destination. Each order’s priority depends on the slack with respect to its due date, such that the lower the slack, the higher the priority; some orders are mandatory and must be loaded in the next trip, while low-priority orders may have to wait for a later subsequent trip because of capacity constraints. Backload orders are also present, representing the return to shore of empty containers, equipment or products demanding recycling or disposal. The problem consists of determining which cargoes should be selected for loading and their respective assigned

**Correspondence: André Bergsten Mendes, Department of Naval Architecture and Ocean Engineering - University of Sao Paulo, Av. Prof. Mello Moraes, 2231, São Paulo, SP 05508-030, Brazil.*
E-mail: andbergs@usp.br

positions on the deck in order to maximize an overall benefit function given by the sum of the cargo's priority, while respecting a set of operational constraints related to vessel capacity, safety and existing aisles that allow crew accessibility and circulation, as well as cargoes' specific requirements such as power supply and hazardousness. The problem can thus be considered as a particular instance of a pick-up and delivery allocation problem (PDAP).

Differently from the articles devoted to the planning of supply operations in the offshore industry (eg, Fagerholt and Lindstad, 2000; Aas *et al*, 2007; Gribkovskaia *et al*, 2008; Halvorsen-Weare *et al*, 2012) where each cargo is specified by its area, our problem considers each cargo's individual dimensions (length and width), given that we are solving a two-dimensional packing problem (Wäscher *et al*, 2007) where cargoes must be selected and positioned on the deck of a supply vessel. The problem studied herein arises in the context of Brazilian state oil company Petrobras. Since in the case studied the supply of general cargo and bulk cargo is managed by distinct company areas, and thus using different vessels, we do not take into consideration the operational issues related to the allocation of bulk cargoes, which are different in nature. Therefore, our focus is solely on the selection and allocation of deck cargoes.

Despite having experienced ship planners managing the supply operations, the manual process of selecting cargoes requires a lot of effort in the absence of effective planning tools, as a natural consequence of the problem complexity, scale and time for completion. Since it is essential to avoid under-utilization of such costly vessels because of erroneous planning in high-demand scenarios, the proposed heuristic is intended to conveniently support decision makers in their planning activities. To the best of our knowledge, the problem considered herein has not been described before.

The remainder of this paper is organized as follows. A literature review will be given in the next section, followed by a detailed presentation of the problem and the proposed heuristic. The instances generated for testing are then introduced followed by computational results. Lastly, the paper will be summarized, highlighting the main contributions and future development.

Literature review

The offshore oil industry is greatly affected by the efficiency of its logistics support activities, which are undertaken by a range of specialized support vessels. For instance, seismic survey vessels are responsible for locating the best possible area for oil drilling (Bacon *et al*, 2007); anchor handling tug supply (AHTS) vessels tow and anchor rigs (Ritchie, 2004) while drilling and completion takes place; survey vessels examine the seafloor's topography to avoid laying pipes and cables in potentially hazardous areas (Bai and Bai, 2012); and pipe layer vessels launch pipes on the seafloor and connects them to the subsea infrastructure (Gerwick, 2007). Production platforms are towed, anchored and connected to the subsea equipment, thus allowing production to begin. During the lifespan of oil fields, maintenance vessels will be requested for preventive and corrective actions of the subsea infrastructure (El-Reedy, 2012), which will be accomplished by means of diving or by a remotely operated underwater vehicle (ROV); moreover, wells might require maintenance interventions by stimulation vessels or workover rigs in order to maintain or improve productivity (Bassi *et al*, 2012). Finally, during the entire period offshore units will rely on platform supply vessels (PSVs) (Aas *et al*, 2009), which are ships specially designed to transport supplies to offshore oil platforms and to return used equipment and items to shore for recycling and disposal.

Despite the importance of the abovementioned activities for the oil industry, few contributions have been reported so far related to the planning of these support operations. We do not refer to the planning of the exploratory assets, but rather to the role of the offshore support vessels in the process of extracting and processing oil and natural gas (readers interested in the planning and scheduling of offshore drilling rigs can refer to Bassi *et al* (2012)). Nor have we considered worker and crew transportation, which has been mostly carried out by helicopters (Menezes *et al*, 2010; Qian *et al*, 2011). In regard to AHTS vessels, which are responsible for towing drilling units and anchoring them to the seafloor, Shyshou *et al* (2010) studied a fleet design problem using discrete event simulation. Their problem is highly stochastic because of the adverse weather conditions found on the Norwegian shelf, which influence the duration of the anchor handling operations. In addition to modelling the impact of weather on the service durations, different scenarios were also analysed concerning future freight rates for the AHTS spot chartering market.

With respect to offshore support vessels to supply offshore units, Fagerholt and Lindstad (2000) proposed a route generator procedure coupled with a mathematical model for determining the optimal fleet design and the corresponding schedule to serve a set of offshore installations on a weekly basis. The authors analysed the influence of suspending operations at the offshore installations during the night and considered the total slackness found in each solution as a way of evaluating its robustness. Aas *et al* (2007) treated the supply problem as a pick-up and delivery problem, given that a substantial part of what is delivered to the installations must be sent back to the supply base. Instead of defining optimal routes for the entire fleet, the authors proposed a mathematical model based on integer linear programming for defining the optimal route for a single vessel, considering a set of installations to be visited for which the pick-up and delivery demands were known. In addition, the authors considered the limited storage capacity of each installation as a binding constraint, which affected the pick-up and delivery sequence. The evaluated instances were optimally solved by commercial software. Gribkovskaia *et al* (2008) tackled the same problem and proposed different constructive heuristics and a tabu search procedure to solve larger instances.

The proposed methods were compared with the optimal solution of the corresponding travelling salesman problem and proved to be effective. Halvorsen-Weare *et al* (2012) proposed a route generator coupled with an integer linear mathematical programming model to solve a periodic routing problem embedded in a fleet composition problem. Special attention was given to the selection of each installation's distribution schedule, in such a way to have them evenly spread throughout the planning period. Although the instances tested could be optimally solved by commercial software, the authors mention that larger instances will demand using other solution schemes such as heuristics or column generation.

We have observed that the papers devoted to oil supply operations consider a simplification regarding deck occupation, where each cargo has an area attribute, and any solution whose total area does not exceed the available deck area is feasible. In our problem, this premise may not be valid given that we are actually concerned with the exact cargo positioning on the deck. For instance, a $16\,m^2$ (4×4 m) cargo cannot be assigned to a $42\,m^2$ (3×14 m) deck area, if the actual dimensions are taken into consideration. Aside from the geometric issues, other constraints to be detailed further are binding, making our problem substantially different from those found in the literature.

Thus, it becomes relevant to also include a review from the cutting and packing perspective. According to the typology proposed by Wäscher *et al* (2007), this problem can be classified as a two-dimensional orthogonal knapsack with an 'output maximization' type, where a set of small items has to be allocated to a given set of large objects such that the chosen elements yield a maximum assignment value. In our case, only one large object is used, that is, a vessel deck with known dimensions. Moreover, the items to be packed are rectangular, strongly heterogeneous in terms of dimensions, and 90° rotations are allowed when packing them in such a way that their dimensions are always aligned with the deck's longitudinal and transversal dimensions. The literature on two-dimensional knapsack (TDK) problems comprises exact approaches, such as the one proposed by Hadjiconstantinou and Christofides (1995), who devised an enumeration scheme using bounds based on Lagrangean relaxation. Fayard and Zissimopoulos (1995) proposed an efficient heuristic based on the resolution of a sequence of one-dimensional knapsack problems. Caprara and Monaci (2004) proposed a relaxation given by the one-dimensional knapsack problem with item weights equal to the rectangular areas and assessed the worst-case performance of the associated upper bound. Hopper and Turton (2001) evaluated the use of a local search heuristic and three meta-heuristics to solve the TDK. These methods were based on a two-stage approach, where a heuristic packing policy was applied after each element to be packed was chosen, this policy being based on a bottom-left (BL) stability rule. Egeblad and Pisinger (2009) represented a given allocation by a sequence pair notation, and devised an algorithm for generating the corresponding packing solution and to evaluate its total profit. On the basis of this representation scheme the authors applied a simulated annealing meta-heuristic by modifying the sequence pairs in order to generate and explore the neighbourhood. Leung *et al* (2012) solved the TDK heuristically by determining which rectangle was to be first packed into a given position, with the support of an innovative fitness rule. This rule was embedded in a simulated annealing meta-heuristic that in addition to being fast was capable of generating high-quality solutions.

The classical TDK problems present only a few variants. While the heuristic proposed by Egeblad and Pisinger (2009) allows the items to be rotated, most applications found in the literature consider a fixed orientation for the rectangles. Furthermore, while most authors consider the associated value of each rectangle equal to its area, Hadjiconstantinou and Christofides (1995) admit any possible value. Last, in the so-called bounded variable version (Caprara and Monaci, 2004; Egeblad and Pisinger, 2009) each item can appear in the cutting pattern no more than a fixed number of times. On the other hand, when unbounded variables are assumed (Fayard and Zissimopoulos, 1995), each piece can appear any number of times in the pattern. In our problem, each item to be delivered or picked up is intrinsically unique and thus cannot be replicated. Rotation is allowed and it will be considered that the profit of each rectangle (ie, transportation order) is given by its slack to its due date, such that the smaller the slack, the greater the benefit. Despite the relevance of the indicated contributions in solving the TDK, the existing methods found in the literature are not suitable to our PDAP as they are not able to deal with other specific and essential operational constraints that are present, as detailed in the section that follows.

Problem description

The PDAP considered in this research consists in selecting and stowing a subset of cargoes among those to be transported to/from offshore units by a PSV with a known visiting sequence, such that the overall benefit given by the sum of each cargo priority is maximized. Differently from a classical vehicle routing and scheduling problem (Laporte and Osman, 1995) where optimal or near-optimal routes are searched for, in the PDAP the route (ie, the sequence of stops) assigned to each vessel is known in advance inasmuch as the offshore units are usually clustered because of geographic constraints and economies of scale (Aas *et al*, 2009). Thus, a fixed schedule for the routes that supply these facilities is known in advance.

Most of the deck cargo is packed in offshore containers (generally smaller, more robust and heavier versions of conventional containers), skips (normally used for waste and similar) or baskets (Aas *et al*, 2009) and can be considered rectangular loads. Owing to safety regulations, the stacking of containers and baskets is not allowed. Pipes and offshore risers (a special type of pipe)are placed directly on the deck (one may refer to Chan *et al* (2006) for a comprehensive discussion about packing issues in logistics systems).

The whole load planning process begins by selecting one route comprising a set of offshore units to be visited and assigning it to an available vessel. In the sequence, all pending transportation orders of the selected units are then retrieved from the oil company's main corporate database; they usually surpass the vessel capacity (deck area), thus requiring a prioritization scheme that yields to the maximum efficiency of the cargo allocation, in such a way that the sum of the priorities of the selected cargoes is maximized.

The following data characterizes a transportation order: *origin* (port or platform); *destination* (platform or port); *due date; priority*, which depends on the cargo's due date; *urgency status* (true or false), indicating whether the cargo is mandatory and thus cannot wait for a later trip; *refrigerated* (true or false), indicating whether a power supply is needed; *cargo dimensions* (length, width); *weight* (tons); *cargo density* (tons/m^2); and *cargo stacking* (true or false), indicating whether similar items can be stacked. It should be mentioned that only pipes and risers can be stacked; in this case, additional information should be provided, such as diameter and maximum stacking height.

In the absence of any planning tool, the ship planner initially selects all priority cargoes (ie, those that cannot wait) and the remaining ones according to their priorities until the deck is 75% occupied. This threshold is empirically fixed based on the planners' past experience, and usually allows the selected cargoes to be properly stowed while observing all positioning requirements. In case there is still a remaining free area on the deck after having all constraints verified, the planner may interactively include additional cargoes.

The offshore units to be serviced influence the way the ship will be loaded. Typically, both drilling and production units are either rectangular semi-submersible anchored platforms or adapted ships, whose cranes, for lifting cargoes from the deck, are mounted either by its portside board (ie, unit's left side) or by its starboard (ie, unit's right side), or on both sides. Even when cranes are available on both sides it is very likely that one of the boards will offer better and safer operational conditions because of environmental factors such as wind, waves and sea currents. An experienced ship master who has been servicing a given cluster of platforms usually indicates the preferred board for heading an offshore unit given his previous knowledge and experience regarding environmental issues, including weather forecast. Moreover, his choice is also influenced by each particular ship's manoeuvring capacity and its capacity to stand at an imposed distance from the unit, which depends on the so-called dynamic positioning system. In addition to the unit's preferred board, the vessel's board should be selected as well (portside or starboard). Furthermore, the vessel may head perpendicularly, instead of alongside the platform, until its rear reaches a safe distance limit.

One additional feature is that the ship master can pre-assign certain areas that define the boundaries for the selected cargoes that are destined for each of the serviced offshore units. This practical rule is based on the ship master's previous experience concerning the best way to distribute the cargoes, given the operational and environmental conditions expected at each destination. If such area indication is made, the problem size is reduced as the candidate positions for placing the cargoes on the deck are reduced.

As previously mentioned, the planners usually consider a 75% limit in order to guarantee that the selected cargoes will fit the deck. In addition to the packing issues, this 25% slack enables a mandatory quasi-central corridor of a given width from bow (front) to stern (rear) to be assigned that serves as an escape route for the crew. This corridor also allows the crew to reach the cargoes and ensure they are properly fixed to the crane when being loaded and unloaded. The corridor does not necessarily need to be rectilinear, nor must it be located at the ship's central section. In addition, when assigning cargoes to the deck, one must ensure that the hose area is not blocked and inaccessible. Furthermore, dangerous goods are usually restricted to a specific area, usually at or adjacent to the stern of the ship.

One should note that the allocation of the cargoes to be returned from the platforms should be planned simultaneously with the ones bound to the platforms, before the vessel's departure. As a result, a vessel may leave the origin port with part of its deck unused to make room for the later loading of returning cargoes. As mentioned previously, each cargo is assigned a priority based on its due date, such that the nearer the due date, the greater the priority.

On the basis of the above, we can formally state the constraints that must be observed:

- *Corridor*—a quasi-central corridor range must exist, allowing crew members to transverse the deck from bow to stern. Its width usually varies between 1 and 2 m and it should be placed by the ship's central line, with a 15% tolerance (in regard to the ship's width).
- *Packing constraints*—two distinct cargoes cannot be placed or stacked in the same deck area; exceptions apply to risers and pipes, which can be stacked according to specific rules.
- *Cargo density*—given that some PSVs may have specific areas on their decks with distinct density limits (eg, 5 t/m^2 in the bow, 10 t/m^2 in the stern), maximum density must be respected whenever a cargo is to be assigned to a given position.
- *Adjacency of delivery cargoes*—cargoes bound for a common destination must be contiguously arranged, forming a 'cluster'. This facilitates the unloading operation at each offshore unit and reduces the ship's total operating time. However, if the amount of cargo to the same destination is high, such that the central corridor would become blocked, up to two clusters (one on each side of the corridor) are then allowed.
- *Adjacency of pick-up cargoes*—as a general rule, the collected cargoes must also be clustered, in order to keep the deck organized. This is also valid for urgent pick-up cargoes and dangerous (or hazardous) pick-up cargoes as well.

- *Dangerous cargo positioning*—owing to safety reasons dangerous cargoes must be placed in specific designated areas, usually in the stern of the ship.
- *Access to delivery cargoes*—at least one cargo (from a given cluster) must be accessible by the crew from the central corridor as each cargo needs to be manually connected to the crane, before being hoisted up towards the offshore unit. This verification also applies to dangerous cargoes, in case they are placed in a different (ie, a specific) area on the deck (usually in the rear part of the ship).
- *Access to refrigerated cargoes*—refrigerated containers must be reachable by crew members, so that their temperature can be properly monitored.
- *Access to emergency cargoes*—it may be requested by some offshore units that emergency cargoes be the first ones to be delivered. In such cases, they also need to be positioned by the central corridor for priority access.
- *Access to hose area*—wherever a hose area exists, a connected corridor must allow crew members to reach this area.
- *Power supply*—the number of stowed refrigerated containers is limited by the number of power supplies; additionally, each power supply has an extension lead whose length also restricts where it can be positioned.
- *Total weight*—all the cargoes loaded in the ship at any time (before departure of a port or from an offshore unit) is limited by the ship's deadweight tonnage.
- *Crane capacity*—the assigned position for each cargo has to be reachable by the unit's crane and be within the weight limit for the corresponding distance.

The adopted procedure for pipes and risers, which are stackable, was to convert them into an equivalent container size before assigning them to the deck. This is accomplished by applying practical empiric rules that limit their stacking height and width.

Proposed heuristic

In this section, we describe our heuristic for solving the PDAP that determines the optimal cargo allocation for a PSV servicing offshore units. This method comprises a *set-up* phase and of an *allocation–verification* phase, which has a *local search* mechanism embedded. Finally, a *general scheme* of the heuristic is given.

Set-up

In order to devise a cargo manifest, one first needs to establish which areas of the deck are suitable and thus candidates to receive the cargoes bound for each destination. This is an important decision as it will determine the potential area for positioning cargoes on the ship's deck, given each crane's maximum range and its associated weight capacity. As mentioned before, the definition of such areas may be influenced by the captain's preference, based on his previous experience. Therefore, the captain may specify areas of the deck for each destination, thus simplifying this definition. In case such input is not given, the heuristic has to be able to decide how the ship will approach the units and which areas on the deck will be allotted to each offshore unit. These areas will ultimately be dependent on the selections made concerning the unit's board, the ship's board and the crane assigned to each offshore unit. However, in the real case studied, only one board was usually considered for the offshore unit, the one that ensured safer operating conditions for both the ship and the unit. Therefore, the main decision is actually focused on how the ship will head towards each unit, having as possibilities the combinations indicated in Table 1.

Table 1 Vessel's heading combinations

Combination	*Portside (Left board)*	*Starboard (Right board)*	*Perpendicularly*
1	x		
2		x	
3			x
4	x	x	
5	x		x
6		x	x
7	x	x	x

Some vessels allow only one heading alternative. If two alternatives exist, the perpendicular heading being one of them (Combinations 5 and 6), then the board (left or right) will be chosen, since it allows cranes to have a higher coverage area, thus increasing the flexibility in positioning cargoes. Finally, when one has to choose between right and left boards, a more sophisticated rule is applied. Let *counterLeft* and *counterRight* be the number of times that the left and the right boards were previously chosen. The probabilities of having each of the boards selected are given by Expressions (1) and (2), respectively.

$$P(\text{left}) = \frac{\alpha\, counterRight}{(\alpha\, counterRight + \beta\, counterLeft)} \quad (1)$$

$$P(\text{right}) = 1 - P(\text{left}) \quad (2)$$

The idea is to balance the board selection, by giving a higher probability to the board that has been momentarily less frequently selected. Hence, it is expected that the proposed rule will yield a fully occupied deck, as areas for different destinations will be evenly assigned on the left and on the right boards. The multipliers α and β are used to enhance the balance achievement by increasing the difference between P(left) and P(right) when updated in the following way:

$$\alpha = \beta = 1.0, \text{ whenever } counterRight = counterLeft \quad (3)$$

$$\alpha = 1.5;\ \beta = 1.0, \text{ whenever } counterRight > counterLeft \quad (4)$$

$$\alpha = 1.0;\ \beta = 1.5, \text{ whenever } counterRight < counterLeft \quad (5)$$

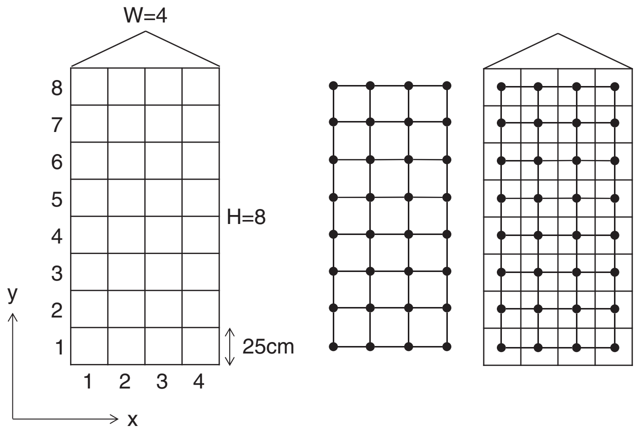

Figure 1 Graph representation of a vessel deck.

After the board is selected, a crane installed by it has to be chosen. In case more than one crane is available, a random selection will be made. Finally, the *set-up* phase generates a grid representation of the deck. The discretization factor is an input, being the default value $25 \times 25\ \text{cm}^2$ as indicated in Figure 1.

Cargo allocation–verification

The subsequent *cargo allocation–verification* phase is called for three different cargo groups. First, an attempt is made to allocate the refrigerated cargoes. Next, the urgent cargoes are evaluated; finally, all the remaining cargoes undergo the allocation and verification process. Priority was given to refrigerated cargoes for they must be placed by the central corridor in order to have their temperatures checked. The allocation process, for each cargo group, begins by sorting the cargoes in non-increasing order of their priority. Let j be a cargo of the set of cargoes J to be delivered and collected along the route, p_j its priority and d_j its due date. Let $i \in J$ be the cargo with the latest due date, that is, $i = \max_{j \in J} d_j$. Then, each cargo priority is determined by Expression (6), which yields higher priority for cargoes with latest due dates.

$$p_j = d_i - d_j + 1 \qquad \forall j \in J \tag{6}$$

For each cargo group, the list of pending cargoes will be traversed sequentially following their priorities. Each cargo will be selected and an attempt to allocate it will be made. This allocation begins by first generating a list of feasible allocation positions with respect to the following constraints: *packing constraints* (ie, not placing two or more cargoes in the same area), *deck density limit* and *adjacency* (a cargo must be adjacent to others bound for the same destination, either an offshore unit if inbound or a port if outbound). It is important to stress that this list considers the 90° rotation of the selected cargo and takes into account the specific area where cargoes bound for each destination must be placed, including the *positioning areas of dangerous goods*. After having evaluated all possible positions and orientations, one is randomly selected from the list. However, since there are other constraints to be checked, it may be that the selected position may not be feasible in regard to the other constraints. Therefore, a second verification has to be made. This complementary checking actually encompasses three types of verifications; if any of them fails the verification is suspended and the allocation is undone, which means that the cargo is then rejected at that iteration.

First, access verification is called with the purpose of checking the *access to delivery cargoes*, the *access to refrigerated cargoes* and the *access to urgent cargoes*. The second verification is focused on the corridor, and consists of checking whether a quasi-central non-rectilinear corridor may be found linking bow (front) to stern (rear). This is accomplished by a dynamic programming algorithm based on Dijkstra's shortest path algorithm using a graph representation of the deck, as illustrated in Figure 1. It is important to mention that this verification has to be done in each stage of the route, in order to check whether any pick-up cargo might have blocked the central corridor. Furthermore, the verification is needed in order to check whether a corridor of a given width linking the *hose area* to the central corridor does exist. Lastly, the 'general' simulation checks whether the number of *refrigerated cargoes* surpassed the number of available power supplies; in the sequence, an assignment problem is solved in order to match each refrigerated cargo to a power supply, by observing the extension leads' length. The *total amount of cargo* is also checked in respect to the vessel's net tonnage limit, and, last of all, the *cranes' capacity* and range are verified.

Local search heuristic

Given that the PADP is a difficult combinatorial problem with many classes of constraints, and given that introducing modifications on a complete solution could be very costly, the proposed solution scheme calls a local search heuristic every time a candidate cargo is selected and assigned to the deck. This is intended to maintain the ship deck 'organized' in order to receive new cargoes. This selection–allocation procedure is common when solving TDK problems. Our heuristic follows the same general scheme as the one proposed by Hopper and Turton (2001). In their case, once an element to be packed was selected, a subsequent allocation procedure based on a BL stability rule was called. In our case, we randomly assign a position and an orientation on the deck among feasible candidate positions and then submit this partial solution to a local search heuristic, with the sole purpose of generating a better arrangement of the partial stowage plan. The local search can thus be viewed as an extension of the allocation process and will not improve the original objective function, defined as the sum of the priorities of the selected cargoes. Therefore, a surrogate objective function will be used, which considers all the positions that surround the contour line (ie, boundary) of each cargo cluster present on the deck by the time the ship is about to leave the port, and of the cargo clusters present on the deck when the ship returns to the port. The sum of all positions will be called *type-1 scattering measure*, being an indicator of how the cargoes are actually scattered. This can be accomplished as we are using a discrete (ie, grid) representation for the deck. Our goal is to minimize the surrogate function, which means that we are looking to produce the most compact cargo stowage arrangement as possible.

Consider, for instance, a hypothetical example shown in Figure 2. The part of the figure on the left illustrates a vessel deck with cargoes bound for two offshore units, thus forming two clusters. The type-1 scattering measure is given by the number of positions surrounding each cluster, which is equal to 20 (unit 1) + 26 (unit 2) = 46. By assuming that the cargoes were hypothetically rearranged according to Figure 3, the type-1 scattering measure would result in 18 (unit 1) + 24 (unit 2) = 42.

The *type-2 scattering measure* applies only in case there are refrigerated and urgent cargoes that must be placed by the central corridor during the first and second allocation attempts. Each refrigerated or urgent cargo will have its longer dimension (length or width) multiplied by the distance from its geometric centre to the ship's central line and by a constant. For scaling reasons, the resulting value will be divided by the ship's half width in discrete units (4.5 in this example). Summing all these values (penalties) for refrigerated and urgent cargoes with regular type-1 scattering measure will result in type-2 scattering measure. Figure 4 gives an illustration of the distance to the central line of a given cargo. Using 10 as a constant, the penalty for this cargo will be: $10 \times \max(3; 2) \times 3/4.5 = 20$.

The neighbourhood of a current solution will be given by the removal of every assigned cargo and by repositioning it in every feasible position, considering also the cases of 90° rotation. Just as in the constructive phase, a list of feasible candidate positions will be generated, observing the packing constraint, the deck density limit and the adjacency constraint. After evaluating the complete neighbourhood, that is, the removal and reinsertion of all previously inserted cargoes, the movement that results in the greatest reduction in the scattering measure will be chosen and have the other constraints verified. If it turns out to be a feasible movement, it will be made. This process is repeated while the scattering measures are being reduced.

General scheme

After having introduced the *set-up* phase, the *cargo allocation–verification* phase and the *local search* heuristic, in this section it is our intention to clarify the overall scheme. Figure 5 gives an overview of our heuristic.

In addition to the above-mentioned input data, the following parameters and variables are also required: *time limit*—establishes the overall time for processing the heuristic; *allocation trials*—establishes the number of allocation trials for each cargo group; *objective function*—registers the sum of the priorities of the selected cargoes; *best objective function*—registers the best

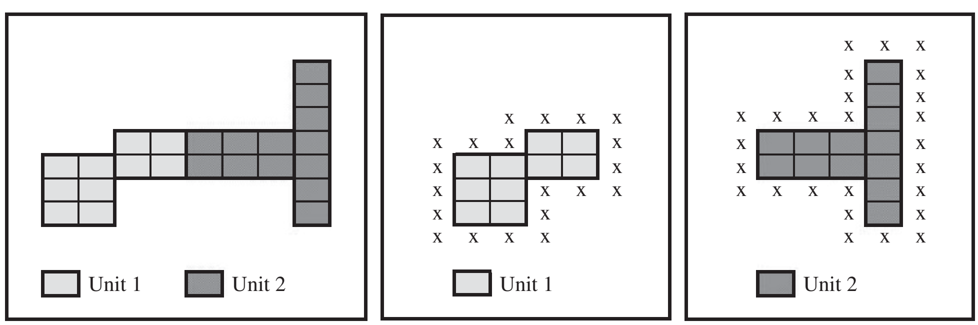

Figure 2 Type-1 scattering measure.

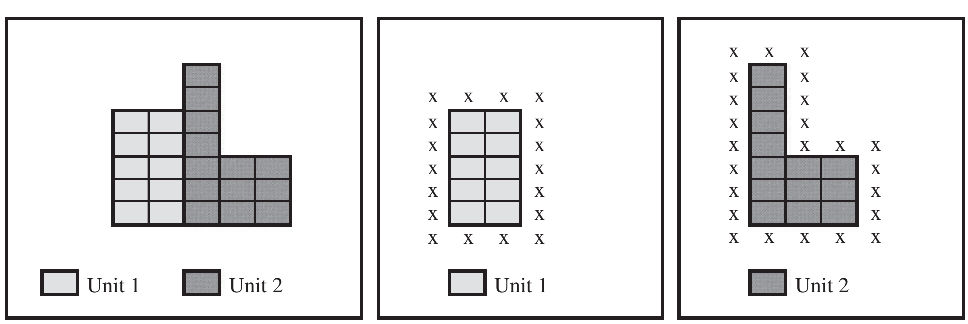

Figure 3 Type-1 scattering measure for a new arrangement.

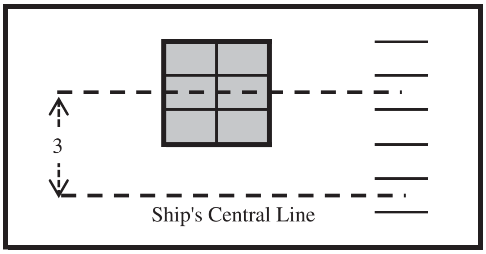

Figure 4 Calculating type-2 scattering measure.

```
0. Repeat
1.   // Set-up Phase
2.   Define the ship's heading board for each unit to be visited
3.   Select the cranes
4.   Generate the deck grid
5.   // Cargo Allocation & Verification Phase
6.   For each cargo group do // {refrigerated, urgent, remaining cargoes}
7.     Sort the list of candidate cargoes according to their priorities
8.     Repeat
9.       For each cargo in cargo group do
10.        Generate a list of candidate insertion positions and orientations
11.        Randomly choose one position and orientation from the list
12.        Verify all remaining constraints for the selected position
13.        If insertion is feasible then
14.          Call Local Search heuristic
15.        Else
16.          Undo allocation
17.        End if
18.      Next
19.    Until allocation trials is reached
20.  Next
21.  If objective function is better than best objective function then
22.    Update best solution and best objective function
23.  End if
24. Until time limit is reached
```

Figure 5 Heuristic's pseudo code.

objective function; and *best solution*—registers the best generated solution.

It should be noted that the general scheme comprises an outer loop (lines 8–19), which has been introduced in order to allow cargoes that were not assigned because they violated some constraints (line 12) new opportunities to be allocated in later iterations. This process is repeated until the number of *allocation trials* is reached.

The heuristic stopping criterion is given by the time limit, when at least one solution will be generated, or by the number of solutions to be generated. If the time limit and the desired number of solutions are not reached, the whole process will be repeated from the very beginning, that is, from the set-up phase. This heuristic can be easily implemented in a multi-thread architecture, not requiring any interaction between threads.

Allocation examples and computational results

In order to illustrate the cargo allocation problem, a set of instances were randomly generated. In order to do this, a list containing different types of existing offshore containers was prepared. We registered their outside dimensions, their tare weight and their maximum payload. On the basis of our visits and interviews we then identified a subset of container types that are most likely to appear in a standard operation, which are listed in Table 1 of the available online appendix.

The following rules were applied in order to generate the instances: (i) The number of cargoes to be collected (or picked up) is a percentage of the amount of cargoes to be delivered. The following values will be tested: 0, 30, 50 and 80% to cover a variety of real scenarios. (ii) Containers are randomly selected from the list indicated in Table 1 of the available online appendix. (iii) The weight of a loaded container is determined by a uniform distribution having as minimum and maximum values 25 and 75% of the container maximum gross weight, respectively. (iv) A uniform distribution ranging from 1 to 10 is used to generate each cargo's slack to its due date. (v) Each crane can reach up to 75% of the ship's width (ie, ship beam) without any weight limit. (vi) Each offshore unit has two cranes, one on each board. (vii) Two instance sizes will be evaluated: small, where four offshore units are visited in each trip; and large, where eight offshore units are visited in each trip. (viii) The small instances will have a demand level such that the total area of all the demanding cargoes is 140% of the deck area. In the large instances, this factor is changed to 220%. (ix) Up to 30% of the demand can receive emergency status. (x) Up to 10 non-refrigerated-non-food-containers or tank containers can receive dangerous cargo status. (xi) The constraint that imposes corridors to access hose areas is relaxed. (xii) There are no established areas on the deck for any destination. (xiii) Two vessels are considered: (a) The first vessel has a free deck of $16\,m \times 57\,m$, deck capacity of 2600 t, required minimum aisle width of 1.5 m, 6 uniformly distributed electric outlets along each side, 12 electric cables of 20 m, one hose area of 1.5 m^2 located at 19 m from the stern on each side, deck pressure capacity of 10 t/m^2 on stern and 5 t/m^2 on bow, and a rectangular area for dangerous cargo of 80 m^2 on stern. (b) The second vessel has a free deck of $12.45\,m \times 43.65\,m$, deck capacity of 1600 t, required minimum aisle width of 1.5 m, 5 uniformly distributed electric outlets along each side, 10 electric cables of 20 m, one hose area of 1.75 m^2 located at 14.5 m from the stern on each side, deck pressure capacity of 10 t/m^2 on stern and 5 t/m^2 on bow, and a rectangular area for dangerous cargo of 62.25 m^2 on stern.

The following notation was used to specify the test instances: ship size (S—small; L—large), instance size (S—small; L—large) and percentage of pickup cargoes (0, 30, 50, 80%). In order to clarify, the following data will be provided together with each instance type: number of platforms, number of delivery cargoes per platform and number of pick-up cargoes per platform. This combination resulted in 16 types of instance: SS0 (4; 26; 0), SS30 (4; 19; 7), SS50 (4; 13; 13), SS80 (4; 6; 20), SL0 (8; 20; 0), SL30 (8; 14; 6), SL50 (8; 10; 10), SL80 (8; 4; 16), LS0 (4; 44; 0), LS30 (4; 31; 13), LS50 (4; 22; 22), LS80 (4; 9; 35), LL0 (8; 34; 0), LL30 (8; 24; 10), LL50 (8; 17; 17) and LL80 (8; 7; 27). For example, LS30 (4; 31; 13) stands for the *large* ship, *small* number of cargoes, 30% of

Table 2 Average results

Instance	*Processing time*	*Deck occupation on port departure (%)*	*Deck occupation on port arrival (%)*	*Deck occupation on port departure + corridor (%)*	*Deck occupation on port arrival + corridor (%)*
SS0	611	72.84	0.00	88.35	15.51
SS30	344	67.62	32.73	83.13	48.24
SS50	295	61.31	59.68	76.82	75.19
SS80	599	31.86	69.38	47.37	84.89
SL0	1046	72.96	0.00	88.47	15.51
SL30	538	70.09	47.1	85.60	62.61
SL50	651	62.52	58.67	78.03	74.18
SL80	1334	38.25	65.53	53.76	81.04
LS0	1248	79.71	0.00	89.57	9.86
LS30	1517	73.95	41.06	83.81	50.92
LS50	1734	65.78	70.13	75.64	79.99
LS80	2456	29.72	79.33	39.58	89.19
LL0	4111	79.47	0.00	89.33	9.86
LL30	4753	74.09	49.82	83.95	59.68
LL50	5195	64.71	68.44	74.57	78.30
LL80	5399	33.33	76.48	43.19	86.34

Delivery cargoes				*Pick-up cargoes*			
Number of allocated cargoes	*Average due date (all cargoes)*	*Average due date (selected cargoes)*	*Average due date (non-selected cargoes)*	*Number of allocated cargoes*	*Average due date (all cargoes)*	*Average due date (selected cargoes)*	*Average due date (non-selected cargoes)*
62	5.39	5.00	5.51	—	0.00	0.00	0.00
56	5.61	5.31	5.73	26	5.47	5.30	5.53
44	5.49	5.34	5.57	48	5.59	5.69	5.54
23	5.69	6.07	5.56	62	5.74	5.31	6.10
66	5.63	4.85	5.79	—	0.00	0.00	0.00
59	5.45	5.12	5.53	39	5.45	5.56	5.33
53	5.68	5.34	5.77	53	5.48	5.52	5.45
29	5.46	5.16	5.57	64	5.55	4.99	5.77
110	5.58	5.16	5.74	—	0.00	0.00	0.00
100	5.41	5.39	5.42	50	5.54	5.58	5.43
81	5.28	5.45	5.14	86	5.58	5.61	5.56
34	5.63	5.65	5.61	109	5.47	4.89	5.93
121	5.58	4.96	5.76	—	0.00	0.00	0.00
106	5.58	5.27	5.66	65	5.57	5.50	5.60
89	5.51	5.30	5.60	97	5.53	5.20	5.78
45	5.37	5.78	5.24	117	5.59	4.83	5.93

the cargoes are pick-up type. In addition, this instance has 4 offshore units, each demanding 31 delivery cargoes and 13 pick-up cargoes. Each instance had 10 different sets of problems randomly generated, which can be found at http://www.pnv.poli.usp.br/cargo_stowage/.

A workstation with an Intel Core i7-3770S 3.10 GHz processor and 7, 83 Gb RAM memory was used to run the program developed in Java. The square discrete unit considered has edges of 25 cm. Eight threads, each generating one solution, are used to solve the instance and the best solution found among all threads is returned. The number of iterations (loop executions that travel the list of cargoes) is set to 1000. No cargo allocation attempt is made after 5400 s of system execution; however, the total computing time may be slightly higher than 5400 s.

Results

The average results are summarized in Table 2, which reports, among other performance measures, the average processing time and deck occupation when the ship leaves the port and when it returns to the port. Given that a rectilinear central corridor, respectively, represents 15.51 and 9.86% of the small and large ship deck area, in this table we also report the average deck occupation with the corridor. Differently from the classical packing problems, our problem contains many other constraints, which may hinder the generation of a fully (near 100%) occupied deck. Moreover, the objective function to be maximized is not the deck occupation, but the sum of priorities. Therefore, the occupation indicators attest that the solutions generated are good. For further details on results of particular

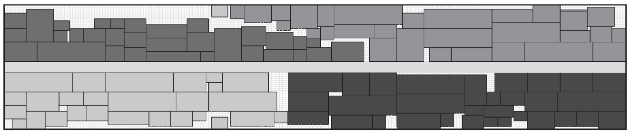

Figure 6 Deck allocation at the port for LS0—Instance #8.

instances, the reader is referred to Tables 2–5 in the online appendix.

Other indicators that help to assess the solution quality are the average due date of the selected cargoes, when compared with the average due date of all candidate cargoes, and with the average due date of the non-selected cargoes. It is expected that the average due date of the selected cargoes will be lower than the non-selected ones, as cargoes with later due dates should be prioritized. Our results indicate that, for all scenarios and for all delivery cargoes, the average due date of the selected cargoes was 3.6% later than the average due date (of all cargoes); the average due date of the non-selected cargoes was 0.9% nearer than the overall due date (of all cargoes); the average due date of the non-selected cargoes was 5.2% nearer than the selected cargoes. When analysing the pick-up cargoes, these figures are, respectively, −3.9, +2.1 and +6.7%.

It is important to mention that this set of test problems may be even more difficult to solve when compared with real problems, given that in many practical cases the ship master may define a specific area on the deck where the cargoes bound for each platform must be assigned. In our tests, any position on the deck could be a starting position for a new cluster, thus posing a greater challenge.

Even though in some cases the total computing time reached the limit imposed, usually the best solution was generated in less time by some thread. It was thus observed that it is possible to terminate the execution with a good solution after the end of some threads without having to wait for all of them to terminate or to reach the time limit imposed. It is worth highlighting that, despite the impact on the total computational cost of the size of the ship and the size of the discrete unit, the proposed algorithm is able to solve large instances for large vessels in an acceptable computation time. In regard to the proposed solution method, we consider that calling the local search routine right after adding a new element to the deck achieved a better performance than calling the local search only after having a complete solution generated by the constructive heuristic. Figure 6 shows the resulting allocation for LS0—Instance#8. In this instance no pick-up cargo exists and the deck is 79% occupied as the vessel departs from the port.

Conclusions

This paper addressed a PDAP found in the oil industry related to the supply of general cargo to offshore rigs and production units. In the real problem studied several operational constraints must be addressed when assigning cargo to the deck of supply vessels. While the existing approaches found in the literature only encompass routing and fleet design issues, our research tackled the inherent packing problem, which is a rich variation of the TDK problem. This problem was solved heuristically by a probabilistic procedure comprising a constructive heuristic and a local search scheme, which yielded good results in the random generated test instances. Although more sophisticated search schemes could have been proposed based on modern meta-heuristics, it should be realized that each time a modification is made on a partial or complete solution many time-consuming verifications must be performed, in order to have all constraints verified. We therefore opted to use a simple but effective search mechanism that would allow the problem to be solved in an acceptable computing time given the practical requirements to reach a solution.

Although the assumptions considered in our study were derived from the real problem observed in the context of Petrobras' operations, we believe that the same features are present in other operational environments. However, even if new constraints were imposed, the modular structure of the proposed algorithm, particularly the feasibility verification process that takes place after selecting and assigning a cargo to the deck, allows the solution procedure to be easily adapted to cope with different constraints, thus making our method quite flexible. Despite this flexibility, however, one should be aware that similar problems from other industries, such as the air-cargo pallets loading problem (Chan *et al*, 2006), or the simultaneous allocation of containers into bays and slots of container ships (Martin *et al*, 1988; Avriel and Penn, 1993), may have substantial differences that make them distinct. Other problems may involve multi-criteria objective functions (Chan *et al*, 2007), hence requiring an appropriate treatment.

The proposed heuristic may effectively support ship planners when dealing with a large-scale allocation problem, with many operational constraints binding. Given that the ship master has the ultimate responsibility and must always give his approval of the stowage plan, an anticipated finalization of the plan can yield a better and more efficient interaction with the master. Planning operations at the port can also be benefited by better coordination with the depot. Moreover, contingencies related to the cancelling or late arrival of transportation orders can be handled in a more efficient way.

Future developments may consider adding routing decisions to the PDAP. Even though the standard problem considers a given tour for a selected cluster of offshore units, it is likely that units outside a cluster could be served during some sort of emergency, contingency or disruption. And, in such cases, routing decisions play an important role. Embedding the proposed heuristic in a decision support system (DSS) (Turban, 1993) is a natural extension of this research and is currently under way. The DSS will allow ship planners to manually assign cargoes to the deck by means of a drag-and-drop mechanism. Interesting modifications on the heuristic include restraining manually added cargoes to be moved from their original positions in a local search phase that tries to organize the deck.

References

Aas B, Gribkovskaia I, Halskau Sr Ø and Shlopak A (2007). Routing of supply vessels to petroleum installations. *International Journal of Physical Distribution & Logistics Management* **37**(2): 164–179.

Aas B, Halskau Sr Ø and Wallace SW (2009). The role of supply vessels in offshore logistics. *Maritime Economics & Logistics* **11**(3): 302–325.

Avriel M and Penn M (1993). Exact and approximate solutions of the container ship stowage problem. *Computers and Industrial Engineering* **25**(1–4): 271–274.

Bacon M, Simm R and Redshaw T (2007). *3-D Seismic Interpretation*. Cambridge University Press: Cambridge.

Bai Y and Bai Q (2012). *Subsea Engineering Handbook*. Gulf Professional Publishing: Amsterdam.

Bassi HV, Ferreira Filho VJM and Bahiense L (2012). Planning and scheduling a fleet of rigs using simulation—Optimization. *Computers & Industrial Engineering* **63**(4): 1074–1088.

Caprara A and Monaci M (2004). On the two-dimensional knapsack problem. *Operations Research Letters* **32**(1): 5–14.

Chan FTS, Au KC, Chan LY and Lau TL (2007). Using genetic algorithms to solve quality-related bin packing problem. *Robotics and Computer Integrated Manufacturing* **23**(1): 71–81.

Chan FTS, Bhagwat R, Kumar N, Tiwari MK and Lam P (2006). Development of a decision support system for air-cargo pallets loading problem: A case study. *Expert Systems with Applications* **31**(3): 472–485.

Chan FTS, Chan HK and Choy KL (2006). A systematic approach to manufacturing packaging logistics. *International Journal of Advanced Manufacturing Technology* **29**(9–10): 1088–1101.

Egeblad J and Pisinger D (2009). Heuristic approaches for the two- and three-dimensional knapsack packing problem. *Computers & Operations Research* **36**(4): 1026–1049.

El-Reedy M (2012). *Offshore Structures: Design, Construction and Maintenance*. Gulf Professional Publishing: Amsterdam.

Fagerholt K and Lindstad H (2000). Optimal policies for maintaining a supply service in the Norwegian sea. *Omega* **28**(3): 269–275.

Fayard D and Zissimopoulos V (1995). An approximation algorithm for solving unconstrained two-dimensional knapsack problems. *European Journal of Operational Research* **84**(3): 618–632.

Gerwick Jr BC (2007). *Construction of Marine and Offshore Structures*. CRC Press: London.

Gribkovskaia I, Laporte G and Shlopak A (2008). A tabu search heuristic for a routing problem arising in the servicing offshore oil and gas platforms. *Journal of the Operational Research Society* **59**(11): 1449–1459.

Hadjiconstantinou E and Christofides N (1995). An exact algorithm for general, orthogonal, two-dimensional knapsack problems. *European Journal of Operational Research* **83**(1): 39–56.

Halvorsen-Weare EE, Fagerholt K, Nonås LM and Asbjørnslett BE (2012). Optimal fleet composition and periodic routing of offshore supply vessels. *European Journal of Operational Research* **223**(2): 508–517.

Hopper E and Turton BCH (2001). An empirical investigation of meta-heuristic and heuristic algorithms for a 2D packing problem. *European Journal of Operational Research* **128**(1): 34–57.

Kaiser MJ and Snyder B (2013). The five offshore drilling rig markets. *Marine Policy* **39**(May): 201–214.

Laporte G and Osman IH (1995). Routing problems: A bibliography. *Annals of Operations Research* **61**(1): 227–262.

Leung SCH, Zhang D, Zhou C and Wu T (2012). A hybrid simulated annealing metaheuristic algorithm for the two-dimensional knapsack packing problem. *Computers & Operations Research* **39**(1): 64–73.

Martin Jr GL, Randhawa SU and McDowell ED (1988). Computerized container-ship load planning: A methodology and evaluation. *Computers and Industrial Engineering* **14**(4): 429–440.

Menezes F *et al* (2010). Optimizing helicopter transport of oil rig crews at Petrobras. *Interfaces* **40**(5): 408–416.

Qian F, Gribkovskaia I and Halskau Sr Ø (2011). Helicopter routing in the Norwegian oil industry: Including safety concerns for passenger transport. *International Journal of Physical Distribution & Logistics Management* **41**(4): 401–415.

Ritchie G (2004). *Practical Introduction to Anchor Handling and Supply Vessel Operations*. Oilfield Publications: London.

Shyshou A, Gribkovskaia I and Barceló J (2010). A simulation study of the fleet sizing problem arising in offshore anchor handling operations. *European Journal of Operational Research* **203**(1): 230–240.

Turban E (1993). *Decision Support and Expert Systems: Management Support Systems*. Palgrave Macmillan: New York.

Wäscher G, Haußner H and Schumann H (2007). An improved typology of cutting and packing problems. *European Journal of Operational Research* **183**(3): 1109–1130.

Received 11 July 2014;
accepted 8 July 2015 after one revision

Supplementary information accompanies this paper on the *Journal of the Operational Research Society* website (www.palgrave-journals.com/jors)