The Berth Allocation Problem:

Application to the Gioia Tauro Maritime Terminal

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1 Introduction

There are more than 2000 ports around the world, ranging from single berth locations handling a few hundred tons a year to multipurpose facilities handling up to 300 million tons a year. According to a report of the World Bank (2003), the expected annual increase in world port traffic is between 4 and 5%. Today more than 80% of the trade with origin or destinations in developing countries is waterborne. In the last 20 years the use of containers for general cargo has increased steadily. Containers are large metal boxes made in standard dimensions and measured in multiples of twenty feet called "twenty foot equivalent units" (TEUs). Between 1990 and 1998, container traffic has doubled worldwide, reaching 175 million TEUs. The forecast is for 270 million TEUs by 2005.

In maritime container transportation the hub and spoke arrangement is widely adopted. Deep sea vessels, also called mother vessels, operate between a limited number of transshipment terminals (hubs). Smaller vessels (feeders) link the hubs with the other ports (spokes). This network topology results in the consolidation of capacity along the routes linking the transshipment ports and in the growth of their importance. In recent years, mother vessels have strongly increased in size attaining up to 6000 TEUs. Transshipment ports are large intermodal platforms and a limited number of them handle an important share of the world traffic. Thus, in 1998 the first ten container ports handled 40% of the total traffic. Ultra-large container vessels cut down transport cost. However, hub ports are forced to invest heavily to accommodate these ships by deepening and widening channels and constructing new berthing facilities of sufficient depth and length. These trends require a continuous improvement in managerial practices at transshipment terminals which can be viewed as material handling systems.

When ships arrive at the port, they enter in the harbor waiting to moor at the quay. The quay is a platform protruding into the water to facilitate the loading and unloading of cargo. The locations where mooring can take place are called berths. These are equipped with giant cranes, called pier or quay cranes, used to load and unload containers which are transferred to and from the yard by a fleet of vehicles. In a transshipment terminal the yard allows temporary storage before containers are transferred to another ship or to another mode (e.g., rail or road). Containers relocation in the yard is also performed to speed up the loading process.

The berth allocation problem (BAP) consists of assigning incoming ships to berthing positions. Managers face two interrelated decisions: *where* and *when* the ships should moor. The problem can be represented in a two-dimensional space where ships are rectangles whose dimensions are the ship length, including a safety margin, and the handling time. These rectangles must be placed in the decision space without overlapping each other and while satisfying several constraints.

In the spatial dimension, there are constraints relative to the depth of the water (allowable draft) and to the maximum distance in relation to the most favorable location along the quay, computed with respect to the location of the outbound containers and to the reserved space for the inbound containers. In the temporal dimension the constraints are expressed as time windows on the completion time of ship servicing. Some time windows are soft and can be relaxed with an appropriate penalty cost.

The planning horizon of the BAP is one week, and the berthing plan is updated every day. Since the problem is solved with a rolling horizon some areas of the berth-time space are not always available when the problem is reoptimized. Some parts of the quay may also be unavailable because of maintenance operations. The arrival time of the ships is known in advance. Every ship has its own time window determined by its arrival and its maximal allowable completion time. Managers want to minimize both port and user costs, which are related to service time. The objective of the BAP is to minimize the total service time of all ships. In some versions of the problem it is possible to include penalty terms in the objective function. For example, as mentioned, there can be a penalty when the service time of a ship exceeds the contracted value.

The BAP can be modeled as a discrete problem if the quay is viewed as a finite set of berths. In this case the berths can be described as fixed length segments, or, if the spatial dimension is ignored, as points. When ships are of different lengths, dividing the quay into a set of segments is, however, difficult to accomplish because requirements vary dynamically. Using long segments will result in poor space utilization while using short segments will likely result in an infeasible solution. Continuous models circumvent these difficulties by considering that ships can berth anywhere along the quay.

2 The Gioia Tauro Maritime Terminal

This study was initiated at the request of the Gioia Tauro Maritime Terminal, located in southern Italy. This port is mainly devoted to transhipment activities involving mother vessels and feeders operating in a hub and spoke manner. Nearly fifty spoke ports are linked to Gioia Tauro. In just a a few years, Gioia Tauro has become the largest transshipment port on the Mediterranean Sea. This achievement is impressive since the port only opened in 1995, and no infrastructures existed in 1993. The traffic forecast for 2003 is 3.2 million TEUs and 3250 ships. The harbor entrance is 250 meters wide and the water depth is 18 meters. The quay length is 3100 meters but only 2850 meters are relevant to our study. The channel along the quay presents a multi-water depth configuration, ranging from 13.5 to 15.5 meters. There are 23 quay cranes available, 18 of which are mounted on rail, while the others roll on tires. A fleet of 75 vehicles, called straddle carriers, transfer the containers between the quay cranes and the yard. These vehicles are capable of transporting up to two containers at a time and can insert containers directly into the right yard slot. Straddle carriers are usually used for the transport of full containers over relatively short distances (less than 500 meters). Different vehicles are used for longer transfers. The yard surface occupies 1.1 million square meters and can store nearly 50,000 TEUs (1,100 of them can be refrigerated). The storage area is divided into bays. Each bay is made up of 32 rows, each having 16 slots. Up to three containers can be stacked in each slot. Empty containers, which occupy approximately 40% of the storage area, have an eight to ten day average dwell time (much more than for a full container) and are located in the most remote positions. A railway station and a connection with the southern Italy highway network are also present. At the time of writing, Gioia Tauro employs 940 workers.

3 Aim of the research project

Our aim is to devise fast and effective heuristics for the discrete and continuous cases of the BAP. We first model the discrete version of the problem and we then extend it to the continuous case. In the discrete case medium size instances can be solved exactly under some assumptions, which enables an assessment of the quality of the heuristic. Since the continuous problem cannot be solved exactly, the assessment of the heuristic developed for this case can only be inferred from the discrete scenario. Two exact formulations for the discrete case will be presented and discussed. Tabu search heuristics for the discrete and continuous cases are introduced and computational results are presented.

4 Exact and Heuristic Algorithms

We consider two different formulations for the discrete case. The first is the *Dynamic Berth Allocation Problem* (DBAP) proposed by Imai et al. (2001). The second is a *Multi-Depot Vehicle Routing Problem with Time Windows* (MDVRPTW) formulation. For small instances, both integer linear programming formulations can be solved by CPLEX. From a computational point of view, DBAP is better than MDVRPTW in that it can solve larger instances. However, neither model can be used for the optimal solution of instances of realistic size. The MDVRPTW formulation is in a sense more interesting than DBAP since it can easily accommodate time windows, and easily lends itself to the development of heuristics. We have developed such a heuristic, based on tabu search for solving the discrete version of the BAP as a variant of the MDVRPTW. Since this heuristic focuses on the temporal dimension we call it T^2S (Time based Tabu Search). An extension of the tabu search heuristic to the spatial dimension is also presented for the continuous case. It is called $(TS)^2$ (Time and Space based Tabu Search).

4.1 T^2S - A tabu search heuristic for the discrete case

Our T^2S heuristic is inspired but different from the MDVRPTW algorithm of Cordeau et al. (2001). In the berth allocation problem, the function to be minimized is the sum for every ship of the service time in the port, as opposed to the distance traveled in the MDVRPTW. Since the cost evaluation of the moves from a current solution is a recurrent step in the tabu search algorithm, some data structures were introduced to track the changes in the cost function in order to reduce the computational load.

The heuristic explores the solution space *S* by moving at each iteration from the current solution *s* to the best solution in its neighborhood *N(s)*. Each solution $s \in S$ is represented by a set of *m* berth sequences such that every ship belongs to exactly one sequence. This solution may, however, violate the time window constraints associated with the ships and the berths. The time window constraint on ship *i* on a berth *k* is violated if the completion time of the ship is larger than the time window's upper bound. Similarly, the time window of berth *k* is violated when the completion time of a ship *i* assigned to berth *k* is larger than the berth time window's upper bound.

Let *c(s)* denote the cost of solution *s*, and let *w(s)* denote the total violation of time window constraints, equal to the sum of the violations on the *n* ships and the *m* berths. Solutions are then evaluated by means of a penalized cost function $f(s) = c(s) + \alpha w(s)$, where α is a positive parameter. By dynamically adjusting the value of this parameter the relaxation mechanism facilitates the exploration of the search space and is particularly useful for tightly constrained instances.

The tabu search method is based on the definition of attributes used to characterize the solutions of *S*. They are also used to control tabu tenures and to implement a diversification strategy. With each solution $s \in S$ is associated an attribute set *B(s)* = *{(i,k)*: ship *i* is assigned to berth *k*}. The neighborhood *N(s)* of a solution *s* is defined by applying a simple operator that removes an attribute *(i,k)* from *B(s)* and replaces it with another attribute *(i,k')*, where $k \neq k'$. When ship *i* is removed from berth *k* , the sequence is simply reconnected by linking the predecessor and successor of the ship. Insertion in sequence *k'* is then performed between two consecutive ships so as to minimize the value of *f(s)*. When a ship *i* is removed from berth *k*, its reinsertion in that berth is forbidden for the next θ iterations by assigning a tabu status to the attribute *(i,k).*

An aspiration criterion allows the revocation of the tabu status of an attribute if that would allow the search process to reach a solution of smaller cost than that of the best solution identified having that attribute. To diversify the search, any solution $\bar{s} \in N(s)$ such that $f(\bar{s}) \geq f(s)$ is penalized by a factor proportional to the addition frequency of its attributes, and by a scaling factor. More precisely, let ρ_{ik} be the number of times attribute *(i,k)* has been added to the solution during the process and let ζ be the number of the current iteration. A penalty $p(\bar{s}) = \lambda c(\bar{s}) \rho_{ik} / \zeta$ is added to $f(\bar{s})$. The scaling factor $c(\bar{s})$ introduces a correction to adjust the penalties with respect to the total solution cost. Finally, the parameter λ is used to control the intensity of the diversification. These penalties have the effect of driving the search process toward less explored regions of the search space. For notational convenience, assume that $p(\bar{s}) = 0$ if $f(\bar{s}) < f(s)$.

4.2 *(TS)*^{2} - A tabu search heuristic for the continuous case

Since the T^2S heuristic works with a given set of berthing points, the ship allocation to these points may not always satisfy the spatial constraints when the berthing points are too close to each other. Discrete models can be applied when the length of the quay is not a limiting factor for the terminal performance. This is not true for large transshipment terminals. To properly take ship lengths into account we have examined the ship length distribution obtained from the Gioia Tauro database. The average length is 183 meters, and the standard deviation is 71 meters. The maximum length is less than twice the average and the minimum length is almost equal to half the average. We therefore subdivide the quay into m berth segments where each segment k has a length close to the ship length average. A segment k that is not the initial or the final berth segment ($k \neq 1$ and $k \neq m$) is then divided into two equal parts, left and right. Each segment has two neighbours, the right part of the segment $k - 1$ and the left part of the segment $k + 1$. The initial and final segments are considered as special cases with only one neighbour and are not divided. These end segments can be used to model not only the beginning and the end of the quay, but also natural discontinuities on the quay, like sharp curves. In fact at Gioia Tauro there is such a discontinuity in the middle of the quay.

The length of a segment can be dynamically adjusted during the course of the algorithm. Thus a segment can accept a ship larger than its length, expanding itself toward one or the two of its neighbours. Conversely, when a segment accepts a ship smaller than its length, the unused space can be allocated to ships berthing in neighbouring segments. Of course the relation between the length of segments and ships matters. If ship lengths had been highly variable, our discretization approach would have caused a heavy fragmentation of the decision space. Representing the quay as a collection of variable length segments induces some changes in the tabu search algorithm. Every ship insertion or deletion in a berth sequence has an impact on the neighbouring berth segments.

5 Computational results for the discrete case

The DBAP formulation was implemented in CPLEX 7.1 with a time limit of two hours. Some sensitivity analyses to the CPLEX MIP solver parameters were carried out, but the best results were obtained with the default values of these parameters. The tabu search algorithm was implemented in ANSI C. Computational experiments were performed on a SUN workstation (900 MHz). Instances of a first subset called I1 were easily solved by CPLEX and T^2S, which are almost always able to reach the optimum. However, this subset was only used as a first benchmark. The more challenging instances are those of a second subset called I2. Here CPLEX could not reach an optimal solution within the time limit. We therefore used a truncated branch-and-bound which stops with the best feasible solution identified after two hours. In contrast T^2S was capable of identifying, within a few seconds, a much better solution than the truncated CPLEX algorithm.

6 Computational results for the continuous case

In the continuous case the only available exact formulation developed by Kim and Moon (2003) is capable of solving only very small size instances. Therefore, the results of the $(TS)^2$ heuristic were evaluated against two benchmarks:

- The final solution of the T^2S heuristic applied on the same input data, but of course, discarding the spatial constraints. The discrete case can be regarded as a relaxation of the continuous case since the solution of the T^2S heuristic may be infeasible with respect to the spatial constraints.

- The starting solution, provided by a greedy procedure called FCFS-G. This comparison estimates the possible savings that the heuristic can provide to the port with respect to a manual plan.

Thirty instances were randomly generated. The $(TS)^2$ heuristic finds solutions which are, on the average, 8% better than those obtained by the FCFS-G procedure. This improvement is highly significant in practice.

7 Conclusions and future developments

We have provided two formulations for the discrete version of the BAP and we have developed two heuristics, one for the discrete case and one for the continuous case. The solution values provided by the first heuristic was compared on small instances to the optimal values generated by the exact DBAP formulation. On these instances our heuristic for the discrete case (T^2S) always yields optimal solutions. On larger instances it always outperforms the truncated CPLEX algorithm applied to the DBAP. Since the discrete model does not always satisfy the spatial constraints, we have developed another heuristic ($(TS)^2$) for the continuous case. Comparisons were made with the discrete case and with a simple constructive procedure. Both heuristics are capable of solving more realistic instances than those previously considered by other authors. Our two heuristics can handle the various features of real-life problems, including time windows, favourite and acceptable berthing areas, etc. The objective function can easily accommodate average container loading and unloading times which are dependent on the berthing position, leading to a bicriterion optimization problem. The integration of the berthing and quay cranes assignment problems will be the object of a further study. The authorities of the port of Gioia Tauro plan to incorporate our heuristics in their decision support system.

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