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Artificial intelligence hybrid heuristic based on tabu search for the dynamic berth allocation problem

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ABSTRACT

This paper considers the Dynamic Berth Allocation Problem, in which vessels are assigned to discrete positions in berths. This problem, whose goal is to minimize the total time the vessels stay at the port, constitutes one of the most important processes at any containers terminal. We propose a hybrid metaheuristic that combines Tabu Search with Path Relinking, T^2S^*+PR. The results reached by this hybrid algorithm are compared with the optimal values given by the best mathematical model that appears in the literature for this problem, *GSPP*, and with a tabu search algorithm from the literature, $\mathtt{T}^2\mathtt{S}$. For small instances, the algorithm T^2S^*+PR is able to obtain most of the optimal solutions in an amount of computational time that is lower than the time required to solve the *GSPP* model. For medium and large size instances, *GSPP* cannot be solved to optimality, whereas the proposed hybrid algorithm outperforms $\mathtt{T}^2\mathtt{S}$. Moreover, the computational experiments carried out in this paper confirm the robustness of the proposed algorithm with respect to both the parameters governing the procedure and the problem size.

1. Introduction

According to the data provided by the Eno Transportation Foundation, more than 60% of the products that travel over the sea are stored in containers. This percentage rise up to almost 100% over some routes connecting economically strong stable countries. The total amount of cargo reaches several millions of TEUs (measure unit equivalent to the dimensions of a standard container). Ports compete to become interchange points (hubs) or origin–destination points of the transportation routes. Regional and national governments consider a strategic objective to have ports where to locate container terminals since they are sources of economic growth. The competitiveness in this area is huge. The main criteria used by the operators to choose a port as operations base are the geographic location, politic and social stability, as well as operational costs.

Broadly speaking, the loading and unloading processes in a container terminal consist of several phases as indicated in Stahlbock and Voß (2008), Steenken et al. (2004), Vis and de Koster (2003). Once a vessel reaches the port, it is allocated to a berth. Then, its containers are unloaded and driven to the yard, where they are temporally stored. Finally, they are moved to trucks, trains or ships to proceed with the delivery phase. Complex planning and management problems, which are very important for the transport operators and port authorities, arise in each of the previous phases. Their effective resolution drives to important savings, being the berthing one of the tasks with the highest impact in the final costs.

Given a set of vessels, the goal of a berth allocation problem is to determine how to allocate them to the berths in order to optimize some cost function. The features of the vessels and the port or its resources determine the constraints that have to be satisfied to obtain feasible solutions. One of the most used cost functions to measure the efficiency of a port terminal is the sum of the waiting and working times of each vessel. Other cost functions are the workload of terminal resources (Lim, 1998) and the number of vessels which cannot be attended in it (Imai et al., 2008).

Bierwirth and Meisel (2010) describe different integration schemes. In a functional integration by a feedback loop, the output solution of one problem is given as input to the other problem in a loop that is executed until a solution satisfying the decision maker expectations is reached. Therefore, it is quite relevant to design and develop procedures that provide high quality solutions (no necessarily optimal) with a low computational cost. An example of these designs can be seen in Giallombardo et al. (2010), where a two levels heuristic is proposed to solve the joint problem of allocating vessels and assigning quay cranes to them. In the first level, a quay crane

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profile is assigned to each vessel and in the second level, the corresponding berth allocation problem is solved. These steps are then repeated until a stopping condition is met.

In this work, we propose a hybrid heuristic that combines the Tabu Search metaheuristic with Path Relinking (T^2S^*+PR) (artificial intelligence methods) to solve the Dynamic Berth Allocation Problem. This procedure incorporates to a Tabu Search algorithm based on T^2S, proposed by Cordeau et al. (2005), a set of elite solutions which consists of a subset of all the local optima found along the tabu search process. This set is then used to build new starting solutions for the tabu search by executing a path relinking algorithm. Moreover, we include an additional neighborhood structure that allows swaps of vessels both among berths and in the same berth. Therefore, we obtain a tabu search procedure that uses two neighborhood structures to guide the search, T^2S^*. The results obtained by the proposed hybrid algorithm are then compared with the results given by the exact resolution of the mathematical model GSPP (Generalized Set Partitioning Problem) presented by Buhrkal et al. (2011) and with the results reached by the T^2S proposed by Cordeau et al. (2005). The computational experience corroborates that T^2S^*+PR outperforms T^2S. It obtains optimal or near-optimal solutions in most cases in a smaller amount of time than GSPP. Moreover, for medium and large size instances, for which GSPP cannot be solved to optimality, T^2S^*+PR significantly outperforms T^2S.

Note that the tabu search algorithm used in this paper is based on the tabu search T^2S, proposed by Cordeau et al. (2005) to solve the Discrete Dynamic Berth Allocation Problem (DBAP), but that it is not exactly the one proposed by these authors. The main difference between both tabu search algorithms is the fact that our algorithm uses two different neighborhood structures, instead of the single one used by Cordeau et al. Since several neighborhood structures are considered, it is also required to define the pattern that has to be followed to perform the different moves. This constitutes one of the contributions of our paper and is explained in Section 4. Moreover, our method combines tabu search with path relinking. It is also important to notice the fact that it is not guaranteed that a hybrid method combining several heuristics will reach better solutions than its single parts. In this work we obtain a hybrid algorithm that outperforms T^2S considering both the solution quality and the computational times.

In the following, we present the outline of the paper and highlight its contributions. The literature review of the dynamic berth allocation problem as well as its description are provided in Section 2. The paper contribution relies upon the solution algorithm introduced in Section 2 that combines a tabu search algorithm, which makes use of two different neighborhood structures, with path relinking, so providing a hybrid algorithm. The computational experience carried out in this paper is summarized in Section 4. This experience confirms that the proposed method is effective since it reaches the optimal solution for most of the solved instances. Furthermore, the algorithm is significantly more efficient than the resolution of the mathematical model GSPP studied in Buhrkal et al. (2011). Therefore, it can be used as an efficient method for solving the berth allocation problem in integrated designs as the one proposed by Giallombardo et al. (2010). Finally, we draw our conclusions in Section 5.

2. Berth allocation problem

In many multi-users container terminals, the quay is divided into a finite set of berths to which the vessels can be assigned for loading and unloading purposes. The problem associated to this assignment scheme is referred to as Discrete Berth Allocation Problem. The goal of this problem is to minimize the total time that vessels stay at the port.

In the static version of the problem, all vessels arrive at the terminal before the starting planning time, while the dynamic version takes into account the vessels that arrive at any time of the planning horizon. The static problem has been studied in Imai et al. (1997, 2001, 2008) and Lee and Chen (2009). The dynamic problem has been studied in Imai et al. (2001, 2003, 2007, 2008), Cordeau et al. (2005), Monaco and Sammarra (2007), Hansen et al. (2008), Silva et al. (2008), Liang et al. (2009) and Giallombardo et al. (2010).

Imai et al. (2001) propose a heuristic based on the Lagrangian relaxation of the proposed model and develop an extensive computational experience that corroborates the effectiveness of the proposed heuristic in real applications. Imai et al. (2003) consider a variant of the problem that includes service priority associated to the vessels. These priorities let distinguishing the vessels according to their size, work volume, etc. The resulting model is then solved using a Genetic Algorithm. Cordeau et al. (2005) propose a new formulation that includes the weighted sum of the service times and time windows of the berths. They also develop a Tabu Search to solve the problem. Imai et al. (2007) tackle the berth allocation problem in which the vessels can be loaded and unloaded from both sides of the berth. The problem is solved by using a Genetic Algorithm. Monaco and Sammarra (2007) propose a more compact mathematical formulation of the problem, which is then solved using a Lagrangian heuristic. The joint problem of berth allocation and quay cranes assignment is introduced by Imai et al. (2008), who solve it by means of a Genetic Algorithm. Liang et al. (2009) also consider the previous joint problem. In their model, the position and time for berthing and the number of quay cranes must be determined in order to minimize the amount of working time, waiting time and delay of each vessel. Hansen et al. (2008) propose a Variable Neighborhood Search for a variant of this problem in which each vessel has both a reward and a penalty for finishing earlier or later the preestablished time, respectively. Silva et al. (2008) propose a heuristic algorithm based on Genetic Algorithm to solve a particular real case in a Brazilian port. Giallombardo et al. (2010) propose a heuristic that combines Tabu Search and Mathematical Programming to solve a new model of berth allocation and quay cranes assignment.

The Discrete Dynamic Berth Allocation Problem was first formulated as a mixed integer programme by Imai et al. (2001) as an extension of the formulation proposed by Imai et al. (1997) for the discrete static berth allocation problem. Alternative formulations for the dynamic problem have been proposed and studied by Monaco and Sammarra (2007), Cordeau et al. (2005) and Buhrkal et al. (2011). These models are described and compared in Buhrkal et al. (2011). The main conclusion is that the model by Christensen and Holst is superior to the other models, since it is able to reach the optimal solutions for the set of instances used by all these authors.

We report an example of the berth allocation problem. Fig. 1 shows feasible solutions for the static and dynamic berth allocation problems, for which the working times (C_{ij}), berths availability (S_i) and arrival times (A_j) of the vessels are summarized in Table 1. Note that in the dynamic version of the problem, which is the version considered in this paper, idle times may appear in the berths planning. Note that in both cases, static and dynamic, berths 1 and 2 are opened in times 4 and 3, respectively. In the static case, all the vessels arrive at the port before the opening time of the berths, while in the dynamic case, the vessels can arrive at any time along the planning horizon.

Let us focus on the dynamic part of this example, since the problem tackled in this paper is the dynamic one. In this case, vessels v_4, v_1 and v_2 are assigned to berth 1, while vessels v_3 and