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Intelligent Heuristic Techniques for the Optimization of the Transshipment and Storage Operations at Maritime Container Terminals

Abstract This paper summarizes the main contributions of the Ph.D. thesis of Christopher Expósito-Izquierdo. This thesis seeks to develop a wide set of intelligent heuristic and meta-heuristic algorithms aimed at solving some of the most highlighted optimization problems associated with the transshipment and storage of containers at conventional maritime container terminals. Under the premise that no optimization technique can have a better performance than any other technique under all possible assumptions, the main point of interest in the domain of maritime logistics is to propose optimization techniques superior in terms of effectiveness and computational efficiency to previous proposals found in the scientific literature when solving individual optimization problems under realistic scenarios. Simultaneously, these optimization techniques should be enough competitive to be potentially implemented in practice.

Keywords: Intelligent Heuristic, Optimization Problem, Maritime Container Terminal.

1 Introduction

Maritime container terminals are complex infrastructures located in seaports that have become backbone elements within global supply chains. They are aimed at facing challenges derived from the huge volume of freights moved around the world. In general terms, it can be claimed that their main function relates to the transfer of the incoming freights packaged into containers between the different transport means brought together, usually container vessels, trains, and trucks.

Terminal managers recognize the need to redesign the ways logistic operations are today being carried out to address the challenges brought about by the international shipping industry. The main reason is found on the impact the performance of maritime container terminals has on the trade competitiveness of the countries. In this environment, two general approaches are persistently considered. The former is intended to promote investments in new infrastructures and technologies which increase the capacity to handle ever-increasing freight volumes. However, this approach has obvious drawbacks in terms of environmental impact or financial sustainability, among others. Furthermore, the latter is based on the improvement of the operations carried by the terminals, but the heterogeneity, interdependence, and complexity of the processes constitute a major challenge for stakeholders.

The temporary and profitability needs of the processes found at maritime container terminals give rise to optimization problems classified as $\mathcal{NP}$-hard in terms of the *Computational Complexity Theory*. This means that efficient optimization approaches have to be applied in order to cope with them. In this regard, the approximate optimization techniques, such as heuristic and meta-heuristics, have proven to be a comprehensive tool to solve intractable optimization problems due to the fact that they exhibit a suitable balance between quality of the solutions reported and affordable computational requirements.

This thesis pursues to analyse outstanding optimization problems derived from the transshipment and storage operations carried out in a maritime container terminal. These are the Quay Crane Scheduling

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Problem, Pre-Marshalling Problem, Blocks Relocation Problem, and Stacking Problem, as well as some of their most relevant variants. In this regard, terminal managers demand high-efficient optimization approaches to solve these optimization problems with the aim of maintaining or even gaining market share. With these goals in mind, several intelligent heuristics have been designed, implemented, and validated during this thesis. The experimental results obtained reveal that the proposed techniques are appropriated to be applied in practice, in an isolated fashion or embedded into general integration schemes. In most of cases, these reduce significantly the computational times required by the best approaches previously presented in the literature and improves the quality of the solutions obtained.

2 Transshipment and Storage Operations

Over the last years, the logistic problems at maritime container terminals have received a great deal of attention within the scientific literature. The main reasons are their huge impact on the terminal competitiveness and the undoubted importance for the economy of the regions where they are located. A general overview of the main logistic processes in this field is provided in [8]. In the following, the most highlighted optimization problems related to the topic of the thesis at hand are reviewed and a brief summary of the main contributions from the papers obtained is also presented.

2.1 Quay Crane Scheduling Problem

The Quay Crane Scheduling Problem, in short QCSP, is stated as determining the finishing times of the tasks performed by each one of the available quay cranes allocated to a vessel. The goal is to minimize the service time of the container vessel at hand. That is, its turnaround time or makespan [5]. In the context of this thesis, a task represents the loading/unloading of a group of containers onto/from a given deck or hold of the container vessel at hand. The QCSP is already known to be $\mathcal{NP}$-hard [7].

In order to solve the QCSP, an Estimation of Distribution Algorithm (EDA) is proposed in [1]. The EDA keeps a probabilistic learning model which records statistical information about the explored search space. This model is based on a probability matrix. Each value of the matrix defines the probability of assigning a task to a given quay crane in the model sampling step. The structure of the QCSP enables to incorporate a priori knowledge in the scheme of the proposed algorithm in a straightforward manner. Intuitively, the probability that a task is performed by a quay crane in a promising solution is highly influenced by the distance between them. For this reason, the initialization step is based on the use of a Gaussian function in a discrete way for computing initial assignment probabilities. Its use is based on the fact that it enables to assign a higher weight to quay cranes initially located close to the corresponding task and it is decremented as the distance between them increases.

The empirical computational results have demonstrated that the proposed meta-heuristic approach is highly competitive in the scenarios analysed with respect to state-of-art algorithms. It allows to obtain optimal unidirectional solutions for small scenarios and high-quality solutions for large cases. In the largest instances, the EDA achieves the best-quality solution in one instance. Moreover, the computational effort is very reduced and the robustness is high in each case, showing the convenience of applying it to real scenarios.

2.2 Container Storage

The layout of a yard in a maritime container terminal is composed of similar three-dimensional storage areas, termed *yard blocks*. The yard blocks can be placed in perpendicular or parallel direction to the quay. Each block is composed of bays. A bay is a storage composed of stacks made up of a given number of tiers each one. The storage capacity of a terminal is expressed in terms of number of containers that can be stored on it and derived from the dimensions of its yard blocks. In this regard, the capacity of a given bay depends upon its stacks and tiers. The positions in which a container can be placed in a bay are termed *slots*. Similarly, the capacity of a yard block is the sum of capacities of its individual bays.

The Pre-Marshalling Problem, PMP, is the problem of reshuffling the containers in a bay with the purpose of obtaining a new container bay layout in which there is no container with a given retrieval time placed above other container with earlier retrieval time. That is, the initial non-located containers have to be skipped in the target bay layout by means of relocation movements.

The Lowest Priority First Heuristic is an optimization approach proposed in [3] to solve the PMP. The underlying idea of this heuristic is that if the containers with the latest retrieval times are placed at the bottom of the stacks, then they will not have to be relocated in the future because they do not avoid the retrieval of other containers with earlier retrieval times. In fact, according to the definition of the PMP, each container has to be placed at the bottom of the bay or above other container with later retrieval time in any target bay layout. For this purpose, the proposed heuristic iteratively places each container either at the bottom of a stack or above other containers with later retrieval times. Finally, an improvement process based on stack filling is applied to reduce the number of non-located containers. The stack filling reasoning is based upon trying to take advantage of the empty slots in the destination stack, filling them with non-located containers in the most adequate sorted sequence.

The computational results of the comparative analysis carried out with respect to previous approximate approaches from the scientific literature and an exact approach demonstrate the high performance of the heuristic algorithm developed in this thesis. Moreover, its robustness has been statistically demonstrated since it is able to solve scenarios with varying difficulties and sizes.

Moreover, the Blocks Relocation Problem, in short BRP, is an optimization problem that can be described as follows. Given a set of homogeneous containers placed in a two-dimensional bay, the goal of the BRP is to find the shortest sequence of movements aimed at retrieving all the containers one after the other according to their increasing retrieval times. Without loss of generality, it is assumed that the retrieval order is defined by following the retrieval times. This way, the container with the earliest retrieval time must be retrieved before that with the second earliest retrieval time; the container with the second earliest retrieval time must be retrieved before that container with the third earliest retrieval time; and so forth, until all the containers are retrieved.

In this thesis, an optimization approach for solving the BRP is proposed in [4]. The cited paper has a twofold contribution. On one hand, it presents an optimization model for the BRP that overcomes several shortcomings of a model termed BRP-II found in the literature. In contrast to the proposed optimization model, BRP-II reports infeasible solutions and does not guarantee the optimality of the achieved solutions in some cases. The reasons are found in that (i) several containers currently placed above the next to retrieve cannot be relocated to the same destination stack and (ii) the containers placed below the next to retrieve can be relocated. Consequently, the reported solutions cannot be implemented in practice. On the other hand, [4] presents a Branch and Bound algorithm aimed at solving the BRP to optimality by means of short computational times. This algorithm includes an intelligent strategy to explore the most promising nodes in the underlying tree. Thus, the performance of the Branch and Bound algorithm can be easily adapted to report high-quality solutions at the expense of sacrificing the optimality guarantee.

The computational experiments carried out in [4] reveal that the proposed optimization model can be only applied in small-size scenarios due to its high computational burden. However, the exact algorithmic approach based upon the framework of the Branch and Bound reports all the optimal solutions for the problem instances found in the related literature by means of short computational times. This high performance encourages its integration in potential intelligent systems, where the decision maker controls its inputs to obtain appropriate sequences of movements aimed at retrieving the containers.

Finally, the Stacking Problem, in short SP, is an optimization problem in which the flow of homogeneous containers in a bay is optimized during a well-defined planning horizon [6]. That is, it seeks to determine the slot in which each incoming container must be stored during its release time and the movements to carry out for its removal during its retrieval time. The objective of the SP is to minimize the number of movements required to store and retrieve all the containers by means of a stacking crane.

A high efficient heuristic algorithm is proposed in [2] for solving the SP. The rationale behind this heuristic algorithm is to exploit those time periods in which there are no containers being moved in the bay with the aim of minimizing the number of non-located containers.

The computational results indicate that the heuristic proposed in [2] is more competitive than those approaches already presented in the literature and used as benchmark. In fact, the results indicate there is statistical significance related to the heuristic and previous approaches. Also, the proposed heuristic reports solutions with better objective function values on average than those obtained by means of the remaining approaches. The reason of the improvements obtained in the computational experiments arises from reducing the number of non-located containers in the two-dimensional bay. In this regard, every time the number of non-located containers is reduced in the bay, more stacks in which non-located containers are built. Consequently, the probability of requiring new container relocations in the future is minimized.

3 Conclusions

In spite of the efforts made in the development of exact approaches in maritime logistics, no efficient techniques have been reported in most of cases. Alternatively, heuristic techniques have stand as the promising candidates because they report (near)optimal solutions within short computational times. Specifically, several intelligent heuristic and meta-heuristic techniques are successfully proposed in this thesis to solve the Quay Crane Scheduling Problem, Pre-Marshalling Problem, Blocks Relocation Problem, and Stacking Problem, as well as some of their most relevant variants. In general terms, it can be claimed that the proposed techniques have demonstrated to be more competitive than state-of-art approaches, reporting solutions with higher quality in shorter computational times in all the cases under study. In addition, the techniques are versatile enough to easily adapt to new variants of the optimization problems for which they have been devised. This means that these techniques are suitable for being implemented in practice.

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