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Minimizing the Waiting Times of block retrieval operations in stacking facilities

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ABSTRACT

This paper addresses the Blocks Relocation Problem with Waiting Times. Its objective is to retrieve a set of homogeneous blocks from a two-dimensional storage by minimizing the waiting times during their retrieval. An integer programming model and a heuristic algorithm are developed to solve this optimization problem. The mathematical model is able to solve small-size cases to optimality in reasonable computational times. Unfortunately, it requires large computational times when tackling medium and large-size scenarios. For its part, the heuristic algorithm overcomes the problems associated with the computational burden of the model by bringing forward the availability of blocks to retrieve from the storage. With this goal in mind, several look ahead strategies dedicated to perform the most promising predictive block relocation movements are proposed. The computational results disclose the proposed heuristic algorithm is able to report high-quality solutions through very short computational times, less than one second, in practical cases.

1. Introduction

Stacking is the most extended strategy to store homogeneous robust items (*e.g.*, boxes, containers, ISO standard pallets, etc.), termed *blocks*, in industrial environments (*e.g.*, warehouses, container terminals, distribution centers, etc.). In stacking facilities, the blocks are piled up vertically in a well-defined set of stacks until they are retrieved in response to a certain customer request, frequently named *order-picking*, de Koster, Le-Duc, and Roodbergen (2007). The stacks usually have a maximum number of tiers derived from, according to the application field, the physical characteristics of the environment, block crushability, or technical features of the machinery used in the operations, among others. An excellent survey dedicated to analyze the warehouse design and performance evaluation is proposed by Gu, Goetschalckx, and McGinnis (2010).

Stacking precludes the access to the blocks, Dekker, Voogd, and Asperen (2007). The reason is found in the inherent Last In First Out (LIFO) strategy imposed by the stacks, Caserta, Schwarze, and Voß (2011a). This way, only those blocks placed at the top of the stacks can be directly accessed through the machinery (*e.g.*, gantry cranes, reach stackers, forklifts, etc.). The remaining blocks require to be freed up before their access. This is done by relocating those blocks placed above them in other locations of the storage, Jang, Kim, and Kim (2013).

Relocating blocks has a negative impact on the overall throughput of the stacking cranes in terms of, for instance, working time and fuel consumption or electric energy consumption, whereas maintenance cost and emissions can be also greatly increased. de Koster et al. (2007) estimate the cost of retrieving products from their storage in a warehouse to be as much as 55% of the operating expense. In the same vein, Tompkins, White, Bozer, and Tanchoco (2010) indicate that between 20% and 50% of the total operating expenses is attributed to handling costs. Lastly, Park and Kim (2010) study the trade-off between the handling costs derived from relocations and the total amount of required space. Moreover, there is a direct connection between the efficiency in the retrieval operations and the customer satisfaction. Specifically, the longer the waiting times of the blocks in retrieval operations, the lower the customer satisfaction, Anderson, Fornell, and Rust (1997).

The previous discussion reveals a critical logistic problem in industrial environments based upon block stacking strategies: the just-in-time availability of the blocks. In this regard and according to Tompkins et al. (2010), implementing efficient optimization approaches dedicated to improve the performance of

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the stacking facilities enables to deliver higher customer service level and can reduce the operating costs by at least 10–30%.

In this paper, the Blocks Relocation Problem with Waiting Times (BRP-WT) is presented, whose objective is to minimize the waiting times of the blocks during their retrieval. This optimization problem constitutes a shift in focus with respect to the traditional crane-oriented approaches found in the literature (see Section 3), which seek to only minimize the number of movements performed by the stacking cranes and rule out the service quality.

The main contributions of the present paper are outlined below:

1. Introducing the definition of the BRP-WT, Lehnfeld and Knust (2014).
2. Proposing an optimization model aimed at solving the BRP-WT. The computational results indicate that this model is useful to solve small-size problem instances in reasonable computational times.
3. Developing a heuristic algorithm for solving the BRP-WT from an approximate standpoint. The computational results reveal the algorithm provides high-quality solutions in all the environments under analysis by means of short computational times.

The remainder of this paper is structured as follows. Section 2 introduces the BRP-WT. The relevant literature is reviewed in Section 3. Afterwards, an optimization model for the BRP-WT is presented in Section 4. Section 5 describes a heuristic algorithm dedicated to solve the BRP-WT from an approximate point of view. Section 6 illustrates the computational experiments carried out in this work. Finally, Section 7 extracts the main conclusions from the work and indicates several lines for further research.

2. Blocks Relocation Problem with Waiting Times

The Blocks Relocation Problem with Waiting Times, in short BRP-WT, is an $\mathcal{NP}$-hard optimization problem that seeks to retrieve a set of homogeneous robust blocks denoted as $C = \{1, 2, \ldots, nC\}$ from their current locations in a stacking facility. It is assumed that the blocks have similar dimensions and have enough load strength to withstand the stacking of multiple blocks above them without suffering crushability.

The stacking facility is represented as a well-delimited two-dimensional storage. This is composed of a set of stacks, $S = \{1, 2, \ldots, nS\}$, which are vertically organized into a set of stacking tiers, $T = \{1, 2, \ldots, nT\}$. As discussed by Expósito-Izquierdo, Melián-Batista, and Moreno-Vega (2015b), the number of tiers is usually imposed by the physical features of the stacking facility, the load strength, and the stability of the stacks. Thus, its capacity is denoted as $M = nS \times nT$, measured in terms of number of blocks. The number of blocks placed in the stack $s \in S$ during the time period t is denoted as $n(s,t) \leqslant nT$. Also, the initial percentage of capacity used to store blocks in the two-dimensional storage is termed *filling percentage* and is denoted as α. It is worth mentioning that, in each time period, at least $nT - 1$ empty slots must exist in the storage in order to relocate those blocks placed above a block to retrieve from the lowest tier in a full stack, Caserta, Schwarze, and Voß (2012). Otherwise, no feasible solution could be obtained due to the fact that a block in the lowest tier could not be freed up completely.

Each block $c \in C$ must be ideally retrieved during its expected retrieval time, denoted as $e(c)$, which indicates, for instance, the time a certain customer expects to pick up the incumbent block or the time at which the block must be placed on a conveyor within an assembly process, among others. The block with the earliest expected time in the stack $s \in S$ during the time period t is denoted as $min(s,t)$. In general terms, the quality of service, in short QoS, is a measure which indicates the difference between the customer expectations and the performance of the system under analysis, Sureshchandar, Rajendran, and Anantharaman (2002). Given a certain block $c \in C$, the quality of service associated with its delivery, denoted as $QoS(c)$, is measured in the paper at hand by considering only its waiting time as quality dimension, Harvey (1998). The waiting time of c is defined as the elapse of time between its expected retrieval time and its real retrieval time, denoted as $r(c)$ and where $r(c) \geqslant e(c)$. This waiting time is denoted as follows:

$$wt(c) = r(c) - e(c) \tag{1}$$

Thus, the quality of service provided to the customer associated with c is $QoS(c) = wt(c)$. It should be noted that the waiting time of a given block is zero whenever it is exactly retrieved during its expected retrieval time. Otherwise, positive waiting times appear. It is worth mentioning that the blocks cannot be retrieved before their expected retrieval times due to the absence of temporal storage for them out of the stacking facility on which to place them until the arrival of the corresponding target elements. All the potential changes in the expected retrieval times of the blocks can be handled as dynamic variants of the BRP-WT in further research. Furthermore, the waiting time of a given block is measured in terms of crane movements. However, according to the technical characteristics of the stacking crane used in the retrieval process, this can be easily translated into temporal units. For example, a Rubber-Tyred Gantry Crane is able to perform about 20–25 movements per hour, Saanen (2011), which indicates that each movement is performed every 144–180 s on average.

The blocks must be retrieved according to a pre-defined retrieval order, which is derived from their expected retrieval times. That is, block 1 has to be retrieved before block 2, block 2 has to be retrieved before block 3, and so forth, until the last block has been retrieved. Without loss of generality, the block operations are performed by means of a stacking crane. The optimization objective of the BRP-WT is to minimize the waiting times of the blocks during their retrieval. This can be expressed as follows:

$$\min \sum_{c=1}^{nC} wt(c) \tag{2}$$

It should be noted that the average, minimum, maximum, or alternative objective functions can be trivially considered in the BRP-WT. In addition, given a certain scenario of the problem and according to Eq. (2), the QoS provided by the stacking facility management system is similar to the objective function value of the solution reported.

The slots of the two-dimensional storage can be occupied by at most one block during each time period. In this context, the stack in which a block $c \in C$ is stored during the time period t is denoted as $s(c,t) \in S$, whereas its tier is $h(c,t) \in T$. However, the blocks must be stored by following the stacking strategy, in such a way that, they have to be either directly placed on the ground (tier 1) or on top of another block. That is, according to the Last In First Out (LIFO) strategy, Caserta et al. (2011a). Lastly, the set of blocks placed above the block $c \in C$ during the time period t is denoted as $O(c,t)$ and defined as follows:

$$O(c,t) = \{c' \in C \mid (s(c',t) = s(c,t)) \wedge (h(c',t) > h(c,t))\}. \tag{3}$$

It is of note that $O(c,t) = \varnothing$ to retrieve the block $c \in C$ from the storage during the time period t. Otherwise, relocation movements associated with the blocks in $O(c,t)$ must be firstly performed to free up c.

The two-dimensional storage is served by a single stacking crane, which is dedicated to provide and arrange the blocks. This way, it is assumed that the crane can perform at most one