European Journal of Operational Research 000 (2016) 1–15

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

A generalized classification scheme for crane scheduling with interference

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ARTICLE INFO

Article history:
Received 25 December 2014
Accepted 18 August 2016
Available online xxx

Keywords:
Crane scheduling
Non-crossing constraints
Classification
Survey

ABSTRACT

Nowadays, many industries rely on cranes for efficiently executing storage and retrieval operations of goods. Areas of application are, for instance, container logistics in seaports and warehousing operations in automated storage and retrieval systems. Therefore, it is not astounding that plenty scientific papers on crane scheduling in many different yet closely related logistics settings have accumulated. In many of these problems, crane interference occurs. A prominent example is non-crossing constraints where cranes share a common pathway and cannot overtake each other. In order to structure this vast field of research, this paper provides a classification scheme for crane scheduling problems with crane interference. We apply this scheme to classify the existing literature, to determine the status-quo of complexity results, and to identify future research needs.

1. Introduction

The standardization of load carriers, e.g., EUR/EPAL-pallets or ISO freight containers, has considerably added to a strong decline in transportation costs and to a dramatic growth in transport volume. For instance, the number of ISO containers processed worldwide exceeded 540 million TEU (twenty feet equivalent unit) in 2010, see UNCTAD (2012). To efficiently handle such a huge amount of goods an automation of loading and unloading processes seems inevitable. Therefore, many distribution systems rely on cranes to enable efficient and reliable (un-)loading processes for transport vehicles as well as storage and retrieval operations. Perhaps the most impressing examples in this context are the huge quay cranes (QCs) for processing container vessels in modern ports. However, cranes are also inevitable in other important areas of application, e.g., in automated storage and retrieval systems (ASRS) of modern distribution centers or in production environments where heavy and bulky workpieces, e.g., steel coils, are transported.

Given these manifold applications of cranes it is not astounding that crane scheduling received plenty attention among practitioners and researchers. Crane scheduling assigns storage and retrieval moves of goods to cranes and decides on their processing time windows in order to achieve efficient transshipment processes. In this context, a widespread real-world phenomenon is that cranes share a common pathway, e.g., a same rail track, for their horizontal movement, so that they cannot overtake each other. This is reflected in crane scheduling models by so-called non-crossing constraints. Another kind of crane interference occurs, if cranes can principally cross each other, but only under special circumstances (e.g., lifted beam). The occurrence of crane interference distinguish crane scheduling from traditional machine scheduling, so that the former became a (comparatively) new and active field of research in the last decade.

Especially the scheduling of QCs and yard cranes in container ports received manifold attention. Numerous papers have been published on this topic during the recent years. The up-to-date survey papers Bierwirth and Meisel (2010), Bierwirth and Meisel (2015), Carlo, Vis, and Roodbergen (2015), Carlo, Vis, and Roodbergen (2014) and Luo, Wu, Halldorsson, and Song (2011) summarize this research effort. These surveys also propose classification schemes for the addressed scheduling problems, but with a strong focus on attributes that are specific for crane scheduling in container terminals. These existing surveys and classification schemes question the justification of yet another survey paper. However, our paper has a broader focus on crane scheduling and does not exclusively treat the area of container ports. Instead, we try to highlight the similarities to other fields where closely related crane scheduling problems exist by introducing a general classification scheme. This way, the huge knowledge accumulated on crane scheduling in

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http://dx.doi.org/10.1016/j.ejor.2016.08.041
0377-2217/

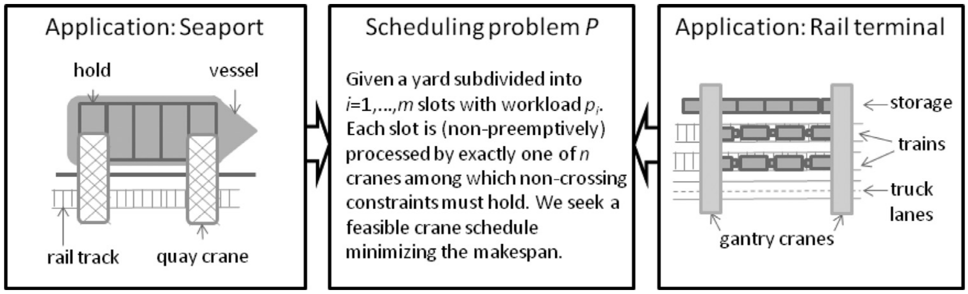

Fig. 1. Problem of multiple crane scheduling applications.

container ports during the recent years might become transferable to these related areas more easily.

Contrariwise, neglecting the similarities in manifold transportation, warehousing, and production settings bears the risk of identical (or at least closely related) crane scheduling problems being ‘reinvented’ and solved multiple times without an awareness for the previous research. Thus, there seems a need for some general view on crane scheduling with crane interference unifying the potential areas of application. This paper and the general classification scheme presented within are a first step into this direction. To highlight the risk of an uncoordinated advancement of research, we next present an example where the same crane scheduling problem P can be applied for coordinating (un-)loading processes in very different areas of applications:

Problem P. Consider a one-dimensional storage yard subdivided into m slots. Depending on the number of containers (to be) stored, each slot $i = 1, \ldots, m$ is assigned a workload (or processing time) p_i. Given $c = 1, \ldots, n$ cranes numbered according to their succession in the yard, all slots assigned to a crane are to be successively processed in a non-preemptive manner. The time it takes a crane to move between two slots is negligible. We seek a schedule of minimum makespan, which ensures that all slots are processed without any crossing of cranes. More formally, a schedule Ω consists of a set of triples $(i, c, C_i) \subset \Omega$ each defining that processing slot $i \in \{1, \ldots, m\}$ by crane $c \in \{1, \ldots, n\}$ has completion time $C_i \geq 0$. We say a schedule is feasible, if for each $i = 1, \ldots, m$ there is exactly one $(i, c, C_i) \in \Omega$, that is each slot is executed exactly once, and for each pair of slots i and i', with $i < i'$, $(i, c, C_i) \in \Omega$, and $(i', c', C_i') \in \Omega$ the schedule meets one of the following requirements:

- Either $c < c'$ which means that non-crossing is guaranteed by the relative positioning of the cranes, or,
- If $c \geq c'$, we either have $C_i - p_i \geq C_{i'}$ or $C_{i'} - p_{i'} \geq C_i$ which ensures non-crossing by separating the processing time windows of the two slots if $c > c'$ and ensures non-overlapping processing time windows for slots handled by the same crane if $c = c'$.

Among all feasible schedules, we seek one schedule Ω minimizing $\max_{(i,c,C_i)\in\Omega} \{C_i\}$. Problem P can directly be applied for two important cranes scheduling problems, see Fig. 1. On the one hand, problem P is known as the quay crane scheduling problem (e.g., Zhu & Lim, 2006; Lee, Wang, & Miao, 2008a; Bierwirth & Meisel, 2010) for scheduling the (un-)loading processes of QCs serving a container ship at a port. Here, the slots represent bays of a ship. The workload is defined by the containers to be (un-)loaded per bay. As QCs share a special rail track for their horizontal movement along the quay, non-crossing of cranes needs to be ensured. Minimizing $\max_{(i,c,C_i)\in\Omega} \{C_i\}$ keeps the port stay time of the ship as short as possible.

On the other hand, the very same problem P can be applied to schedule the unloading processes in rail terminals, where containers are to be exchanged between freight trains and trucks. Typically, a rail terminal is subdivided into a grid of rows (e.g., rail tracks, driving lanes for trucks, storage lanes of containers) and columns (e.g., number of standard railcars fitting in the yard) in order to identify the positions of containers and to assign parking positions to trucks next to their respective container (see Boysen & Fliedner, 2010). Thus, if this grid is applied to subdivide the rail yard such that each column (slot) is to be processed by one of the gantry cranes spanning the rail tracks, then problem P can directly be applied to minimize the processing time of a group of trains that are served simultaneously at the terminal.

Given the manifold applications of crane scheduling problems, a general classification scheme for crane scheduling with interference constraints may help to coordinate the research effort of the community in a concerted manner. After defining the scope of this paper in Section 2, such a classification scheme analogously to the famous tuple-notation of Graham, Lawler, Lenstra, and Kan (1979) for machine scheduling is presented in Section 3. The scheme is used in Section 4 to classify the relevant literature in various fields of crane scheduling research. For each research paper, we define the tuple-notation, so that practitioners and researchers can quickly identify the previous research relevant to a respective problem. In Section 5, we identify future research needs. Section 6 concludes the paper.

2. Scope of survey

A *crane* is a special industrial machinery for lifting materials at some start position, moving them vertically and/or horizontally, and lowering them at some target destination. Each lifting, movement, and lowering operation executed in direct succession on the same material (without remounting it) is denoted as a (crane or container) *move* throughout this paper. Traditionally, cranes have been designed for a sporadic lifting of heavy and bulky materials, e.g., in the construction industry, whereas modern distribution systems are designed for a mass processing of standardized items. The standardization effects that items can quickly be accessed by the hoisting device (without fixing some chains or wire ropes), so that moves in the mass transportation context are executed in quick repetition and, typically, last at most a few minutes. The standardized items to be moved by cranes can be ISO containers in seaports or rail-terminals, bins of stock-keeping-units (SKUs) in an ASRS, or workpieces, e.g., heavy steel coils lifted by overhead cranes, in a production environment. In this paper, these items are all referred to as *containers*.

One confinement of this paper is to consider only such cranes that move along a fixed pathway. Such a unique horizontal pathway exists for the ASRS and the QCs discussed earlier in this paper but also for gantry cranes in container yards and rail-terminals as well as for industrial cranes in production environments, see Fig. 2a–e respectively. We exclude technical systems where cranes are placed at fixed locations, e.g., tower cranes, slewing pillar cranes, and deck cranes located on a ship. Also excluded are lifting