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Invited Review

A survey on single crane scheduling in automated storage/retrieval systems

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ABSTRACT

This paper addresses the scheduling of a single storage/retrieval machine (or crane) in automated storage/retrieval systems (ASRSs). A novel classification scheme is presented for precisely defining different versions of the crane scheduling problem, when varying the layout of the ASRS, the characteristics of the storage and retrieval requests, and the objective function. This classification scheme is then applied for presenting different (known and novel) exact algorithms and complexity proofs for a variety of crane scheduling problems, for reviewing the literature, and for identifying future research needs.

1. Introduction

Since their introduction in the 1950s, automated storage/retrieval systems (ASRSs) are widely used in warehouses and distributions centers all around the world. Their main advantages over traditional (pickers-to-parts) warehousing systems are high space utilization, reduced labor costs, short retrieval times and an improved inventory control. Due to these benefits along with the following exemplary industry trends there are grounds for the supposition that ASRSs will keep (or even increase) their widespread application in the foreseeable future:

- The ongoing *proliferation of product variety* observable in many industries increases the variety of stock-keeping-units (SKUs) to be handled in an average warehouse. For instance, the plant in Dingolfing of German automobile producer BMW receives material in more than 13,000 containers delivered by about 600 suppliers on more than 400 trucks each day (Boysen, Emde, Hoeck, & Kauderer, 2015). Handling such a huge amount of parts by reliable in-house logistics processes seems hardly manageable without automated warehousing.
- An *increasing ecological awareness* of customers puts stress on supply chains to reduce, e.g., their carbon footprints. An ASRS stores inventory more densely and, thus, eliminates the need for energy to heat, cool, light and ventilate excess storage space. According to the Material Handling Industry of America (MIH, 2009), the food industry saves up to 30 percent cooling cost in refrigerated warehouses applying ASRSs.
- With an aging society in many developed countries and an increasing legislative burden (e.g., EU Machinery Directive, 2006/42/EC, 89/391/EEC, Occupational Safety and Health Act) *ergonomic aspects* require special consideration in warehousing. Repetitive lifting tasks put considerable ergonomic strain on the workforce (e.g., see Grosse, Glock, Jaber, & Neumann, 2015), so that an automation of stressing workplaces by ASRSs seems advantageous.

An ASRS consists of one or multiple racks which are accessed by one or multiple storage/retrieval machines (or cranes) for automatically storing and retrieving products. An important decision problem for efficiently operating an ASRS is the crane scheduling problem, which decides on the sequence of crane moves for processing specific storage and retrieval requests. Depending on the ASRS layout, the order characteristics and the objective function a wide variety of different scheduling problems arises. For instance, an ASRS may own a single interface (IO-point), at which SKUs are interchanged with preceding and succeeding process steps, or multiple ones, an order set can either exclusively consist of storage, retrieval and reshuffle orders or a mixture of them, and either the total travel distance or the number of late retrieval requests according to some given due date can be minimized. This paper provides a novel classification scheme inspired by the well-known triple notation for machine scheduling of Graham, Lawler, Lenstra, and Kan (1979) for briefly defining varying ASRS settings. This classification scheme is then applied for summarizing known and novel results with regard to (optimally) solving the respective crane scheduling

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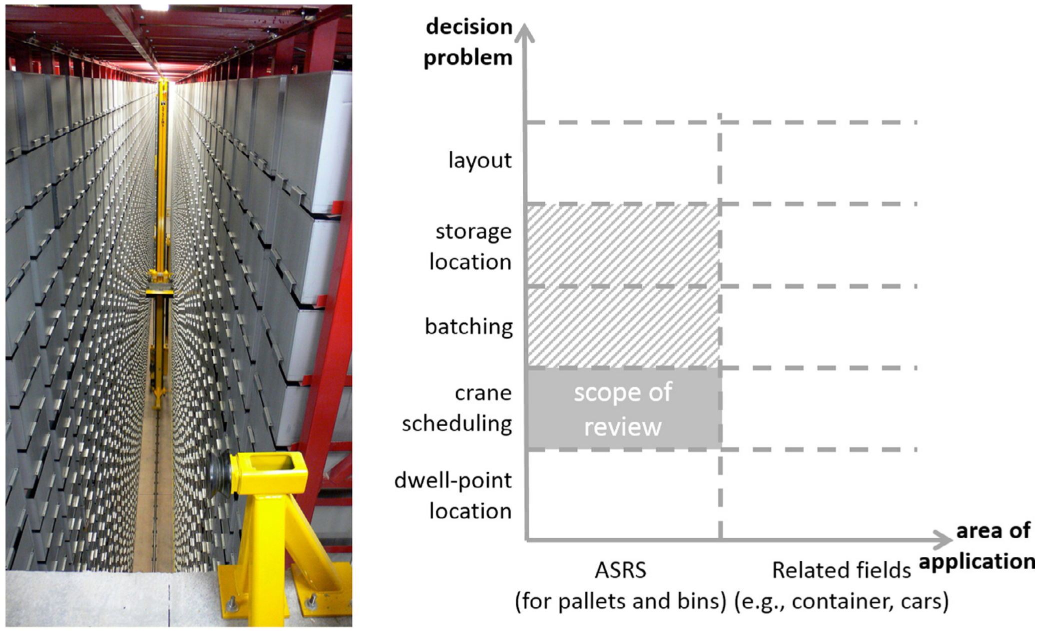

(a) Picture of an ASRS aisle **(b) Scope of survey**

Fig. 1. An ASRS and a schematic representation of the paper's scope. (The ASRS picture is published under the Creative Commons license (CC BY-SA 2.0). The author of the picture is Nelson Pavlosky.)

problems. Furthermore, important future research tasks are identified.

The remainder of the paper is structured as follows. Section 2 defines the scope of this review by characterizing the kind of ASRSs investigated in this paper. Section 3 presents the classification scheme, which is, then, applied for presenting different results for scheduling varying ASRS settings (Section 4). Section 5 specifies future research needs and concludes the paper.

2. Scope of survey

An ASRS is a fully automated parts-to-picker storage system that consists of one or multiple racks accessed by automated storage/retrieval machines (also denoted as *cranes*). Among a multitude of potential ASRS settings we restrict our classification to the most widespread setting, where racks are arranged in pairs along straight aisles. Each rack consists of multiple columns and rows of shelves, in which SKUs are stored. These SKUs are processed by automated stacker cranes, which travel along aisles and perform storage, retrieval, and/or relocation requests. In most applications (as is presupposed in this survey) a single crane is applied per aisle (see Fig. 1(a)).

In horizontal direction, a crane moves along rails that are mounted to the floor and the ceiling. For the vertical direction each crane has one or multiple shuttles each having some fork or conveyor mechanism for storing SKUs in and retrieving them from a shelf. Typically, cranes and shuttles have independent drives, so that travel times and distances are measured by the maximum of the isolated horizontal and vertical travel times and distances (Chebyshev or maximum metric), respectively. Horizontal travel speeds are typically about 3 meter per second compared to vertical travel speeds of about 0.75 meter per second (Tompkins, White, Bozer, & Tanchoco, 2003). Another important element of an ASRS is one or multiple input–output points (IO-points, sometimes also denoted as depots), which build the interface (typically via a conveyor system or some vehicle) to preceding and succeeding process steps.

Preceding process steps, e.g., in the receiving department of a distribution center, define storage requests, whereas succeeding pick and pack processes are the initiator of retrieval requests. A crane operation fulfilling such a request is called a (loaded) *move*. A move is defined by a start and a target position visited by the crane without intermediate shelf access. Note that a move's target position needs not be predefined, but choosing one can be part of the crane scheduling problem. For instance, if no dedicated storage policy is pursued, i.e., each SKU can be stored at any shelf, any currently open location might be suited for a storage request. All moves between two successive visits at an IO-point are denoted as a (command) *cycle*. The crane scheduling problem considered in this paper consists in a sequencing of storage, retrieval and/or reshuffle orders, (potentially) identifying suited storage locations, and (potentially) unifying multiple moves to cycles in order to optimize some objective function, which is predominantly the minimization of total travel time.

This (positive) definition of the paper's scope is now amended by a (negative) demarcation from related fields. In a first step, we exclude other decision problems in the field of ASRSs and related storage and retrieval system for other items, typically, not handled in traditional warehouses, which is schematically depicted in Fig. 1(b).

Once the decision for installing an ASRS is made, its *layout* needs to be determined. In this context, especially the number and length of aisles, the height of the racks, their segmentation into equally sized or diverging shelves, the location of one or multiple IO-points, and the crane configuration (e.g., one or multiple shuttles) are to be determined. Furthermore, at this point in time the control policies for, e.g., determining storage locations, dwell points and crane schedules need to be selected. Decision support in this early stage is especially provided by simulation studies often augmented with analytical models for approximating the performance of a potential ASRS configuration. A more detailed overview of previous research effort in the field of layout planning is provided by Roodbergen and Vis (2009) and Gagliardi, Renaud, and Ruiz (2012).