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Automated and Robotic Warehouses: Developments and Research Opportunities

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The first automated, high-bay, warehouses were introduced some 50 years ago. Since then, developments have continued at a rapid pace. Initially, automation was mainly focused on pallet warehouses with bulk storage facilities. A major reason was to increase the storage density, which could be achieved by making the warehouses higher. Later, mini-load warehouses and order picking warehouses were also automated. In this paper we will discuss the different types of automated systems as well as a number of scientific results that are now known about such systems. We will first discuss storage systems for unit loads (bins and pallets). This will be followed by order picking systems from which individual packages can be picked. Finally, we will provide our future expectations of warehouse automation.

1. SYSTEMS FOR UNIT LOADS

1.1. Automated unit load warehouses with aisle-captive cranes.1

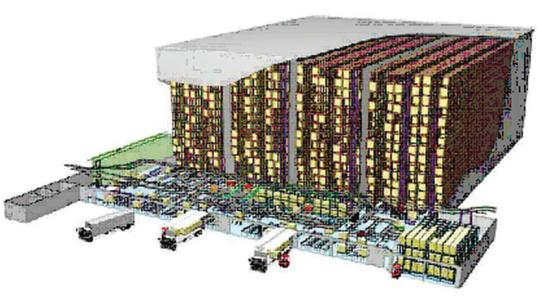

Fig. 1. Automated high-bay warehouse for pallets with aisle-captive cranes.
Source: Daifuku America

These warehouses have already been around since the sixties. Many variants have been developed since then. Figure 1 shows an example of such a warehouse. In such a warehouse (AS/RS: Automated Storage and Retrieval System), an aisle-captive crane retrieves a load, usually from a conveyor, and automatically stores it in the racks at heights of up to 30 m. Driving and lifting take place simultaneously. Retrieval is exactly the opposite. It is also possible to carry out so-called dual command cycles, wherein a storage command is combined with a retrieval command, which saves one movement per dual command cycle. If the stored unit loads consist of bins, the system is also referred to as mini-load. Many studies have been conducted into such systems. One of the first scientific articles was written by Bozer and White and dates from 1984. Among other things, they calculated the cycle time of the crane for single command cycles, for the situation in which any location within the rack is equally likely for the crane to travel to. The average cycle time for a single command cycle (back and forth) is $E[T] = (1 + \frac{(ty/tx)^2}{3}) \cdot t_x$, where t_x is the travel time to the farthest in the rack, and t_y is the lifting time to the highest location in the rack. It is assumed that the travel is the lifting time to the

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highest location in the rack. It is assumed that the travel time to the farthest location is longer than the lifting time to the highest location and the fact that the crane drives and lifts simultaneously has been taken into account. Therefore, if the travelling distance of an aisle is 100 s and the lifting height is 100 s, the average travel time for a single command cycle (without picking up and dropping off the load) is 133 s. This formula can be used to obtain further results, for example, to calculate the optimal ratio between the length and height of an aisle. This proves to be square in time, meaning the travel time to the farthest location and the lifting time to the highest location are identical. Since a crane travels approximately four times faster than it lifts, the aisle should be four times longer than high to achieve a minimal cycle time. The formula can also be used to determine the optimal number of aisles and cranes, including optimal dimensions, at a given storage capacity and throughput.

Over time, the formula has been adjusted to match different storage strategies (such as ABC, or turnover frequency class-based, storage), dual command cycles, different location of the pick-up and delivery point (the above formula assumes one such point, at the head of the rack), multiple load handling devices, combination with order picking stations, etc. In the case of ABC storage, the items are divided into classes (e.g., 3: A, B, C), based on turnover rate. The locations are also divided into groups based on distance to the pick-up and delivery point. This ensures that the items from the class with the highest turnover rate are located closest to that point.

Fig. 2 provides an overview of AS/R systems, based on the type of crane, the type of loads and the types of racks that may be used. The overview also includes carousels and mobile racks, which are usually not considered as part of the classical AS/R systems.

An important impetus for cycle time calculations with ABC storage dates from 1976, by Hausman,Schwarz and Graves. They calculated the optimal class boundaries for known ABC demand curves, for example, 20/70 demand curves, whereby 20% of the products is responsible for 70% of the demand. In the calculation they took account of product replenishment according to a continuous review <s, Q> reordering policy, with order quantity Q being equal to the optimal order quantity. However, they did not take account of the fact that the fewer storage classes there are, the more items are stored in each class, and the less space is required per item, since the space within the classes can be shared by the items. If there are more classes and fewer products are stored per class, it is more complicated to share the space between products and more space is required per product. This means that an optimum number of storage classes can be distinguished. In practice, the optimal number of classes turns out to be small (about 3 to 5) but the cycle time is relatively insensitive to the exact number. At such a limited number of classes, products can perfectly share the space available in the class. However, the required number of locations on top of the average stock level quickly amounts to an additional 40% (Yu et al., 2015).

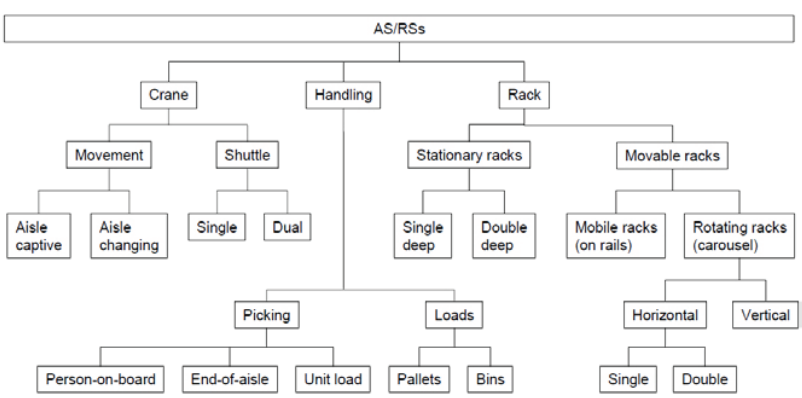

Fig. 2. Overview of AS/RSs (AS/R systems).
Source: Roodbergen and Vis (2009)

1.2. Compact storage

Cranes equipped with satellites.

The AS/R systems can also be used to store loads double deep in the racks. To this end, the cranes can be equipped with double-deep telescopic forks. Often satellites are used if even deeper storage is required. Cranes (or trucks) equipped with satellites have been on the market for several decades and are widely used in refrigerated and frozen storage, where savings in the space to be cooled immediately reduce costs. Other forms of multi-deep storage racks contain mounted conveyors (gravity-flow or powered conveyors), or they are multi-deep racks with multiple, independent satellites. The latter systems are also referred to as AVS/R (automated vehicle-based storage and retrieval) or SBR (shuttle-based retrieval) systems, and are discussed below. For crane systems with multi-deep storage, the first question is how deep the storage locations should be (number of unit loads stored behind each other in one lane). Racks with locations that are too deep have a low location occupancy rate. This effect is also called „honeycombing" (see Tompkins et al., 2010). Insufficiently deep locations require too many locations per product, as a result of which the aisles will be too long, thus increasing the travel time of the crane. In general, all the loads of one product and batch are stored in one location.

A lot of research has been conducted into such aisle-captive cranes with multi-deep storage. It is known, for instance, how to calculate the optimal location depth, how to calculate the crane travel time, what the optimal storage strategies are and in which order the commands should be performed in order to minimise the total time.

Storage on shuttles

Recently, new multi-deep systems have been developed, whereby each load is placed on a shuttle that can move in both directions. Such systems are used e.g. in automated parking garages, particularly on locations where parking is expensive. Fig. 3 shows an example of a system using shuttles and crane for car movement. The advantage of shuttle-based storage is that multiple shuttles can move at the same time, thus achieving a high throughput. In addition, it saves a lot of space, since no transport aisles are necessary. This is why sometimes such systems are called very-high density storage systems (Gue, 2006) or puzzle-based storage (PBS) systems (Gue and Kim, 2007). Depending on the configuration (number of empty positions: 0, few, or many), whether multiple loads in a row can move simultaneously or not), it is known how to calculate the cycle time, what the effect is of the class-bound storage and what the optimal length, width and height ratio of these systems is (Zaerpour et al., 2017a, 2017b, 2017c). If the lift is located in a corner of the system, a cube-shaped warehouse (measured in time) almost (but not quite) minimises the cycle time.

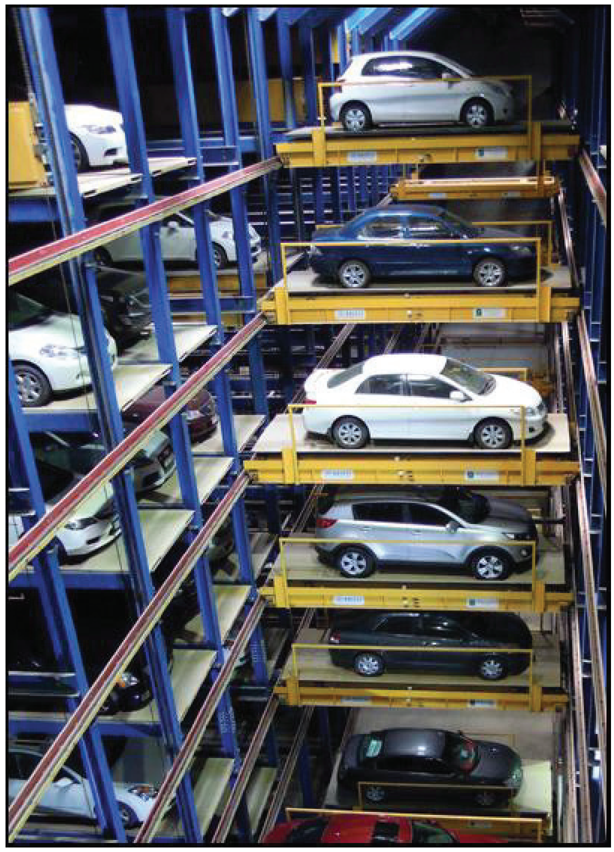

Fig.3. An automated, compact parking garage. Source: avgparking.com

Recently, new technologies have emerged for moving the products in such compact storage systems, including conveyor based solutions (based on modular, click and work conveyor blocks, Gue et al., 2014), and solutions using autonomous automated guided vehicles (AGVs). Such solutions allow a great amount of freedom in use, depending on the software to control the products handled on the grid. For example, moving to designated outputs (Gridflow), or sorting (Gridsort), systems developed by the group of Professor Kai Furmans. Some express parcel handlers use AGV-based solutions as a fully flexible and scalable parcel sortation system from many inputs to many outputs (Shentong, 2018).

1.3. AVS/R systems

Autonomous vehicle-based storage and retrieval (AVS/R) systems are aisle-based systems that do not use cranes, but shuttles, which can drive in the x and (sometimes also in) the y-direction on any level in the aisle, and lifts that can move the shuttles (or the unit loads) between the levels and to the depot. Such systems are increasingly popular because nowadays, the investment is similar to that of AS/R systems, while they offer a much higher retrieval capacity and are significantly more flexible in capacity. By using additional shuttles the capacity can easily be increased, and by removing shuttles, capacity can be decreased. Fig. 4 shows an example of such a system.

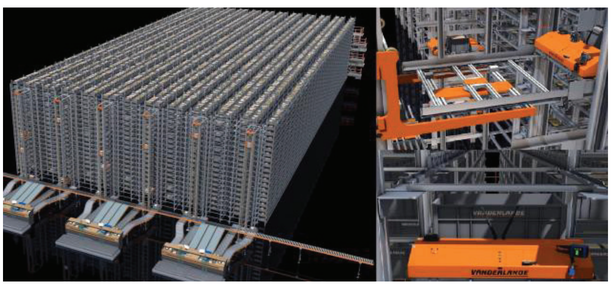

Fig. 4. An AVS/R system with autonomous vehicles at every level (see picture on the right) and lifts at the front. Source: Vanderlande.

Malmborg (2002) was the first to study these systems. By now, a large number of studies has been conducted into these systems. The performance (throughput, mean throughput time of an order, and response time) can be estimated reasonably well as a function of the number of vehicles (see Roy, 2011). This can be used to calculate the optimum length to depth ratio of the racks, or the required number of shuttles in the system. Meanwhile, shuttle-based systems for compact (multi-deep) storage have also been developed (see Tappia et al., 2017).

1.4. Autonomous robotic unit load systems

New variants of AVS/R systems have come up recently. A recently introduced robotic system is the

AutoStore system, in which autonomous mobile robots move on a grid frame above the storage stacks and take unit loads (product bins) from the slots to bring them to the picking stations. A main question is whether multiple loads of a product should be stored in dedicated or in shared stacks (i.e. a stack is shared with other products). A disadvantage of shared stacks is that it may take more time to retrieve a unit load of a product, as the bins may need to be reshuffled before the required bin can be retrieved. However, on the other hand, shared stacks require less stacking space and less space is lost due to honeycombing, which implies that the grid can become smaller to house the same number of products. This problem has recently been studied by Zou et al. (2018b). They show that for most cases (i.e. shape of the demand curve, required throughput, number of products to be stored and replenishment policy parameters) shared storage leads to substantially cheaper optimal (with respect to operational costs) systems than dedicated storage, for the same throughput time.

Another recently introduced AVS/R system no longer needs lifts, but the autonomous vehicles can drive into an aisle, climb to the right level, retrieve a load, and bring it to the depot. Such systems have not been widely researched yet. An exception is Azadeh et al. (2018).

1.5 Robotic moveable rack system

Another type of autonomous robotic unit load system is the Robotic Moveable Rack (RMR) system. This system was conceptualized by Jünemann (1987) and first brought to the market by Kiva systems (now Amazon Robotics). By now there are about 30 suppliers that supply these systems, in Europe, India, while most of them are located in China. In these systems, complete racks („pods") carrying multiple products are moved by robots. If a product is requested by a customer, a robot moves to the rack in which the product is located, picks it up and takes it to a picking station. There, the robot awaits its turn with the rack. The picker takes the requested products and adds them to the bin with the customer order waiting at a different rack, also on top of a robot. The robot then returns the rack with the product to storage, at a location that takes account of the expected moment the item will be needed again. The storage location is therefore fully dynamic. In principle, the layout can be fully adapted both dynamically and automatically to the product and order characteristics. The systems are ideally suited for Internet retailers who require the picking of relatively small orders (meaning not too many items that should be consolidated per order) from a wide product range. The performance of RMR systems has received some academic research attention recently. Examples include Lamballais et al. (2017a), studying the optimal shape of the storage area, and the impact of robot pooling strategies, Zou et al. (2018a), studying the impact of battery charging strategies, and Boysen et al. (2017) and Lamballais et al. (2017b), studying the impact of storage strategies on performance.

2. ORDER PICKING SYSTEMS

The systems discussed in the previous section are unit load systems, which are capable of storing or retrieving unit loads. In addition to systems for unit loads, an increasing number of systems for (semi) automatic picking of goods from racks has been developed. A-frames, fully automatic machines capable of placing products in a passing bin, have been in use in the pharmaceutical industry for some time now. These dispensing machines can achieve a very high picking capacity for products that are suitable for automatic ejection. This section consecutively discusses automated replenishment systems, robotic mobile rack systems and systems with automatic trolley load.

2.1. Automated replenishment systems

Some warehouses can automatically replenish the pick locations, from which items are picked manually or automatically. Products are stored in bins in a mini-load warehouse, which complements a flow rack warehouse. Fig. 5 shows a picking station with flow racks, whereby the locations are automatically replenished by a mini-load system.

Only fast-moving products are stored permanently in bins in the flow racks at the picking stations. The other product bins are delivered just-in-time by the mini-load system. Empty bins and items that are not needed for the next batch are taken back by the mini-load crane. Some studies

Fig. 5. Picking station with automatic replenishment from the back (Technische Unie).

have been conducted for such systems, especially regarding good system designs (layout, required number of picking stations), depending on the necessary storage capacity and the order profile. The design is especially complicated when picking stations are connected in series and order bins must visit several stations. As the number of picking stations increases, the number of stored products per station decreases as well as the size of the station, thus decreasing the walking distance. This results in fewer, but also faster, picks per bin per station. On the other hand, a bin should visit several stations and probably wait more often or longer in total. This trade-off results in an optimum number of stations. The allocation of products to stations also affects the performance. Research into this has led to models that can quickly and accurately calculate and even optimise different configurations. See Van der Gaast et al. (2013). Other researchers have studied the integrated performance of pick stations in conjunction with automated unit-load retrieval systems that supply the pick stations, e.g. Tappia et al. (2018) and Füßler and Boysen (2017).

2.2. Pick support AGVs

Most warehouses still use manual picker-to-parts order picking methods, where the picker moves a pick cart (sometime on a motorized order pick truck) and travels along the aisles to pick products from pallet racks. A simple way to automate this process, without re-layouting, is to use autonomous pick-support automated guided vehicles (PS-AGVs) to transport the pick cart (e.g. a roll cage). The AGV automatically follows the picker closely. Once the roll cage is full, the AGV brings it to the depot and it is automatically replaced with a new AGV carrying an empty roll cage. The picker can continue the picking route without returning to the depot. Many suppliers have developed such systems. Next to systems following the picker, also systems exist where the picker follows the vehicle. See Fig. 6 for some examples.

Some systems automate the entire picking process. An example is the TORU™ picking robot, which can autonomously retrieve items from the storage shelf and bring them to the depot.

The differentiating characteristic of PS-AGVs is the collaboration between human pickers and AGVs. To date, no papers exist that study the interaction between humans and such picking robots, or that model the performance of these automated systems.

2.3. Automatic roll cage stacking

Retail warehouses have been experimenting with automated picking and roll cage or pallet stacking of store orders for about fifteen years. Typically, products received on pallets are stored in an automated bulk warehouse, usually a high-bay AS/R system. Pallets are then automatically retrieved, the cartons are automatically removed from the pallets and they are individually stored, e.g. on a tray, often in an AVS/R system. From this system, the cartons are automatically ejected and sequenced in the specific stacking sequence as required by the store and the roll cage in which they must be stacked. The stacking sequence takes care of family grouping (products of different families must not be mixed toguarantee rapid restocking in the store), product weight and fragility (light and fragile products on top), and warrants high roll cage filling rates. Robot stations then take care of the actual roll cage stacking. If the roll cage is not to be shipped to the store yet, it may be temporarily buffered in an AS/R system, from which it is retrieved in the reverse unloading sequence of the truck route, when the truck is ready to be loaded. Fig. 7 sketches the flow and typical systems used in these fully automated warehouses.

The first fully automated retail warehouse was possibly the Edeka warehouse in Hamm (Germany), where also the roll cages are filled automatically. Since then, many fully automated warehouses have been realized, most of them in Europe and some in the USA.

Fig. 6. PS-AGVs. Left: Locus robotics, right: TMHE Pick-n-Go system.

3. THE FUTURE

Research on automated, or even robotized, warehouses is not yet abundant. With the rise of new technologies, new questions arise and need answering. New models must be made to evaluate performance of the systems and aid in answering design and management questions.

Is the full automation of both storage and picking processes the future? The main advantages of automation are the saving of space (an automated warehouse can be built on a smaller area), savings in labour costs (a 24/7 operation can be achieved relatively easily and inexpensively), availability (it is not always easy to find unskilled personnel willing to do warehouse work), and savings on other operational costs such as heating and lighting. Automation of storage and order picking, however, still has limitations: it requires considerable scale and a long-term vision (investments are high and can only be earned back in the medium or long term). Furthermore, the picking part of the process is still hard to automate and may need to be carried out manually. This part of the process is usually not the

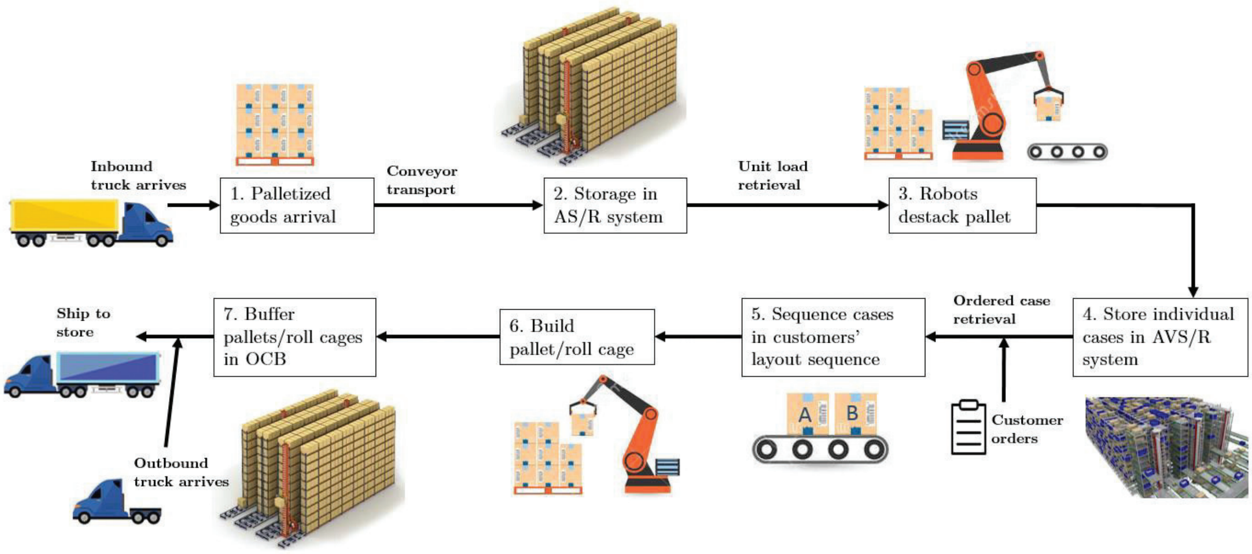

Fig. 7. Flow in a typical fully automated warehouse. OCB=order consolidation buffer. Adapted fromAzadeh et al. (2017).

most interesting work. Especially not if a person is considered an extension of the automation solution. In short, manual warehouses will continue to exist for the time being, despite the new developments, even in economies with high labour costs. Logistics remains a people business and well-managed warehouses perform significantly better in the areas of productivity, process innovation, quality and safety (see De Koster et al., 2011, De Vries et al. 2016, and other literature).

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