Warehousing 2030

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1 Introduction

Automation has gradually changed the type and nature of operations. Automated guided vehicles, or AGVs, were invented in the 1950s. The first fully automated warehouse system, a so-called AS/R system for automated storage and handling of pallets, was introduced in the 1960s by Demag. These systems were later further developed to also handle cases and totes (so-called miniloads). In the late 1960s and early 1970s, automated tilt-tray sorters were introduced with large sorting throughput capacities. Other breakthroughs in material handling technologies were the shuttle-based storage systems of Savoye (introduced in 2000) and the Kiva robots (in 2003), now Amazon Robotics, in which low-sized robots drive underneath the storage racks ("pods") to lift and transport them to order pick stations. Recently, applications with autonomous mobile robots (AMRs) have seen the light. These are basically a further development of AGVs. They are equipped with more sensors; have SLAM (simultaneous localization and mapping) technology, more autonomy, and decentral control; can avoid obstacles; and have possibilities for path re-optimization (see Fragapane et al., 2021).

Software also developed rapidly. Warehouse management systems (WMS), systems that manage inventory on storage locations and that guide all flows in the warehouse, are commonly used. In highly automated warehouses, they work together with warehouse execution systems that control the movements in different automated material handling systems.

Another breakthrough (around 2000) was the development and introduction into practice of mixed-case palletizing software that allows to calculate efficient stacking patterns in real time for pallets and roll cages. These algorithms allow now fully robotized mixed-case pallet stacking and are used, in combination with product

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sequencers, to create custom-built loads more densely stacked than humans could typically do this.

Recently, we have seen the advent of real-time data capturing through sensor technologies, allowing online decision-making. People and objects can be equipped with sensors, and can communicate with their environment, enabling an "Internet of Things" (IoT). Using these data in smart real-time decision-making is still in its infancy.

In the remainder of this chapter, we discuss some of these developments and provide an outlook for the warehouse of the near future. In particular, we discuss warehouse centralization and scale, various robotic technologies, collaborative robots, picking and sorting robots, the role of people and management in the warehouse, safety on the shop floor, sustainable warehouses, and IoT technologies, before we conclude. We also highlight implications for supply chain talents who are interested to pursue a career in a warehousing-related field.

2 Warehouse Centralization and Scale

Over time, warehouses have grown larger. In the USA, according to CBRE (2020), the average size of new warehouses completed between 2012 and 2017 increased from about 7060 m^2 to 17,200 m^2, while the free height increased from 8.7 m to 9.8 m, since the earlier peak in development between 2002 and 2007. In Europe and Asia, a similar growth in size can be observed. In Germany, the Netherlands, and Belgium together, 424 mega distribution centers, with a size of 40,000 m^2 and beyond, have been built between 2013 and 2019, including the mega Amazon warehouse near Dortmund of 225,000 m^2 (Buck and Bulwiesenga, 2020).

The growth in size has multiple causes. Since the 1980s, many companies have started consolidating warehouse operations. Rather than distributing products from multiple countries or states, consolidating operations in a smaller number of larger operations benefits from economies of scale and scope, reducing cost per unit shipped. In addition, assortments have grown, particularly in e-commerce warehouses, where the assortment size is not limited by available store shelf space. The degree to which consolidation pays off depends on the business, i.e., business-to-business- or business-to-consumer-type operations, and the product. Business-to-business operations typically allow somewhat longer but accurate lead times. Perishable products require short lead times and often must be stored closer to the point of consumption.

Due to the increasing competition on short lead times, particularly in e-commerce, it can now be observed that in addition to the large facilities, also smaller facilities are built, closer to city centers. As an example, Amazon recently built a cross-dock facility close to Amsterdam, allowing the company to distribute its products with very short and accurate lead times to customers in the city (Logistiek, 2020). Food home shopping has grown tremendously over the past years, partly due to Covid-19. This also has led to many new, medium-sized (5000–15,000 m^2) grocery warehouses, close to urban areas. Tesco in the UK is investing in even smaller facilities, so-called micro-fulfilment centers placed in the back of large stores, for online grocery picking (The Grocer, 2020). These centers make use of robot technologies.

The expectation is these trends remain; we will see both larger warehouses, focusing on economies of scale and scope, and also an increase in smaller e-commerce warehouses and cross-docks (including public city hubs) close to city centers, focusing on speedy delivery. In Western Europe, there is hardly space left for mega warehouses, although demand for them still exists. This may lead to multistory facilities like in heavily populated areas in Asia (e.g., Japan, Korea, Singapore, or Hong Kong). Such multistory facilities will also become heavily automated to efficiently utilize the available floor space. New robotic systems allow compacting the storage space paired with high throughput capacities.

3 Warehousing Technologies

This section discusses new automated warehouse technologies introduced in the last decades. Figure 1 (modified from Azadeh et al., 2019a) gives an overview of automated order picking systems.

3.1 Warehouse Robotics: Shuttle Systems

Several systems have been developed, deploying robots. Most of these systems are so-called goods-to-man (GtM) systems, where robots (AMRs) or shuttles (these are rail-guided and have less freedom in movement than AMRs) retrieve loads from a storage location and bring them to pick stations, after which the loads are returned to storage. The AMRs also transport loads from replenishment (restocking) stations to storage. Four types of shuttle-based, GtM systems have become dominant (with some subsystems). These are briefly discussed below, while AMR-based MtG ("man"-to-goods) systems are treated in Sect. 3.3. Azadeh et al. (2019a) give a fairly complete overview of the different robotic systems used in warehouses. Below, we discuss AVS/R ("autonomous vehicle-based storage and retrieval," also called shuttle-based storage and retrieval) systems, puzzle-based storage and retrieval (PBS) systems, mobile robotic fulfilment (MRF) systems, and hybrid shuttle/AMR systems.

AVS/R Systems

AVS/R systems consist of aisles with racks and shuttles driving at different rack tiers to retrieve unit loads (e.g., totes) from the racks at both sides of the aisles. Lifts and conveyors are used to transport the totes between the tiers and pick stations at the ground floor. Many variants exist, e.g., with centralized lifts or with lifts per aisle or with roaming shuttles that can move into the lift, travel to the pick stations with a load, and move back to another tier to store the load. Some variants allow deep-lane storage (particularly in use in production warehouses with pallet storage; see Tappia

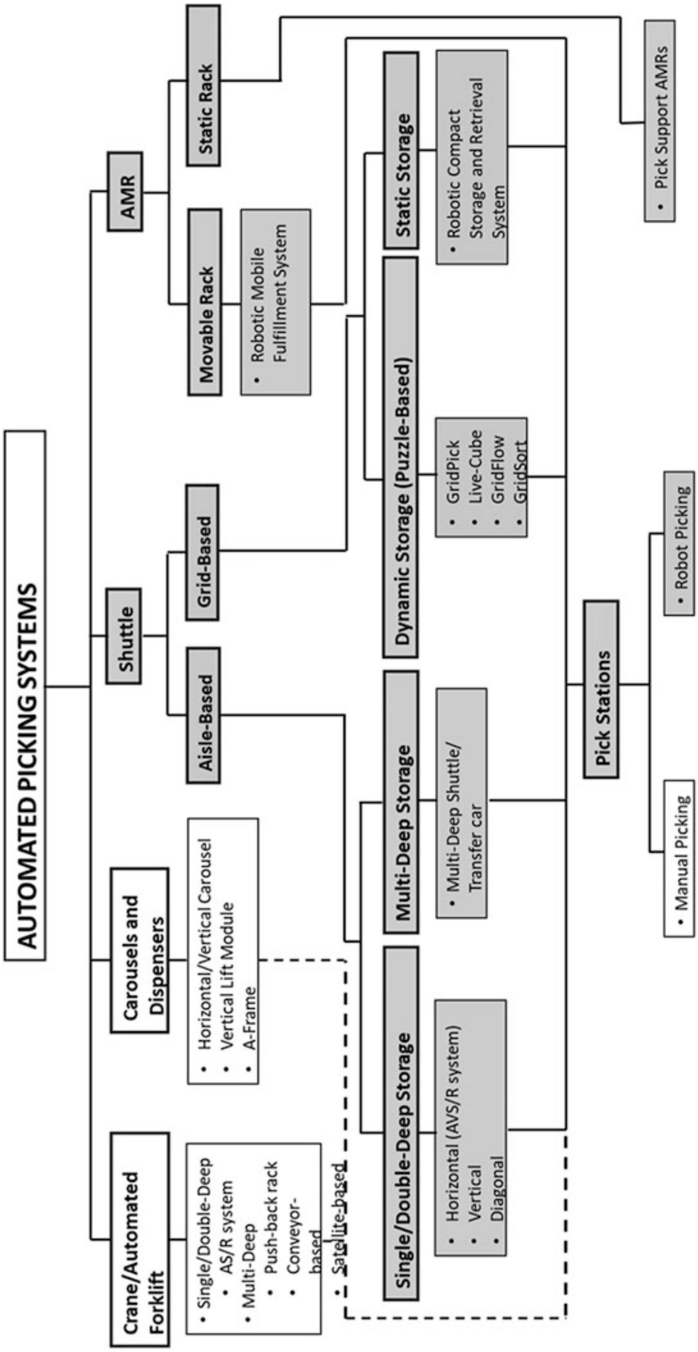

Fig. 1 Overview of automated order picking systems. Gray-shaded robotic systems are discussed in this section. Modified from Azadeh et al. (2019a)

et al., 2017). The technology for such systems has matured and all major material handling suppliers can provide them. Tappia et al. (2019) compare the performance of such systems with AS/R systems connected to pick stations and conclude that using an AVS/R instead of a traditional AS/R-based storage system yields lower investment costs in both the upstream rack system and the downstream system (i.e., smaller number of picking stations), paired with a lower total throughput time to realize a given order arrival rate. This, combined with some flexibility in throughput capacity in AVS/R systems (by adding or removing shuttles), explains why crane-based AS/R systems are less frequently used for order picking.

Malmborg (2002) was the first to analyze AVS/R systems. By now, many studies have been carried out on these systems. The performance (throughput capacity, average throughput time of an order) 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, the number of lifts required, or an adequate distribution of the shuttles across the system. Also operational policies (dwell point choice for the vehicles, vehicle to load assignment policies) can be analyzed.

Puzzle-Based Storage Systems

One of the disadvantages of AVS/R systems is that aisles are still required, occupying precious warehouse space. Recently, multi-deep systems have been developed that are even more compact. Each load is placed on a shuttle (or on a conveyor unit) that can move in four horizontal directions. Very-high-density storage is possible and transport aisles are no longer required. Only few spots must stay open to help maneuver a requested load to a lift located along the periphery of the system. Such systems are used in parking garages in major cities, on locations where land is very expensive, but also in warehouse storage and item sorting. Figure 2 shows an example. 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. Gue (2006) was the first to study these systems. By now, it is known how to calculate the cycle time, what the effect is of class-based storage, and what the optimal length, width, and height ratio of these systems is (Zaerpour et al., 2016). If the lift is located in a corner of the system, a cube-shaped warehouse (measured in time) almost (but not quite) minimizes the cycle time. Not only shuttles can store and transport loads, but also conveyor modules can be used, or AMRs (see Furmans et al., 2010). Nearly all literature assumes that each load is carried by an individual shuttle (or AMR). In medium-demand systems, it is much more economical to have a few coordinated shuttles work together to dig out a requested load. This is studied by Alfieri et al. (2012). However, more work on such systems is required.

Robotic Mobile Fulfilment Systems

In a robotic mobile fulfilment (RMF) system, robots (AMRs) capable of lifting and carrying movable “pods” (shelf racks) retrieve these storage pods and transport them to the pick stations. While empty, the robots can travel underneath the pods. To retrieve a pod, travel aisles are needed. The system is flexible in throughput capacity,

Fig. 2 An automated, compact parking garage. Source: avgparking.com

as more robots and pods can be added to the warehouse. It is also flexible in layout as the pods can be grouped differently in a dynamic fashion. The RMF system was conceptualized by Jünemann (1989) and was US patented by KIVA Systems Inc., which then was acquired by Amazon and rebranded as Amazon Robotics™. Today the system is operational in many Amazon facilities with more than 100,000 robots in total. Meanwhile, many other providers have entered the market with mobile racks in combination with rack-carrying robots.

Due to the rapidly increasing number of implementations, the system has drawn much attention from researchers. By now, about 15 papers have appeared in high-quality journals and many more will appear in the near future. Items covered include layout optimization, storage allocation and item dispersion over pods, product allocation to pods, allocation of orders to pods, allocation of orders and robots to workstations, and allocation of workers to pick or replenishment stations. See Azadeh et al. (2019a) for a review. The big difficulty is, however, that all problems combine and jointly impact performance (throughput capacity, response time). The work by Merschforschmann et al. (2019) studies, using large-scale simulations, the problems in combination. However, more study on integrated control policies and optimization is required, as great benefits can be achieved by taking coordinated decisions.

Hybrid Shuttle/AMR Systems

These systems are fairly recent. They combine properties of both AMR systems (like relatively freely moving in the system) with the guided movement that shuttles exhibit. Examples include the grid shuttles of AutoStore™ and Ocado™ and the rack-climbing robots of Opex™, Exotec™, and Attabotics™.

The grid shuttle systems have become very popular in practice, in a very short time. The items are stored in dense storage stacks with a grid on top. In each cell of the grid, bins that contain the items are stacked on top of each other and form the storage stacks. The workstations are located at the ground level next to the storage stacks. Robots roam on the grid, on top of the storage block. They can lift the top bin from a stack and, if necessary, temporarily place it on a neighboring stack. In this way, the requested bin can be dug out and brought to a workstation for picking. After picking, the robot (shuttle) returns it to a storage stack. The systems have become popular, e.g., in e-commerce fulfilment centers, due to their flexibility and smooth installation. It is possible to expand the grid, or the number of robots without shutting down the system. Surprisingly, little research on how to optimally design or control the system, or when to select such a system, is available. The paper by Zou et al. (2018) is an exception.

The rack-climbing robots of Opex, Exotec, and Attabotics are a new development. They eliminate the need for lifts, as the robots can access all tiers by just climbing the racks. The Exotec robots can also roam the aisles and the warehouse and transport a retrieved tote directly to a workstation. Azadeh et al. (2019b) address the problem of how to route rack-climbing robots, taking into account potential blocking and congestion delays in the rack.

3.2 Warehouse Cobots: AMR Systems

Order picking deploying AMRs is rapidly increasing in popularity. Different variants exist. In one variant a human collaborates with the AMR (or "cobot": collaborative robot), where the cobot is responsible for all transport of the collected items and the human picks the products from the racks. Once the order pick totes, or roll cages, are full, the cobot is automatically swapped with a new cobot carrying empty pick totes. The picker can continue the pick route without returning to the depot, and the cobot automatically transports the full pick totes to the packing stations. Many suppliers now offer such pick-support cobots. The system can be introduced in a manual environment with pickers on foot, using pick carts. As the business expands, gradually more cobots can be added. In some variants the human can even be replaced by a specialized picking robot. However, due to the complexity of the picking task, particularly for items stored in shelf racks, this has not shown to be very successful yet. Optimizing cobotic order picking systems is still very challenging, for example, how to link which cobot with which picker at which point in time? For a fixed assignment, Lee and Murray (2019) solve a vehicle routing problem to minimize the time to pick all items on a pick list. "Zoning" the warehouse is another strategy: the cobots transport the order totes from work zone to work zone, until the last item has been added, after which the cobot brings the complete order to a packing station. However, also more dynamic collaborations exist, where pickers actively and dynamically have to find robots or vice versa. Azadeh et al. (2020) show that also dynamically switching the number of zones can be beneficial, especially in omni-channel warehouses with a large variety in order sizes.

To pick cartons from pallet racks, ride-on cobots have been introduced by several order pick truck suppliers. In this variant the order picker can drive the cobot-truck to a location in the pallet storage area, pick the product, and drop it in a roll cage or on a pallet carried by the truck. From this position onward, the picker can decide to walk or drive. If the picker walks, the cobot will follow the picker in close proximity. Such cobot-trucks can substantially reduce the total travel time, and, as they are only slightly more expensive than conventional order pick trucks, they are now rapidly being introduced in many carton-pick warehouses.

The system by HAIPICK™ is another interesting development. It is an AMR-based goods-to-man system which retrieves totes from a rack and transports them to a picking station. The AMR contains a lift and can retrieve multiple totes, also from high tiers, thereby collecting all totes required for the complete order.

3.3 Fully Automated Order Picking

A distinction can be made in automated picking in goods-to-man (GtM) and man-to-goods (MtG) systems. The biggest successes have been achieved in combination with GtM systems. At this point in time, it is possible for a static robot to pick mixed items from a tote that has been retrieved by a GtM system, at high speed, with relative high accuracy. The problem lies still in the variety of products. Different products might require gripper swapping (e.g., mechanical fingers or a suction head), and the right product unit has to be selected (e.g., one not partially buried under other units) to be fetched at the right position. The robot is equipped with a 3D camera which identifies the object. Two main types of identification algorithms are used, based on deep learning and training on objects, or based on a library with generalized objects and training on object geometries. The latter reduces the learning time substantially. For simple, box-shaped small products, the system works well, although human supervision is still necessary. Also in MtG systems, automated order picking has emerged. The TORU™ picking robot (an AMR) by Magazino is an example. In this variant, the AMR automatically goes to the picking location and picks the item without any help from a human. This puts some restrictions on the size, weight, and shape of the item, as well as on the way it is stored. In general, automated picking of a variety of products from locations still brings many technical problems which will not all be resolved in the coming 10 years.

3.4 Other Robot Applications

Robots are applied for other processes than order picking in warehouse and cross-dock facilities. These processes include (mixed-)pallet stacking and destacking, offloading sea containers, sorting parcels, security surveillance, and inventory scanning and management.

Not all applications are equally successful. In fall 2020, Walmart abandoned the Bossa Nova store inventory scanning and management robots, after it had previously claimed successes (Taulli, 2020). Scanning and measuring store inventory is a task that is hard to automate, since products can be stored multi-deep with limited visibility and since items can be very similar but still different. In a warehouse this may be easier, but also their inventory scanning (e.g., with drones) still requires human supervision. Two robot applications have seen a breakthrough in the last decade: surveillance and sorting. Sorting robots (AMRs equipped with, e.g., a conveyor or tilt-tray mechanism) were used in manufacturing on a small scale and were introduced in China by several parcel carrier companies in large-scale applications, with hundreds of sorting robots. They require less floor and building space than a conventional cross-belt or tilt-tray sorter, which makes them rapidly cheaper for not too high throughput capacity requirements (Zou et al., 2021). They also allow flexible layouts as it is possible to increase the number and position of input stations dynamically. Also the allocation of robots to inputs and outputs can be changed dynamically. This allows the system to cope with temporary peaks.

4 Impact of Recent Trends

This section discusses three recent trends: continuing focus on safety and labor circumstances, sustainable warehouses, and use of Internet-of-Things technology in the warehouse.

4.1 Safety

Warehouse safety is receiving much attention from practice and research. The reasons for companies to engage in worker safety vary, but they include the high costs resulting from having non-safe work environments (e.g., direct and indirect costs from accidents), the belief that safe work environments align with performance (productivity and quality), and the desire to create good and stimulating work environments. In Western Europe, the latter factor is also triggered by the ageing work force and the shortage of qualified personnel in specific regions. Research has demonstrated that the company's safety culture and the warehouse leadership have an impact on worker behavior and thereby on accidents (De Koster et al., 2011; Hofstra et al., 2018). According to work of De Vries et al. (2016c), the manager's prevention focus is associated with a reduced number of accidents, and focus on safety does not trade off with productivity.

Increased automation may also be instrumental to create a better safety climate and to reduce accidents. Most automated equipment strictly separates human from automated work. On the other hand, collaborative robots introduce a new risk as people and robots work simultaneously in close proximity. Such robots therefore move at low speeds to reduce the risk. It is somewhat surprising that particularly the robotized US warehouses of Amazon (which have a GtM operation with physical separation of people from robots) have high accident rates per employee (Evans, 2020). These accident rates are strongly correlated with high peak loads and work stress (Evans, 2020).

Still, with proper deployment, it should be possible to lower the per capita accident rates in automated facilities. Proper robot deployment may also help to create and maintain distance between workers in times of a pandemic.

4.2 Sustainable Warehouses

According to the Global Alliance for Buildings and Construction (2018), buildings (39%) and distribution processes (23%) are a large source of global greenhouse gas and fine particle emissions. For the buildings, this is both through the production of the materials and the construction process (11%) and through the building operations (28%). A large part of the building sector emissions is from carbon, embodied in the buildings (28%), which come available over time. A sizeable percentage of these buildings include warehouses. Operational emissions can be reduced in several ways and most of these go hand in hand with reduction of cost of energy. It is not surprising that many new warehouses in Western Europe apply for BREEAM, LEED, or other sustainability certificates. Embodied carbon can be reduced by going for circular buildings, where use is made of recycled materials and components and where the building can be disassembled into reusable materials and components. The objective is to have a complete circular, environmentally neutral building. This is, however, still in its infancy.

The most popular measures that are gradually becoming a standard include using bioclimatic architecture (shape and orientation of the building), using renewable heat and power (e.g., by equipping the roof with solar panels and storing redundant energy), taking measures to boost energy efficiency (e.g., insolation of buildings, high-performing glazing and windows, minimization of thermal bridges at loading docks, LED lighting, using more energy-efficient material handling equipment), increased recycling, and recovery of energy (heat recovery) and materials (e.g., packaging materials, or water). The major next step is to become a net energy producer.

Part of the measures that should be taken for a BREEAM certificate overlaps with measures that are needed to secure a safe workplace (e.g., separation of traffic flows), or are needed to comply with general laws (waste separation), and are therefore beneficial in general. As sustainability becomes more closely tied with corporate reputation, governmental regulations tighten, and investors and developers aim for future-proof facility portfolios, carbon-neutral warehouses and facilities running on clean energy will gradually become dominant.

4.3 IoT in the Warehouse

Internet-of-Things (IoT) technologies are based on continuously sensing and capturing process data and communicating these between connected actors and devices. The objective is to use these data to optimize decision-making. Many data are kept, stored, and used for process control in warehouses. This started some decades ago with paperless warehouses where, e.g., pick instructions were conveyed to workers via mobile devices such as RF terminals with scanners or pick-by-light or pick-by-voice systems. Nowadays, also pick by AR (augmented reality) glasses are deployed in some warehouses. With such systems, workers can interact with their environment, and, particularly in exception situations, work can be rearranged, or exception measures can be taken. All activities are time-stamped and can be used for individual performance analysis and improvement (e.g., via feedback and incentive systems). It is also possible to optimize the work, taking into account differences between individual workers, the work content, and the work environment (see Matusiak et al., 2017, for an example). Not only order pickers wear communication and sensing devices, these can also be mounted into equipment, such as warehouse trucks. The trucks use a log-in system, so workers can be identified and tracked. Trucks can be equipped with shock detectors and part wear sensors, to track safe behavior and to plan maintenance. In warehouses that use large AMR fleets, the robots have to be able to detect obstacles and other vehicles. They have to communicate, and for large fleet sizes, it is better to use decentralized control in, e.g., path planning (see Fragapane et al., 2021).

In spite of these developments, products and warehouse locations are rarely equipped with sensors or communication devices (not even passive RF tags), and control and planning of human operators is still centrally organized. The full use of all IoT possibilities will only become manifest when good business cases will be shared.

5 Human Factors

In the foreseeable future, people will still be needed on the shop floor, even in highly automated environments. People are inexpensive, fast, accurate, flexible, and able to solve problems. However, the business requires more and more 24/7 operations and flexibility in the volumes that need to be handled and shipped. Part of the work will be carried out by automated equipment and robots, but the remainder must be done by people.

The big challenge for management is therefore how to redesign the work in collaboration with robots and how to retain, motivate, and stimulate people to carry it out. The way individuals behave in warehouses largely determines performance. The set of factors determining this is called "human factors" (Bendoly et al., 2006). Grosse et al. (2015), differentiate warehouse workers based on factors, *physical factors* (e.g., posture), *mental factors* (e.g., learning, forgetting), *perceptual factors* (e.g., human information processing), and *psychosocial aspects* (e.g., motivation, stress, or regulatory focus), as these factors directly impact the performance. Vanheusden (2020) also includes *picker skills* as a factor. These human factors interact with, e.g., incentives, goal setting, and feedback and jointly determine task performance. However, research on how to integrate this in operational warehouse planning systems, and on what the effect is on humans in a collaborative automated environment, is still very limited. Examples of such research include Batt and Gallino (2019), De Vries et al. (2016a, b), Glock et al. (2019), Larco et al. (2017), and Matusiak et al. (2017). We here summarize some well-known results on which measures may interact with human factors to help stimulate performance.

Goal Setting Productivity can be increased by setting challenging (but not too challenging) goals in repetitive work (see the meta-analysis of Locke & Latham, 1990, and the paper by Doerr & Gue, 2013).

Incentives, Nudging, Gamification Incentives (e.g., geared toward productivity or quality) work in enhancing performance, but the way they are formulated has impact. The impact may be different for different people, depending on behavioral traits, such as regulatory focus (Higgins, 1997, 1998). De Vries et al. (2016a) found that in a parallel order picking system (MtG picking), competition-based incentives lead to higher productivity than cooperation-based incentives, for people with a dominant promotion focus. In a sequential zone picking system, cooperation-based incentives are more productive. To apply these findings, managers may reassign employees with a particular regulatory focus to tasks that are better aligned with their regulatory focus.

Feedback Public quantity feedback helps to increase productivity, in particular for bottom-ranked workers (Zhang et al., 2021; Song et al., 2018). Public feedback can be given in different forms, e.g., via Andon sign boards, but also other forms of feedback work. Schultz et al. (1999) and Powell and Schultz (2004) show that workers adapt their speed based on visual signals in serial systems, to avoid downstream workers to become starved, or based on a visual backlog (inventory).

Although these measures work in isolation, the question is whether they also work sustained and how different measures interact with each other and with the above human factors of the workers. So far, experiments reported in the literature are carried out in nonautomated, manual environments. It is largely unknown how these measures work out in combination with collaborative robots in order pick processes. Pasparakis et al. (2021) carried out an order picking experiment with collaborative robots. It appears that the "human leading" in the collaborative order pick tasks leads to higher system productivity compared to the "robot leading." This negative effect of the robot leading is partly mitigated by the worker's "prevention" focus. However, much work still needs to be done.

6 Conclusion

This chapter discusses some recent developments in warehouses that have manifested in the last decades. These developments will continue in the decade to come. We see both centralization and decentralization trends, more automated storage and order picking systems that require a reduced footprint, several new types of robot systems, increased emphasis on sustainability, safe working environments and IoT applications, and attention for human factors. Although these developments have received some research attention, much work is still to be done. Still, important relevant insights have been obtained, which may help managerial decision-making. They are summarized below.

1. Warehouse centralization. Little research is available into under which conditions (both supply and service-related) it pays off to centralize or decentralize with a single- or multi-echelon structure and when to locate close to customers. However, particularly for e-commerce companies, the ability to deliver in tight time windows, with very short lead times, may offset the increased costs of facilities, handling, inventory, and (sometimes) transport. Such centralization decisions must be taken carefully on per market basis.
2. Warehouse robotics systems, including GtM and MtG systems. New robotic systems still emerge continuously. Recent examples include rack-climbing AMRs, unit load retrieval AMRs, and robotic sorting systems. The question is how to deploy, plan, and control these systems, how to analyze these systems for operational and economic performance, and how to select the right system from a portfolio of options. Some tools are already available to compare particular systems for performance, while new models emerge continuously.
3. Human factors. It is largely unknown how people respond to working with robots or how to deploy people in working with robots. The ultimate idea was to automate the boring, repetitive, or heavy part of the work. But what can be seen from some implementations is that people do the part that was difficult to automate, but which now has become much more monotonous and repetitive to execute, as the robots are doing the "fun" part (see, e.g., Scheiber, 2019). Managers must try to maximize joint productivity and focus and on how to design jobs in a sustained fashion balancing worker and system objectives.
4. Safety. Researchers have been trying to link safety on the shop floor to higher productivity and quality levels. This has proven to be difficult to demonstrate, as short-term effects may lead to lower productivity, while long-term effects may be positive (De Vries et al., 2016c). In a recent paper, Pagell et al. (2020) demonstrate, based on a 25-year longitudinal database, that organizations that provide a safe workplace have significantly lower odds and length of survival. However, their research leaves the question of a possible trade-off between warehouse safety and warehouse performance unanswered. As in many environments it is important to retain engaged warehouse workers, managers should focus on creating a safe working environment. According to De Vries et al. (2016c), this leads to a more satisfied workforce and it is not offset by a lower productivity.

5. Sustainability. Circular warehouses are still far out. However, on the short term, many warehouses are going for sustainability certificates, in line with higher company objectives, to reduce long-run costs. On the other hand, higher levels of automation consume much more energy. It would be interesting to find out how to optimize energy consumption of highly automated warehouse systems and to what extent more sustainable warehouses also deliver better operational and cost per unit performance. In any case, warehouses have a great opportunity to lower energy bills by investing in sustainability.
6. IoT. IoT (and other) technologies will undoubtedly penetrate further on the shop floor and benefits are to be expected. Still, except for some examples, the benefits of integrating real-time data into real-time distributed optimization are not yet fully convincing. More is to be expected in the coming decade.

Warehousing in 2030 will not differ much from current warehouse operations. Many trends are already visible now and will become even more clear in the future. But, like the Covid-19 pandemic affecting many operations on a global scale in an unforeseen way, the future may still bring new and unexpected developments.

Management Perspective on the Warehouses of the Future Will Be Automated and Sustainable

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The saying "the future is always beginning now" has never been so relevant. One of the biggest revolutions in the history of the industry is taking place right in front of our eyes. Digitalisation and automation are taking hold in every facet of production and logistics and are altering processes from the ground up. The speed of this development eclipses almost everything that has gone before. It frightens some people. It is certainly associated with challenges. But above all, it holds incredible opportunities that, if seized, will make work in the warehouses of the future more efficient and more sustainable—and therefore better.

In the warehouses of the future, everything will be interconnected, will communicate with each other and will be in motion—transparent, and exactly according to plan, but still flexible. Digitalisation and automation will further accelerate intralogistics and at the same time make it safer, more predictable and thus more productive. It's only natural: People looking to automate want to reliably reproduce recurring processes based on defined standards. This desire is almost as old as humanity itself. The ancient Greeks paid homage to Automatia (also known as Fortuna), the goddess of events that occurred without human intervention. They referred to these events as "occurring freely". Today, the German DIN standard V 19233 summarises this "free

(continued)

occurrence” of technology in sober administrative German as equipment or a facility that “operates as intended, in whole or in part, without human involvement”.

The warehouse is one of these “facilities” in which automation is already particularly advanced. Intralogistics is considered one of the key components of the fourth industrial revolution, and not without reason. Warehouse equipment, material handling equipment and software now form a single entity in which man, machine and material flow cooperate with and complement each other. Today, solution providers for intralogistics also have to be engineers and software developers—like we are at Jungheinrich. Outside warehouse and production facilities, self-driving vehicles are still a vision of the future. Inside facilities, automated guided vehicles (AGVs) are now the state of the art and one of the fastest-growing segments.

Fully automated high-bay warehouses are another application. These deserted halls, up to 40 m high, are being built all over the world. In them, stacker cranes handle all warehouse processes completely independently. The warehouse management system controls incoming goods, order picking and outgoing goods, while the stacker cranes automatically store and retrieve containers or pallets. The systems can operate around the clock—no more breaks, no more downtime and no more light switches. The stacker cranes work in absolute darkness and people only enter these warehouses when something needs to be repaired.

Many people feel uneasy about the fact that, at first glance, humans no longer seem to play a role within these closed systems. AGVs and fully automated high-bay warehouses have become focal points for the new fear about the end of work. But the opposite is true. In fact, automation does not mean that human labour in the warehouse is being phased out. Instead, it will be upgraded. People and technology will work less “hand in hand” than they do today and will instead be increasingly connected “mind to mind”. People will be freed from repetitive routine tasks and will have to drive, pack and pick less, but they will have to monitor and manage the digital systems in their working environment to an increasing extent and thus control the big picture.

This is also necessary. Human labour has become a scarce resource. Dealing with this in a sustained manner is the order of the day because the shortage of skilled workers is a reality and no longer limited to academic professions. Skilled workers and forklift drivers are also desperately needed—not only in Germany. Here, automation provides an opportunity to make warehouses more efficient, and therefore more sustainable. This also applies to other areas: automated processes reduce the risk of errors, prevent accidents and reduce unnecessary movements. Indispensable building blocks for greater energy efficiency and climate protection are central requirements for the warehouse of the future.

(continued)

Automation is not an end in itself. It offers concrete added value for logistics as a whole but above all for those who trust in it. Individuality will play an increasingly important role. The advent of the Internet of Things (IoT) and artificial intelligence (AI) makes it possible to find the right solution for every application. Especially in intralogistics with its many interconnected process steps, each of which must be well-described and expressed in data, this opens up completely new possibilities. Off-the-shelf solutions will no longer be sufficient for the warehouse of the future. Understanding of a customer's needs and detailed analysis of their specific material flow will be at the beginning of any warehouse redesign. The result will be more efficient, more sustainable and therefore ultimately better intralogistics. This is what we stand for at Jungheinrich.

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