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Considerations When Designing an AutoStore$^{\mathrm{TM}}$ System

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***Abstract*—Designing an AutoStore$^{\mathrm{TM}}$ system is a complex undertaking with many interacting decision variables. In this paper we first provide a detailed description of an AutoStore system from the perspective of the main components of the system. We then define the design problem by stipulating the design requirements and decision variables. We then discuss how the decision variables impact the objective function. In so doing we provide many avenues for quantitative modeling by the research community.**

***Index Terms*—top-loading automated storage/retrieval system, goods-to-person systems, complex design optimization**

I. INTRODUCTION

AutoStore$^{\mathrm{TM}}$ (AutoStore) is a company that manufactures goods-to-person (GTP) robotic technology [1]. A GTP, as the name implies, brings the goods (product) to a person (worker) for picking, as compared to a traditional system where the worker travels to a location for picking product. As walking to the product can be a substantial portion of the worker's time, removing it via a GTP system can increase productivity substantially.

The number of AutoStore installations worldwide surpassed 1,000 in 2022, with installations in 46 countries. This is impressive for the relatively new goods-to-person technology (AutoStore's first commercial system was installed in 2005). AutoStore works through a network of integrators versus selling direct to customers. FORTNA has been an AutoStore integrator since 2019. We have installed, or are in the process of installing, an AutoStore system at 10 customer sites to date with another 10 in the design phase. Some of the FORTNA AutoStore systems are amongst the largest in the world.

It is from this perspective that we outline some of the many tradeoffs we consider when designing an AutoStore system. We will provide enough detail so that researchers can consider exploring these tradeoffs as research topics in future work. Additional details may be found in [**?**]. Due to the lack of applicable published research on AutoStore systems, we believe this paper is a significant contribution.

II. AN AUTOSTORE SYSTEM

An AutoStore system consists, at a high level, of seven modules: 1) the grid, 2) the bins, 3) the robots and chargers, 4) the ports, 5) the controller, 6) the workstations and 7) the warehouse execution system (WES) software (which may be one or more software packages). The first five modules are provided by AutoStore and the last two are provided by the AutoStore integrator. Figure 1 illustrates the five AutoStore modules and Figure 2 illustrates how an AutoStore port is integrated within a workstation.

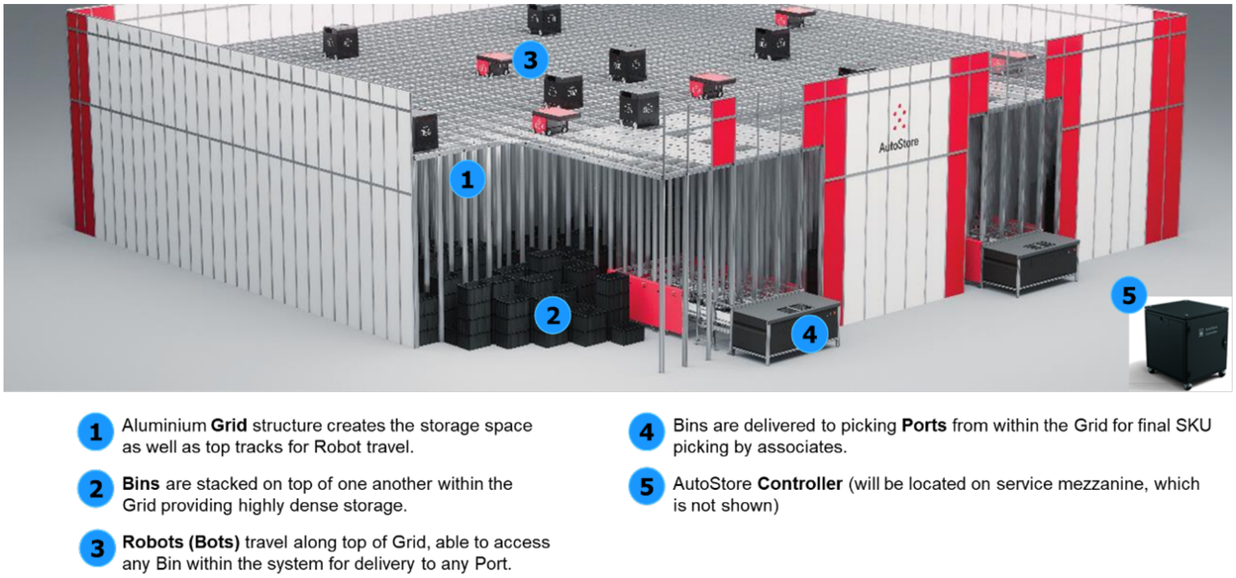
AutoStore refers to their technology as "cube storage." The industry refers to a GTP based on an AutoStore as an example of a "top-loading automated storage/retrieval system (AS/RS)." Another example of a top-loading AS/RS is manufactured by the Ocado Group [3]. In general, a top-loading AS/RS is the densest system possible because there is no vertical space between bins and minimal horizontal space between stacks of bins (to facilitate the grid that is used to facilitate robot movement). However, bins that are not on the top of their stacks need to be "dug out" to facilitate delivery to a port/workstation for picking. Therefore, there is a tradeoff between density and accessibility, which is a common theme in storage system design [4].

To get a better sense of the AutoStore operation, let us consider it from various perspectives.

A. A SKU's Perspective

When designing an AutoStore system, a determination must be made for each stock-keeping unit (SKU). That is, is it optimal to include the SKU in the AutoStore or would it be better to include in some other pick engine. And if included in the AutoStore, how much inventory should be allocated (e.g., all the expected on-hand inventory or only some portion). This determination is complicated and beyond the scope of this paper, but a common strategy is to not include some subset of the SKUs that are fast moving as they will likely require a large number of bins and drive a high throughput requirement if included in the AutoStore and these SKUs can be picked at a high productivity out of the AutoStore.

As a result, a typical AutoStore application will include a high number of SKUs that represent a proportionally smaller percentage of the facility's throughput. Therefore, each SKU included in the AutoStore may occupy only one bin (or one bin compartment) on average. Of course, some SKUs will be allocated more than one bin, but typically not very many. The result of this complex optimization problem will define the AutoStore design requirements for the number of occupied bins (and the appropriate number of empty bins to facilitate



① Aluminium **Grid** structure creates the storage space as well as top tracks for Robot travel.

② **Bins** are stacked on top of one another within the Grid providing highly dense storage.

③ **Robots (Bots)** travel along top of Grid, able to access any Bin within the system for delivery to any Port.

④ Bins are delivered to picking **Ports** from within the Grid for final SKU picking by associates.

⑤ AutoStore **Controller** (will be located on service mezzanine, which is not shown)

Fig. 1. The five modules AutoStore provides in an AutoStore system [1].

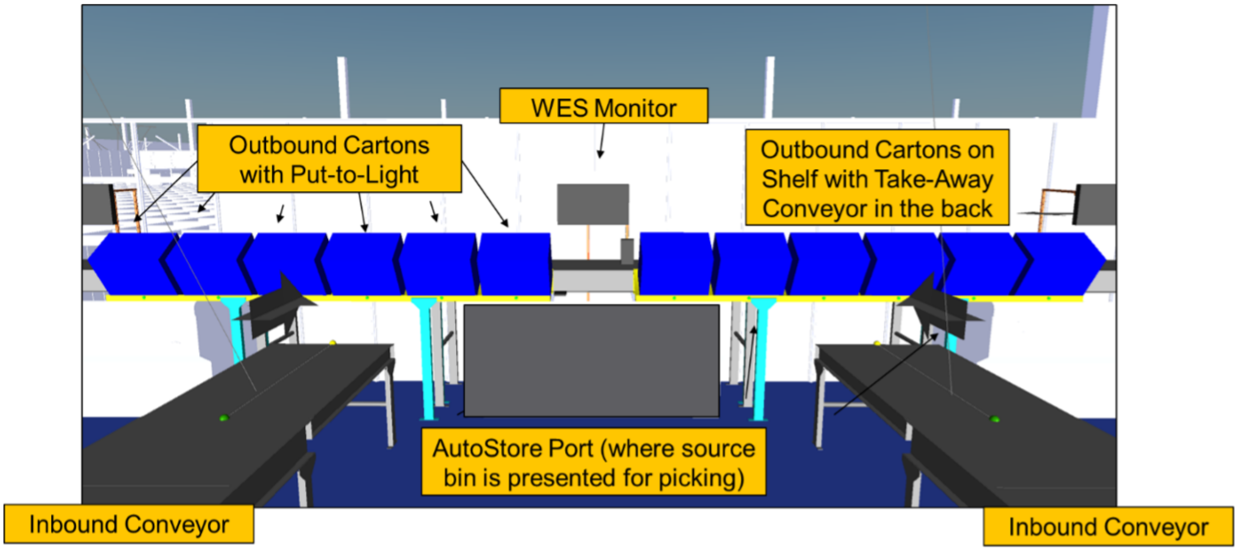


Fig. 2. A picking workstation utilizing an AutoStore port for source bin delivery.

induction activities) in the system as well as the bins/hour throughput the system must achieve (i.e., a summation of inbound and outbound activities).

B. The Aluminum Grid's Perspective

The first observation about the aluminum grid is that its role is not to support the weight of the bins (product) because the bins are stacked directly on the floor and directly on top of one another. This means that the lowest-most bin is under the most stress from the bins stacked upon it. It should then become obvious that the strength of the bin will determine the maximum load and height of the storage system. In AutoStore's case, the bins are a proprietary design manufactured by AutoStore-licensed suppliers that integrators must use. The current bin design limits the stacks to heights of 24 bins in the case of the 220mm height bins (5.28m), 16 for 330mm bins (5.28m) and 14 for 425mm bins (5.95m) with each bin able to hold 30kg of product, regardless of bin height.

So, if the aluminum grid is not there to support the product, what is its role? Its role is to provide a travel network for the robots. The robots navigate from a position above storage locations to ports, between storage locations and between various points in the rack to the chargers. The tracks at the top of the aluminum grid facilitate travel in the north-south and east-west directions following a rectilinear travel norm.

C. A Bin's Perspective

A bin that is needed to fulfill part of an order will be selected by the WES. It is important to note that this selection process cannot be executed by the AutoStore controller because the AutoStore controller does not know what inventory is held in each bin and has no concept of an order — this information resides in the WES.

When the signal arrives for the bin to be prepared, the AutoStore controller will allocate one or more robots to prepare the bin — that is, dig it out of its position in a storage stack (assuming it is not already at the top-most position in a stack). This will require removing every bin that is currently above the bin that needs to be prepared and temporarily placing those bins on top of a storage stack. To ensure these bins do not inhibit the travel of other robots, the top-most position in a certain percentage (e.g., 25%) of the stacks are left open (this is referred to by AutoStore as a "hole").

When this group of robots has successfully dug out the bin that needs to be prepared, the prepared bin is placed in a hole and awaits the signal that it is has been allocated to a specific port queue. In the meantime, the bins that were removed during the digging process are always returned to the same stack as they were removed from, only one level deeper in the stack. That is, if the stack was at full height and numbered from the top position as 1-2-3-4-5-6-7-8-9-10-11-12-13-14 and bin 6 was to be prepared, after the digging out process, the stack will have a hole (H) at the top and now be H-1-2-3-4-5-7-8-9-10-11-12-13-14. That is, the bin that was at level 1 is now at level 2, the bin that was at level 2 is now at level 3 and so on. Note that the bins that were at levels 7-14 remain in their same relative position as they were not removed during the digging process. Also note that due to the limited number of holes in the grid, the process of returning bins that were dug out must occur immediately or other bins cannot be dug out.

Once the bin is called to a specific port queue, a robot will be assigned to bring it to the port queue. Note that this robot will likely not be one of the robots that was used to prepare the bin. Once the port is ready to receive the bin, the robot lowers the bin into position and is then free to be assigned to another task (e.g., picking up a bin from this port). The bin is then under control by the port. When it has completed its activity at the port, a robot will retrieve it and transport it back to any open hole in the grid (i.e., there is no attempt to return the bin to the stack it was retrieved from). As a result, the top layer of the grid is filled with bins that have been recently used at ports (or holes). AutoStore refers to this phenomenon as "natural slotting" — recently used bins are at the top of stacks and bins that have not been used recently "sink" to the bottom.

D. The Robot's Perspective

The robots in an AutoStore system are multi-functional. That is, each robot is able to perform any/all of the tasks: raising/lowering a bin from a storage location and/or port, traveling to/from a storage location to a port location, digging out a bin from a storage stack, or utilizing a charger location. If you followed one robot throughout the day, you would likely observe it in each of these tasks. The assignment of tasks amongst the robots is a complicated task that is managed by the AutoStore controller using proprietary algorithms. The AutoStore controller also handles routing and path management, managing conflicts between robots, when to send robots to chargers, etc. Very few details are provided about the controller by AutoStore.

E. The Port's Perspective

When a port/workstation is in operation and an order is completed and its tote is removed from the workstation, a new order is assigned to the workstation and the bins that are required to complete that order are then assigned to the port queue at the workstation. This is accomplished through the WES software. Likewise, in most systems the WES will have communicated the bins that are needed to fulfil orders in advance so the bins are in a prepared position so the timing of delivery to the port can be orchestrated effectively. If orders cannot be communicated to the AutoStore system in advance (30 minutes is the rule-of-thumb and note that sending too many bins to prepare can lead to placing a newly prepared bin on top of a previously prepared bin), there can be delays in delivering bins to the ports while a bin is dug out, which can lead to idle time for the worker at the workstation. As you might expect, digging out bins and the time requirement to communicate bins for orders is a distinguishing feature of top-loading AS/RSs.

F. The Systems Perspective

Both the AutoStore controller, and its associated control software, as well as the WES play critical roles in the effective operation of an AutoStore. The controller must maximize the effectiveness of the robots and orchestrate their movement while the WES must maximize the effectiveness of the workstations and orchestrate the flow of goods in/out of the system.

G. The Maintenance Perspective

The top of an AutoStore grid is a very active place with many robots moving in all directions. As a result, when maintenance must be performed on top of the grid itself, the entire grid must be turned off. This then means that throughput comes to a halt. Thus, preventive maintenance is stressed and is performed on one or more service platforms that are located on service mezzanines at top-of-grid height (see Figure 3). Robots can be manually recalled to a service platform and will drive themselves over and control of the robot will be transferred from the controller to manual controls on the robot itself that are accessible by maintenance personnel. When the maintenance is complete, the robot is transferred back onto the grid physically and will then again be under the control of the controller.

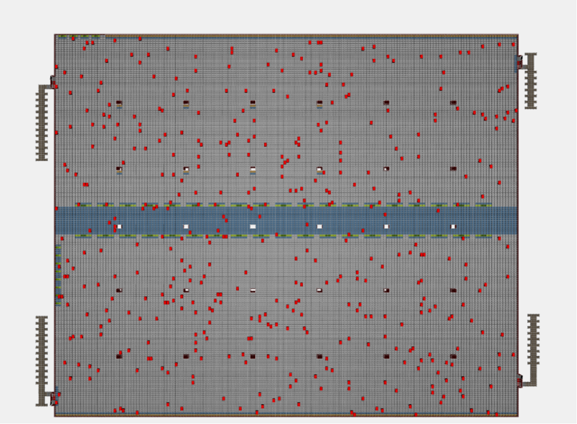


Fig. 3. The top of an AutoStore grid with four service mezzanines (supporting structure not shown).

III. DESIGNING AN AUTOSTORE SYSTEM

There are many degrees of freedom when designing an AutoStore system. It is the intent of this paper to outline the design problem and enumerate a non-exhaustive list of the decision variables that may be varied to optimize the design of an AutoStore system.

Design Problem Statement: Minimize the total cost of the system, which includes both the cost of the equipment and software as well as a quantification of the floorspace costs, subject to storing the required units of each product designated for the AutoStore and fulfilling the specified level of picking and induction throughput (from both a robot perspective as well as a port/workstation perspective).

Tradeoffs to be considered in the design process that are detailed in the remaining sections of the paper:

- Bin Height
- Grid Height
- Grid Shape
- Port Type
- Robot Type
- Number of Chargers and their Placement
- Robot Orientation
- Percentage of Holes

A. Bin Height

In an AutoStore system, each bin has a fixed footprint (649mm x 449mm outside / 603mm x 403mm inside). There are three bin height choices (220mm/202mm, 330mm/312mm and 425mm/404mm) as shown in Figure 4. Each system is only allowed one height choice. As in most AS/RS, the bin dimensions will have an impact on the total cubic storage provided in a system. That is, choose a bin height value that is too low, and some product cannot be stored in a bin and will need to be stored in another, less dense, storage system. If the chosen bin height value is too high, a larger set of products can be stored in the AutoStore, but there may be wasted space in each bin. So, one of the first decisions that needs to be made is the choice of bin height value.

Fig. 4. The three heights of AutoStore bins [1].

Beyond the traditional cubic storage tradeoffs, because the maximum grid height is constrained and roughly the same for all bin heights, the bin height choice has an impact on the performance of the robots in an AutoStore system. That is, with a 220mm bin height, an AutoStore can store up to 24 bins in one stack of bins. But with a 330mm bin height, only 16 bins can be stored in one stack and with a 425mm bin height, only 14 bins. And because of the "digging" aspect of AutoStore, even if a system with 220mm bins had the same cubic storage capacity as a system with 425mm bins, there would be much more time spent by robots digging in the 220mm bin system. For example, in a system with 425mm bins, the time to dig out the bottom-most bin is 177 seconds (plus lateral travel time, which is dependent on the percentage of holes and their distribution), whereas in a system with 220mm bins the comparable time is more than two times that value (414 seconds).

One can imagine an improved system where multiple height bin choices could be accommodated given the interacting impacts of cubic storage and the performance of the robots in an AutoStore system.

B. Grid Height

The choice of grid height will have a very significant impact on the floorspace requirements for the grid, but also has a complicated impact on the throughput of the system. For example, a taller grid leads to less lateral movement of the robots (which can decrease the number of robots required in the system), but also increases the time robots spend digging (which can increase the number of robots required in the system).

Here is an actual example utilizing 330mm tall bins in a grid with approximately 100k bins. When the grid is "full height" (or 16 levels of bins), the resulting floorspace of the grid is 2,457 m^2. However, when the grid is only 8 levels of bins, the resulting floorspace increases to 4,988 m^2. (The reason the lower height system is not a perfect doubling of the higher height system has to do with the percentage of "holes" in the grid — see section below — and how ports and other grid features, which may be fixed between the two grids, consume an entire column of bin positions.) But just as impactful, the productivity of the robots increases from 29 bins/robot/hour at 16 levels to 36 bins/robot/hour at 8 levels (with a 80/20 bin distribution; i.e., 80% of the bin retrievals come from the top-20% of the levels). So, depending on the throughput needed, which will dictate the number of robots and the relative cost factors, this is a very interesting optimization problem in and of itself. In practice, perhaps due to perception, the only time we design grids to be less than full height is when there are building constraints and/or we are using 220mm bins, which result in a great deal of time associated with digging at full height.

C. *Grid Shape*

The shape of the grid affects lateral robot movement. That impact is fairly clear. But grid shape also impacts how much grid perimeter is available for port placement as well as charger placement — although chargers can be located in the grid interior, they take up more space in doing so and are also more difficult to reach for any maintenance. So, when possible, chargers are placed on the grid perimeter. And another option in terms of grid shape is to put ports under a tunnel. See Figure 5 for an example grid with a tunnel. Doing so also has the advantage of minimizing the maximum distance traveled by robot (although the tunnel must be supported by a structure). It is clear that even for something as relatively straightforward as grid shape is complicated by multiple tradeoffs.

D. *Port Type*

AutoStore provides many different types of ports: Conveyor, Carousel, Swing, Relay, Pickup, Fusion (and its derivative, Fusion Port Staging) and the adaptable Transfer Cell. These ports serve as the centerpiece of the integrator-supplied workstation. In general, the cost of the port increases as the maximum rate through the port increases. Confidentiality agreements do not permit the sharing of cost data, but maximum rates on the most common ports located on the floor vary from ∼220 bins per hour for the conveyor port (Figure 6) to ∼300 for the carousel port (Figure 7) and up to 500 bins per hour for a fully equipped relay port (Figure 8).

Port rates can be increased by raising the ports to the top of the grid. Doing so reduces the time it takes to lower and raise a bin out of the port drop off position, which means the current robot can move out of the way and make room for another robot to drop a bin into the port position (and vice versa on bin takeaway from a port). Of course, doing so requires building a platform to support the raised ports/workstations.

Workstation rates cannot exceed the rate of the port or the rate of the worker at the workstation. In general, as the worker's responsibilities at the workstation change, the type of port that is implemented changes as well. For example, in an induction operation, the worker may be responsible for scanning an inbound case of product, opening the case, (potentially) counting the contents, scanning the items in addition to placing the many items into an AutoStore bin. So, the maximum rate may only be ∼60 bins per minute. As a result, the less expensive conveyor port is typically used for induction operations. Alternatively, for a picking operation where the worker only has to grab the item(s) and place it/them in an outbound tote, a relatively expensive relay port may be justified to support the worker's 400 bins per hour rate. But when the worker also has to scan the item from the AutoStore bin and perform opportunistic cycle counts and/or replace completed order totes, etc., which may reduce their rate to 250 bins per hour, a carousel port may be the right tradeoff of rate and port cost. It is in this way the designer of the system must consider current and future operations that will occur at a workstation to choose the best port, especially when grid perimeter is limited.

E. *Robot Type*

There are currently three robot types (R5, R5+, B1) with the main tradeoff being in terms of battery type (R5 and R5+ robots sit at a charger while their batteries are charging and B1 robots perform a hot swap of batteries) and performance (B1 robots have faster acceleration and top speeds than R5/R5+ robots). Accordingly, B1 robots are more expensive as well as their lithium-ion batteries (R5/R5+ robots use a lead-acid battery). Determining the optimal robot type choice must consider the performance of the two types of robots (R5 and R5+ only differ in terms of the bins they can work with — R5+ robots can work with a 425mm height robot and R5 robots cannot) as well as the cost and availability throughout the work day, which may encompass a 24-hour operation during the peak times of the year. Note that a system with B1 robots will require significantly less robots in some situations, which could reduce any potential congestion due to too many robots in too small a grid.

F. *Number of Chargers and their Placement*

The number of chargers will affect the battery levels throughout the day, which will affect system performance. When too few chargers are provided, robot performance will decrease the bins/robot/hour that can be achieved. When too many chargers are provided, cost and storage density will be negatively impacted.

Charger placement can affect the performance of a system due to robot travel to/from the chargers. But as noted earlier, placing robots in the interior portion of the grid can reduce maintenance access, which can negatively impact the uptime of the grid (as discussed earlier, in general, when a maintenance technician or another worker must travel onto the grid, the entire grid must be locked out).

G. *Robot Orientation*

In talking about AutoStore grids and R5/R5+ robots, robots are oriented either with the bin the robot is carrying to the north of the robot or the south of the robot. See Figure 9, which illustrates the cantilever design of an R5/R5+ robot as well as its two sets of wheels that allows for robot movement in the north-south or east-west direction. (Robots are never oriented on the grid such that they carry the bin to the east or

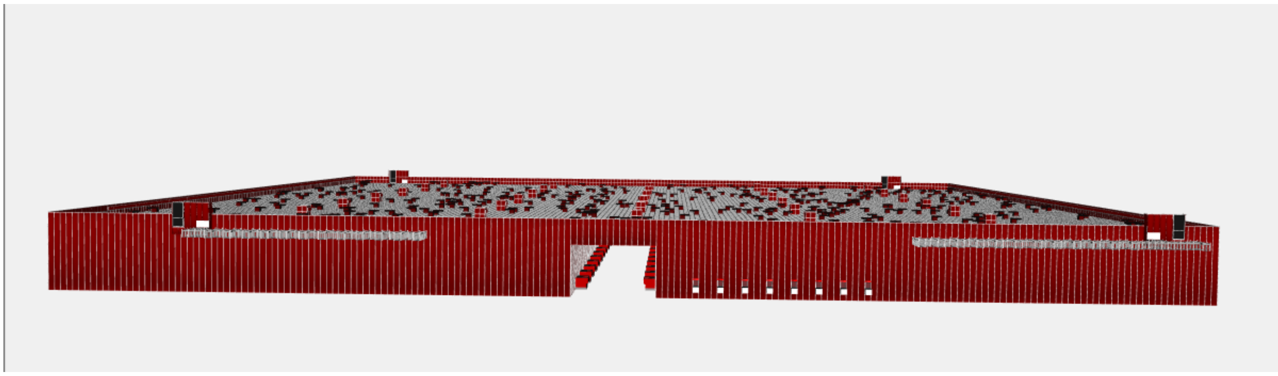


Fig. 5. An AutoStore grid with a tunnel.

Fig. 6. AutoStore conveyor port [1].

Fig. 7. AutoStore carousel port [1].

Fig. 8. AutoStore relay port [1].

Fig. 9. AutoStore R5 Robot [1].

west of the robot.) For example, in referring back to Figure 1, the robot at Point 3 is a south-carrying robot (the side of the AutoStore in for the forefront is, for convenience, designated as the south side regardless of its actual compass orientation). Note that it cannot access the last row of bins "behind it" on the north side of the grid. (This same issue arises with B1 robots.)

Using robots of only one orientation simplifies the control of the system as there is more pooling of resources. However, to ensure all positions can be accessed by the robots, the grid must be constructed with an "overhang" (i.e., cells are provided with no storage below them, supported by an external platform, which must be paid for). Thus, it is a tradeoff between the robot cost saved due to increased effectiveness versus the cost of the external platform.

And even in the extreme case of all robots oriented in one direction, the split between the directions can impact the operation of the grid and is another decision variable to consider. In general, port delivery (and take away) is impacted by the split in robot directions while digging is not significantly impacted.

H. Percentage of Holes

In the AutoStore vernacular, a "hole" is an AutoStore grid cell at the top-most layer of the grid that is not factored into the storage capacity of the grid. The holes "float" (because, as noted above, bins that are returned to storage are returned to the top of any available stack) and are used to temporarily store bins that are "dug out" to get to the requested bin. A higher hole percentage minimizes the lateral travel associated with "digging," but decreases storage density.

IV. ADJACENT GTP TECHNOLOGIES

Many of the above design decisions apply to adjacent GTP technologies. In this section we outline how an AutoStore compares to them to provide some insight into why one GTP technology is used instead of another.

Shuttle systems [5] where each level of the aisle's storage rack in every aisle has a shuttle that delivers totes to/from lift(s) at the end of the aisle is sometimes referred to as a "fixed shuttle system." Such a system is perhaps the easiest to think about in terms of design. The number of tote positions needed divided by the number of tote positions/aisle will provide a minimum number of aisles. Likewise, the number of tote presentations per hour divided by the number of tote presentations per hour per aisle will provide another representation of a minimum number of aisles. The maximum of these two minima will provide the true minimum number of aisles needed (rounded up, of course).

The advent of "roaming shuttle systems" arose from the observation that for some set of requirements, the two minima above can be very different. And especially the situation where the minimum number of aisles needed to meet the throughput requirements is much less than the minimum number of aisles needed to meet the storage requirements, the concept of roaming shuttles is very appealing.

Besides the top-loading AS/R systems, there are shuttle systems with racks that appear very much like a fixed shuttle system with the critical difference that the shuttles are not fixed within an aisle or to a level within an aisle. That is, the shuttles can roam between aisles for a fixed level (like in the EVO system by Knapp [6]) or can roam across levels (like in the Perfect Pick system by OPEX [7]). Note that the former still requires a lift at the end of at one or more aisles while the latter removes the lift (but there is no roaming between aisles). And the latest roaming shuttle systems permit the shuttles to roam outside of the rack structure altogether (like in the Exotec Sky Pod system [8] or the OPEX Infinity system [7], among others).

All the above systems employ a rack structure to store the products, which inherently adds "air" to the storage system (vs. the top-loading systems where bins are stacked directly on bins). The implication is top-loading systems have an inherent storage density advantage, although rack systems can be taller. The rack-based systems have an advantage with respect to storage selectivity and so for some distributions of product usage, they will then have a higher throughput per robot. Therefore, as noted earlier, in designing a GTP there is a tradeoff between density and accessibility.

V. CONCLUSIONS

AutoStore systems are increasingly being used in industry. Designing an AutoStore system is a complex optimization problem with many interacting decisions. We have outlined a number of the decisions along with a brief summary of the tradeoff involved in the decision. In addition to the design tradeoffs illustrated herein, there are a few other research questions that could be explored. That is,

- **Restacking bins in created holes** As noted above, the AutoStore controller returns unneeded bins from the preparation process *in exactly the same order* as they were taken out. In some situations, with some information available on future activity, this may not be optimal. In addition, there may be multiple stacks that are involved in the stacking process at any given time. So, it?s not only an issue of in which order to return the bins, but also to which hole?
- **Returning bins to the top of a stack after the picking process** Of the many holes at the top layer of the grid, which one is the correct location for the bin that just completed its picking process?
- **The bin distribution realized in a dynamic system** AutoStore advocates using the SKU ABC profile to determine the bin distribution. In simple terms, if every SKU were allocated one bin in an AutoStore and the SKU activity followed an 80/20 distribution, then AutoStore advocates that 80% of the bins would be retrieved from the top-20% of the levels in the AutoStore. But given the dynamic nature of bin retrievals and returning to created holes, is this the case (even with a stable SKU ABC profile)?
- **Reaching a steady state bin distribution** AutoStore grids are typically loaded in an arbitrary fashion such that, before the grid is put into operation, fast-moving SKUs may be found at the bottom of the grid and slow-moving SKUs may be found at the top. How long will it take for the grid to arrive at a steady state bin distribution under typical operating conditions?

We hope that along with the description of the AutoStore operation, the research community can provide guidance in some of these decisions.

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