Technical Note

This technical note consists of two parts. Part A explains storage design for turnover based dedicated and random storage policies, which are commonly employed by warehouses. Part B introduces the working and economics of a forward reserve storage arrangement in a rack of an automated storage/retrieval system (AS/RS).

Part A: Storage design for turnover based dedicated and random storage policies

One of the major objectives in designing a storage system is efficient order picking through low travel time. A strategy that a storage designer can sometimes use to reduce travel time is to allocate high turnover products to premium slots that are faster to reach. Thus, it is imperative to determine premium slots by ranking them based on the time taken to reach them from the aisle entrance point.

Ranking of storage slots based on travel time

Consider a storage slot with position (*m*,*n*). Then horizontal and vertical distances of the storage slot from the aisle entrance are $m\Delta x$ and $n\Delta y$ meters respectively where Δx and Δy are the horizontal (length) and vertical (height) dimensions of the storage slot in meters.

In an AS/RS with a storage/retrieval (S/R) machine that allows simultaneous horizontal and vertical motions of the crane and carriage respectively, the time taken by the S/R machine to reach a particular storage slot follows Chebyshev or maximum distance metric. Hence, the time *t* taken by the S/R machine to reach a storage slot with position (*m*,*n*) in the rack is given by equation (A-1) where v_x and v_y are the horizontal and vertical velocities of the S/R machine, respectively.

$$t = Max\left(\frac{m\Delta x}{v_x}, \frac{n\Delta y}{v_y}\right) \qquad \text{(A-1)}$$

Consider a storage rack with total 50 storage slots (10 storage slots along the length of the picking aisle and 5 storage slots along the height of the rack) for storing products A, B and C. The horizontal and vertical dimensions of each storage slot are assumed to be 1 m each (i.e. $\Delta x = \Delta y = 1$). The horizontal and vertical speeds of the S/R machine are v_x=1.6 m/s and v_y=0.6 m/s. The one-way travel time (in seconds) to reach each storage slot computed using equation A-1 is given in Table A-1.

Table A-1: One-way travel time to each slot in the storage rack from the aisle entrance

Position along the height (*n*)	**5**	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
	4	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
	3	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.6	6.3
	2	3.3	3.3	3.3	3.3	3.3	3.8	4.4	5.0	5.6	6.3
	1	1.7	1.7	1.9	2.5	3.1	3.8	4.4	5.0	5.6	6.3
Aisle Entrance		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
		Position along the picking aisle (*m*)									

The storage slots are ranked based on their travel time values such that a slot having lower travel time is more premium than one with higher travel time. For example, the storage slot at position (1,2) with travel time 3.3 seconds will be ranked higher than the storage slot at position (3,4) with travel time 6.7 seconds.

Random and turnover based dedicated storage policies

A storage policy is a rule to assign each consignment of incoming material to a storage location in a warehouse. This affects the storage space requirements to hold inventory of products as well as the expected travel distance in the warehouse. This technical note illustrates two major storage policies, namely turnover based dedicated storage policy and random storage policy.

Under dedicated storage, each product gets a fixed number of storage locations exclusively assigned for it based on product turnover. No other product can occupy these storage locations even if they are empty. Under this policy, high turnover products are assigned locations close to the aisle entrance point to reduce the expected travel in the warehouse.

Under random storage, there are no pre-assigned storage slots for products and any product may be assigned to any available location to reduce the overall space requirement. Thus, unlike dedicated storage, under random storage, the storage location of a particular product doesn't remain fixed over time and different products share the storage slots over time.

Designing a storage system generally requires making three interrelated decisions: determining the space (i.e., the total number of storage slots) requirement, allocation of products to the storage slots and evaluation of design by computing average travel times.

Determination of storage space requirement

For the purpose of demonstration, consider three products A, B and C to be stored in an AS/RS. Daily product demands and planned inventory, both, expressed in unit loads are given in Table A-2.

Table A-2: Product demands and replenishments

Product	**Daily demand (in unit loads)**	**Maximum inventory level (in unit loads) to be stored**	**Inventory received on days in the planning period**
A	4	8	1, 3, 5, ..
B	4	16	2, 6, 10, ..
C	6	18	3, 6, 9 ..

Following the inventory plan and consumption data from Table A-2, the inventory levels at different time periods can be derived as shown in columns 2, 3 and 4 of Table A-3 for products A, B and C respectively. Under the dedicated storage policy, sufficient space is allocated to each product to accommodate its maximum inventory level in the planning horizon. While under random storage policy, the total space allocated in the warehouse is sufficient to accommodate the maximum aggregate inventory level of all the products in the planning horizon. Accordingly, the space requirements for these products under the two storage policies are computed and shown in the last two rows of Table A-3.

Table A-3: Inventory levels of SKUs in different periods in the planning horizon and computation of storage slot requirements under the two storage policies.

Period	**Planned inventory of each SKU**			**Aggregated inventory level of all SKUs in unit loads**
	A	**B**	**C**	
1	8	4	12	24 (8 + 4 + 12)
2	4	16	6	26 (4 + 16 + 6)
3	8	12	18	38 (8 + 12 + 18)
4	4	8	12	24 (4 + 8 + 12)
5	8	4	6	18 (8 + 4 + 6)
6	4	16	18	38 (4 + 16 + 18)
:	:	:	:	:
15	8	12	18	38 (8 + 12 + 18)
:	:	:	:	:
Maximum inventory level in the planning horizon	8	16	18	38
Storage policy	Dedicated storage policy			Random storage
Number of slots allocated	8 to A	16 to B	18 to C	38 for the three SKUs

For this example, under dedicated storage policy, the total storage space requirement is 8 (for A) +16 (for B) +18 (for C) =42 storage slots (for unit loads) (see Table A-3).

Under random storage policy, the aggregate inventory for the three products (i.e., the sum of planned inventory for A, B and C) for each time period is examined (see column 5 of Table A-3). The required storage space should be sufficient to hold the maximum of aggregate inventory over the planning horizon. Accordingly, under random storage policy, 38 storage slots (for unit loads) are adequate. This is 9.5% lower than that required under dedicated storage.

Allocation of products to storage locations

As discussed earlier, under random storage, no fixed slot is allocated exclusively for any product; instead, each incoming product can be allocated any unoccupied storage slot in the warehouse randomly. There are only a few rules that may be followed under random storage policy such as assigning the incoming product to the closest unoccupied storage slot. On the other hand, under turnover based dedicated storage policy, products are allocated fixed storage slots exclusively for them which are kept empty if the product is unavailable. Under this policy, the turnover of the product is considered before allocating it to a storage location. The turnover based dedicated storage policy assigns more premium storage slots i.e. storage slots closer (in time) to the aisle entrance to products with higher turnover per allocated storage slot. The turnover rates of products A, B and C are determined as the ratio of their respective daily demands to their respective maximum inventory levels (or maximum storage slots required) given in Table A-2. Using the data from Table A-2, the turnover rates of A, B and C are determined to be 0.5, 0.25 and 0.33 respectively. Thus, here product A will get more premium slots than B and C and so on so that more premium slots are allocated to high turnover products. The assigned products along with their turnover rates are shown in Table A-4.

Table A-4: Assignment of products to storage slots under turnover based dedicated storage policy

Along the height (row number)	**5**	B (0.25)	B (0.25)	B (0.25)	B (0.25)	B (0.25)	B (0.25)				
	4	C (0.33)	C (0.33)	C (0.33)	C (0.33)	C (0.33)	B (0.25)	B (0.25)	B (0.25)	B (0.25)	
	3	C (0.33)	C (0.33)	C (0.33)	C (0.33)	C (0.33)	C (0.33)	C (0.33)	B (0.25)	B (0.25)	
	2	A (0.5)	A (0.5)	A (0.5)	A (0.5)	C (0.33)	C (0.33)	C (0.33)	B (0.25)	B (0.25)	
	1	A (0.5)	A (0.5)	A (0.5)	A (0.5)	C (0.33)	C (0.33)	C (0.33)	B (0.25)	B (0.25)	
Aisle Entrance		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
		Along the length (column number)									

The allocation of products to storage locations directly influences the average travel time under each storage policy.

Computing average travel times under turnover based dedicated and random storage policies

Different products may occupy the same slots under the two storage policies considered. This would result in variation in turnover generated through these slots and expected travel distance across the two storage policies.

Turnover based dedicated storage policy

The expected travel time under turnover based dedicated storage policy is determined as the weighted arithmetic mean travel time for all the storage slots with their corresponding turnover rates acting as weights. Thus, for the given example, first, the travel time to each storage location (as given in Table A-1) is multiplied with its corresponding turnover rate (as indicated in Table A-4). Then the sum of all these products is divided by the sum of the turnovers at each storage location given in Table A-4. The expected one-way travel time under turnover based dedicated storage policy is determined to be 4.9 seconds.

Random storage policy

Under random storage policy, each storage location is equally likely to be visited and any product may be assigned to any slot. Thus, for the storage rack in Table A-1, the expected one-way travel time under random storage policy is computed using the arithmetic average of travel times to all the slots.

From Figure A-1, the value of expected one-way travel time under a random storage policy is found to be 5.6 seconds. Thus, for this example, the travel time under random storage policy is found to be 15% higher than that under turnover based dedicated storage policy.

Part B: Forward-reserve configuration for automated storage/retrieval system

The random storage policy helps use the storage space efficiently but results in longer expected travel times in executing storage and retrieval requests. The dedicated storage policy, on the other hand, helps reduce the expected travel time by implementing dedicated turnover based storage. However, the storage space requirement under a dedicated storage policy is larger than that under random storage policy. A storage arrangement, which combines the benefits of these two basic storage policies, is a storage arrangement known as forward-reserve configuration.

Forward –reserve configuration

Under the Forward -reserve configuration, the storage rack is divided into two parts: 1) Forward pick area and 2) Reserve storage area. Figure B-1 shows a forward-reserve configuration for the rack under consideration with a forward area, as indicated with 18 storage slots.

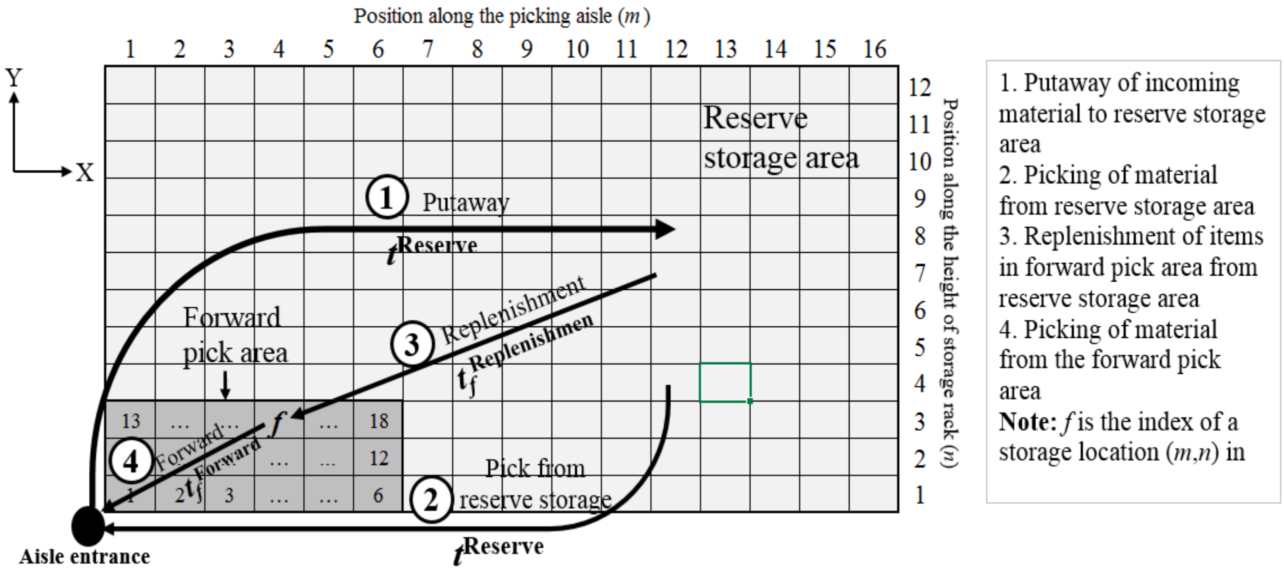

Figure B-1: Flows in the forward reserve configuration

Each storage slot in the rack is identified based on its position from the aisle entrance along the picking aisle, *m* (along the X-axis) and along the height of the storage rack, *n* (along the Y-axis). Thus, each storage slot has a unique combination (*m*, *n*) indicating its location in the storage rack. Further, each storage slot in the forward pick area is referred to by its index *f*.

The forward pick area is designed to gain order picking efficiency by hosting unit loads of high turnover items in the minimum quantity and by locating these closer to the aisle entrance following the dedicated storage policy. The reserve area hosts the bulk of inventory using shared space storage for better space efficiency. Usually, the forward storage has size much smaller than the forward area to preserve travel efficiency.

Material movement in a forward-reserve configuration

The following notations are used in the remainder of this reading material.

i	Index for all the products
j	Index for products selected for storage in the forward area
f	Index for storage location in the forward area
P_i	Number of picks of product *i*
P	Total number of picks ($P = \sum_i P_i$)
P_R	Total number of picks from the reserve storage area
P_F	Total number of picks from the forward storage area
d_i	Volume of picks of product *i* in unit loads
D	Total pick volume in unit loads ($D = \sum_i d_i$)
t^{Random}	Within rack expected one-way travel time per request under random storage policy (in seconds)
t^{Reserve}	Average one-way travel time between the entrance to the picking aisle and reserve area (in seconds)
t_f^{Forward}	Average one-way travel time between the storage slot *f* in the forward pick area and entrance to that picking aisle (in seconds)
$c_f^{\text{Replenishment}}$	Total within rack travel time for each internal replenishment at location *f* in the forward pick area (in seconds)
$t_f^{\text{Replenishment}}$	Average one-way travel time required for moving a unit load from the reserve area to storage location *f* in the forward pick area (in seconds)
$t_{L\&UL}$	Total time required for loading the cage in the carriage of the S/R machine from the reserve area and unloading it into the destination storage slot in the forward area (in seconds)

When a forward reserve configuration is used, there would be three distinct material movement operations in the system:

1. **Putaway:** "Putaway" is the operation in which the cage containing spare parts is moved from the P/D point to an appropriate storage slot for storage. All the material received from the suppliers in the warehouse is putaway to the reserve storage area (see flow 1 in Figure B-1).

2. **Picking:** A retrieval operation of an item is called a "pick". Picking of items in the forward and reserve areas follow separate flows.
   a. Picking from reserve area: The items for which no storage slot is assigned in the forward pick area are picked directly from the reserve storage area, as indicated by flow 2 in Figure B-1.
   b. Picking from forward pick area: Item selected for storage in the forward area has cages carrying its SKUs in both the forward as well as reserve storage areas. However, picking is carried out only from the cage (unit load) in the forward pick area. Flow 4 indicates this movement in Figure B-1.
3. **Internal replenishment:** Items in the forward pick area need to be internally replenished from time to time from the reserve storage (See flow 3 in Figure B-1) to avoid stock out. The replenishments are made in unit loads only.

Economics of Forward-Reserve configuration

The total travel time under forward reserve configuration can be compared to that under random storage policy to assess the effectiveness of forward-reserve storage arrangement. Under the random storage policy, the time required for the putaway is $2 \times t^{\text{Random}} \times D$ and for the pick is $4 \times t^{\text{Random}} \times P$. The total travel time under random storage policy, thus, would be the sum of these two components.

In comparison to the random storage policy, under forward-reserve configuration, the presence of a forward area near the aisle entrance pushes the bulk storage area further from the aisle entrance point (See Figure B-1). This makes the travel path between the aisle entrance point and the reserve storage area longer (See flows 1 and 2 in Figure B-1). The resulting one-way travel time t^{Reserve} will be thus greater than t^{Random}. t^{Reserve} is computed in a manner similar to the calculation of t^{Random} , i.e. t^{Reserve} is determined as the average of the one-way travel times for all the storage slots in the reserve storage area. The times required for various activities under the forward-reserve configuration are:

1. Put away: The number of put-away operations in the planning period remains the same at D as under random storage policy. Consequently, the total putaway time $T_{Putaway}$ is determined as $T_{Putaway} = 2 \times t^{\text{Reserve}} \times D$.
2. Picking: The picking of the SKUs will be split along two paths as shown by flow 2 and flow 4 in Figure B-1.
   a. Picking from forward pick area: If P_j is the number of picks for item *j* selected for storage in the forward area at location *f*, then the total travel time in the forward pick area for picking item *j* is $4 \times t_f^{\text{Forward}} \times P_j$. Thus, the total time for picking all the products in the forward area $T_{Forward}$ is computed as $T_{Forward} = \sum_j 4 \times t_f^{\text{Forward}} \times P_j$.

b. Picking from the reserve area: The picks from the reserve area will follow flow 2. As the picking of SKUs in the forward area shall strictly be carried out from the forward area, the number of picks from the reserve area, say P_R, will be less than *P*. Let the total number of picks from the forward pick area be P_F determined as $P_F = \sum_j P_j$. Then, $P_R = P - P_F$. The total travel time for picking from the reserve area is given as $4 \times t^{\text{Reserve}} \times P_R$.

c. Internal replenishment: For each internal replenishment trip for a unit load, a crane travels empty from the aisle entrance to the location of the cage holding the required item in the reserve storage area, loads the cage in the carriage of the S/R machine, moves the cage to the forward pick area (flow 3), unloads the cage into the forward location and then returns empty to the aisle entrance point (flow 4). Hence, the total within rack travel time for each internal replenishment at location *f* is given as $c_f^{\text{Replenishment}} = t^{\text{Reserve}} + t_f^{\text{Replenishment}} + t_f^{\text{Forward}} + t_{L\&UL}$.

   If item *j* is assigned location *f* in the forward area from where all its picks are to be carried out, then the total replenishment time $T_{Replenishment}$ required for internal replenishments of items from the reserve area during the planning period will be $T_{Replenishment} = \sum_j c_f^{\text{Replenishment}} \times d_j$. It is assumed that internal replenishments are carried out after a putaway operation when the S/R machine is already in the picking aisle.