Warehousing

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Contents

1. The Need for Storage and Warehousing

A warehouse is the point in the supply chain where raw materials, work-in-process (WIP), or finished goods are stored for varying lengths of time. A *public warehouse* is a business that rents storage space to other firms on a month-to-month basis. They are often used by firms to supplement their own private warehouses. Warehouses can be used to add value to a supply chain in two basic ways:

- Storage—allows product to be available where and when it's needed.
- Transport economies—allows product to be collected, sorted, and distributed efficiently.

Warehouses only add value if the benefits of storing products in a warehouse enough to offset the additional cost associated with carrying any inventory. Other potential benefits associated with storage include the following: time bridging, which allows product to be available when it is needed (e.g., storing spare machine parts at the facility); processing, where for some products (e.g., wine), storage can be considered as a processing operation because the product undergoes a required change during storage; and securing, e.g., nuclear waste storage.

In production, ideally, raw material should arrive at a manufacturing facility just when it is needed and then immediately processed, the resulting products should be fabricated and assembled without delay, and the final finished products should be immediately shipped to their customers; in this situation (what could be termed pure "Just-In-Time" or JIT) there is little need for buffering or storing materials. In practice (including real-world JIT), there usually are economic benefits associated with the buffering and/or storage of raw materials, work in process (WIP), and/or finished goods.

In distribution, the ideal of no storage can sometimes be realized using cross docking, where there is a direct flow of material from trucks at the receiving docks to the shipping docks without buffering or storage in-between, but cross docking requires detailed planning and coordination (e.g., implemented using EDI) that in many cases may not be feasible.

In most cases, the benefits associated with buffering and storage are due to the fixed costs associated with the other elements of production and the impact of variability pooling on achieving a target service level. Storing a product allows the other elements of production to operate more efficiently on a per-unit basis because the fixed costs associated with utilizing the element can be spread over more products; e.g., storing up to a truckload of product in a facility reduces the per-unit costs of shipping, and WIP buffering or storage enables batch production, which reduces the per-unit setup costs.

2. Storage System Design

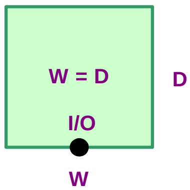
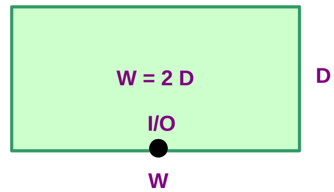
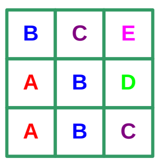
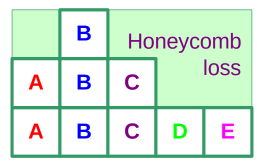
Each distinct type of load is termed an **item** or *stock-keeping unit* (or **SKU**); e.g., each different style, size, and color of a garment would be assigned a unique SKU. Units of each item are stored in **slots** (short for storage location). A slot is a generic term for any of a variety of different types of identifiable storage locations (e.g., racks, bins, marked-off floor areas for block storage). Each slot-item combination has an associated capacity corresponding to the number of units of the item that can be stored in the slot.

The handling costs for the units within a SKU can usually be minimized by always storing and retrieving a unit at the nearest (i.e., least handling effort or cost) available location, or what is termed a *closest open location* (or COL) policy. As long as the inventory levels of each SKU are controlled, a COL policy will result in an approximate uniform rotation of the items; but, if inventory is not controlled, using a COL policy can result in items remaining at far away slots for a long time. If a strict uniform rotation of the items is required (e.g., due to the items being perishable), then a *first-in, first-out* (or FIFO) policy can be used. In addition, a *last-in, first-out* (or LIFO) policy can be used.

Design Trade-Off

As shown in Table 1, warehouse design involves the trade-off between building and handling costs. Handling costs usually dominate building costs when a warehouse is only used for short-term storage, while building costs dominate for longer-term storage.

Table 1. Design Trade-Off

min *Building Costs*	vs.	min *Handling Costs*
⇕		⇕
max *Cube Utilization*	vs.	max *Material Accessibility*
 Square shape minimizes perimeter length for a given area, thus minimizing building costs	*Shape* vs.	 Aspect ratio of 2 ($W = 2D$) minimizes expected distance from I/O port to slots, thus minimizing handling costs
 Maximizes cube utilization, but minimizes material accessibility	*Storage* vs.	 Making at least one unit of each item accessible decreases cube utilization

Storage Locations

Each accessible storage location in a warehouse is assigned a unique address. Multiple units of an item assigned to a single location correspond to the capacity of the location. It is common to alternate between numeric and alphabetic characters in an address to improve readability, and to use even and odd numbers to designate each side of a down aisle.

The single address scheme shown in the Figure 1 can be used for each different storage medium in the warehouse:

- Pallet racks: Compartment dimension not used since only the front unit of each position is accessible.
- Shelves: All dimensions can be used if compartment dimension is accessible.
- Drawers: Position dimension not used if drawer has odd shaped compartments.
- Block stacking: Only building, aisle, and bay dimensions used to address each lane of storage.
- Misc. locations: Receiving, shipping, holding areas, outdoor trailer storage, etc., can all be given unique addresses.

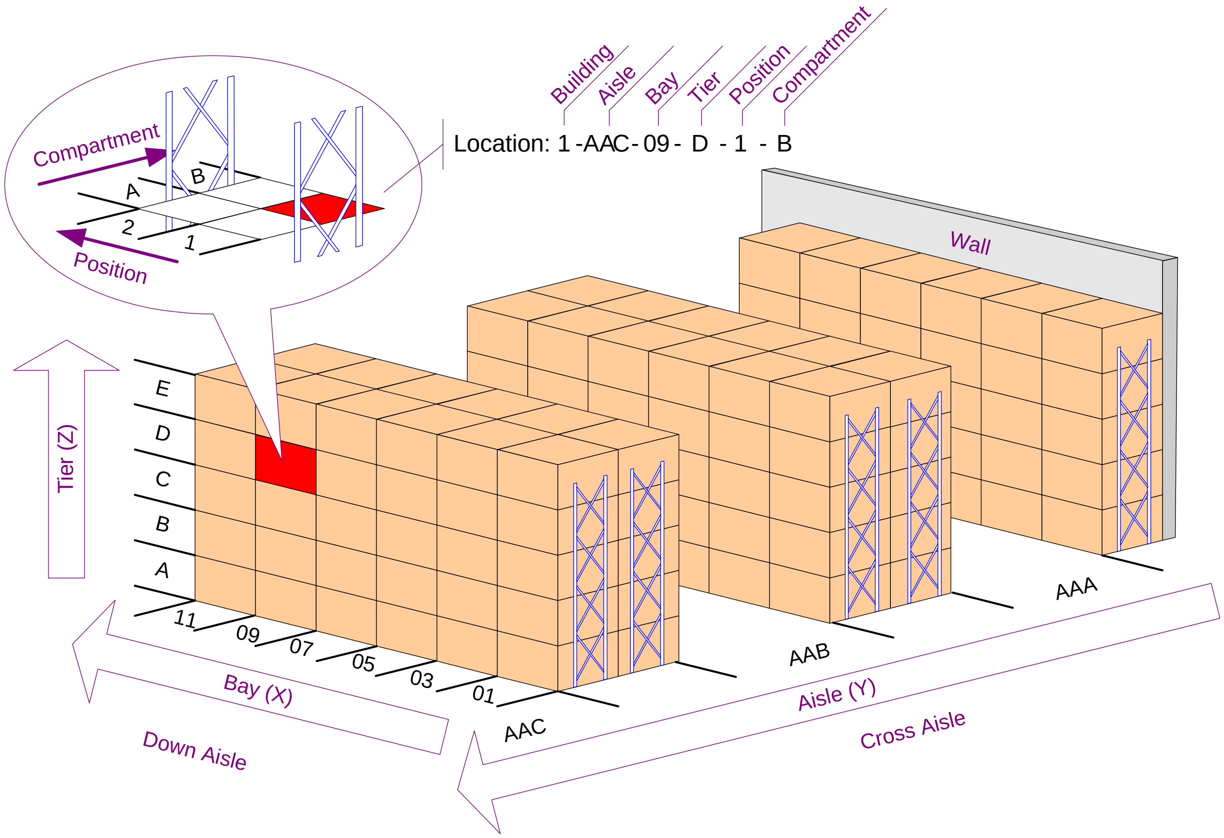


Figure 1. Storage locations.

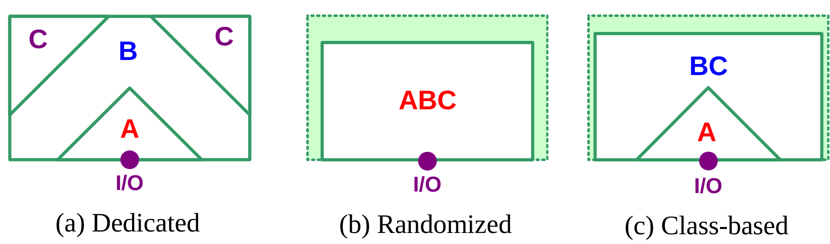


Figure 2. Storage area for SKUs, A, B, and C under different policies.

Storage Policies

For multiple SKUs, three types of storage policies (see Figure 2) can be used to select storage locations (or *slots*):

1. **Dedicated (or Fixed Slot) Storage**—each SKU has a predetermined number of slots assigned to it.

   The total capacity of the slots assigned to each SKU must equal the storage space corresponding to the maximum on-hand inventory of each *individual* SKU, where the actual storage space might be greater than this due to "honeycomb loss."

Minimizes handling cost and maximizes building costs. Control is not difficult because each lane can be identified with a permanent label.

2. **Randomized (or Open Slot or Floating Slot) Storage**—each SKU can be stored in any (usually the closest) available slot.

   The total capacity of all the slots must equal the storage space corresponding to the maximum *aggregate* on-hand inventory of all of the SKUs, where the actual storage space might be greater than this due to honeycomb loss.

   Minimizes building cost and maximizes handling costs. Control is more difficult than dedicated storage because the identity of SKU stored at each slot needs to be recorded for retrieval purposes.

3. **Class-based Storage**—a combination of dedicated and randomized storage, where each SKU is assigned to one of several different storage classes.

   Randomized storage is used for each SKU within a class, and dedicated storage is used between classes. Building and handling costs in-between dedicated and randomized.

   Classes can be formed from SKUs whose individual on-hand inventory is negatively correlated (or, at least, uncorrelated).

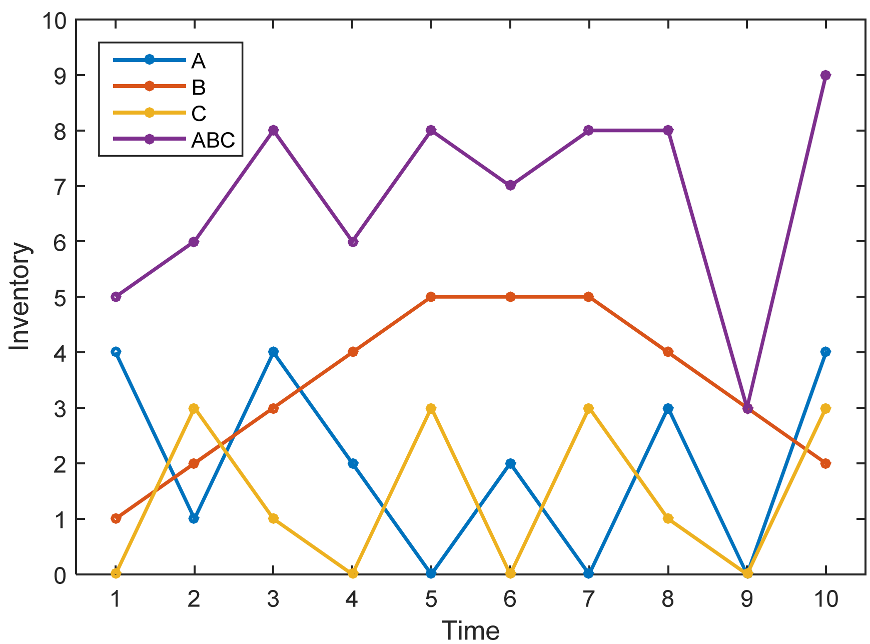


Figure 3. Inventory profiles for dedicated and randomized storage policies.

Table 2. Inventory and Storage Requirements for Different Storage Policies

	Dedicated			Random	Class-Based		
Time	A	B	C	ABC	AB	AC	BC
1	4	1	0	5	5	4	1
2	1	2	3	6	3	4	5
3	4	3	1	8	7	5	4
4	2	4	0	6	6	2	4
5	0	5	3	8	5	3	8
6	2	5	0	7	7	2	5
7	0	5	3	8	5	3	8
8	3	4	1	8	7	4	5
9	0	3	0	3	3	0	3
10	4	2	3	9	6	7	5
M_i	4	5	3	9	7	7	8

In the example shown in Figure 3 and Table 2, the on-hand inventory over 10 time periods for SKUs A, B, and C and the aggregate inventory for all three SKUs. If a dedicated storage policy is used, then a fixed number of slots must be reserved for each SKU for the entire 10 periods. In this example, SKU A has a peak of 4 in periods 1, 3, and 10; SKU B has a peak of 5 in periods 5 through 7; and SKU C has a peak of 3 in periods 2, 5, 7, and 10. If a randomized policy is used, then the aggregate inventory has a single peak of 9 in period 10. As long as the on-hand inventory of each SKU is not at its maximum at the same time, randomized storage will require a lesser number of slots as compared to dedicated storage and the minimum class-based policy (AB-C).

Table 2 shows the same on-hand inventory profiles shown in Figure 3 for dedicated and randomized storage. In addition, the three possible class-based storage policies, A+BC, B+AC, and C+AB, are shown, where the single SKU A forms one Class A and the aggregate of levels for SKUs B and C form a second Class BC, etc. (the single SKU classes are not shown because they are the same as the profiles for dedicated storage). Assuming that the storage space required for each unit of each SKU is the same and the capacity of each slot is one unit, the total number of slots for each storage alternative is as follows:

- Dedicated = sum of max SKU levels = 4 + 5 + 3 = 12 slots
- Randomized = max aggregate level = 9 slots.
- Classes C+AB = 3 + 7 = 10 slots (the other two possible class-based require 12 slots).

Based on just storage space requirements, a randomized policy would be preferred; but a dedicated or class-based policy may be preferred because they can sometimes reduce the handling requirements enough compared to randomized to offset their increase in storage requirements (this is an example of the trade-off between building and handling cost). In general, as long as the on-hand inventory of each SKU is not at its maximum at the same time, randomized storage will require a lesser number of slots as compared to dedicated storage.

A combination of dedicated and randomized storage termed “supermarket” storage is used in most less-than-unit-load order picking operations, where randomized storage is used for *reserve stock* and dedicated is used for *forward stock*. Cartons are picked from forward stock (in flow-through racks), and full pallet loads of cartons are taken from reserve stock (in bulk storage) and used to replenish the forward stock.

Cube Utilization and Honeycomb Loss

When storing multiple SKUs in a single region, full utilization of all of the available space is not desirable because it could result in some items not being accessible. *Honeycomb loss*, the price paid for accessibility, is the unusable empty storage space in a lane or stack due to the storage of only a single SKU in each lane or stack since storing items from different SKUs would block access. The empty space associated with partially filled lanes and stacks is termed “horizontal” and “vertical” honeycomb loss, respectively (see Figure 4). When a single SKU is stored in a region, there need not be any honeycomb loss since the depth and height of the region can exactly match the storage space need for the SKU.

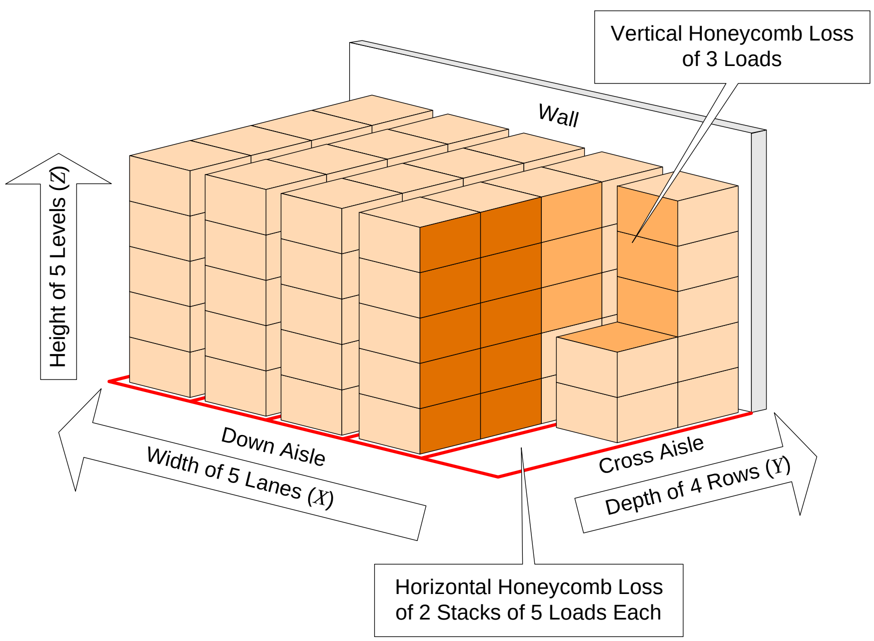


Figure 4. Horizontal and vertical honeycomb loss.

Cube utilization is the percentage of the total space (or “cube”) required for storage actually occupied by the loads being stored. There is usually a trade-off between cube utilization and material accessibility:

$$\text{increasing cube utilization} \Rightarrow \text{ decreased accessibility, and}$$

$$\text{increasing accessibility} \Rightarrow \text{ decreased cube utilization.}$$

Bulk storage using block stacking can result in the minimum cost of storage since cube utilization is high and no storage medium is required, but material accessibility is low since only the top of the front stack is accessible and loads at bottom of a stack must not require support. Storage racks are used when support and/or material accessibility is required.

Given a contiguous region where several different SKUs are to be stored, the principal decision variable for deep-lane storage is D, the number of rows of storage for the region. Given a load depth of y, the resulting lane depth is $Y = yD$. Different row values for the region will result in different cube utilizations. Since the space occupied by the items is assumed to be known, cube utilization can be determined once the total space is determined, where the total space is the item space plus honeycomb loss and the space used for access (e.g., down aisles). Given D and assuming *identical size loads for all items*, the cube utilization for dedicated and randomized storage can estimated as follows:

$$\text{Cube utilization} = CU = \frac{\text{item space}}{\text{total space}} = \frac{\text{item space}}{\text{item space} + \begin{pmatrix}\text{honeycomb}\\ \text{loss}\end{pmatrix} + \begin{pmatrix}\text{down aisle}\\ \text{space}\end{pmatrix}}$$

$$CU(\text{3-D}) = \begin{cases} \dfrac{x \cdot y \cdot z \cdot \sum_{i=1}^{N} M_i}{TS(D)}, & \text{dedicated} \\[2ex] \dfrac{x \cdot y \cdot z \cdot M}{TS(D)}, & \text{randomized} \end{cases} \qquad (1)$$

$$CU(\text{2-D}) = \begin{cases} \dfrac{x \cdot y \cdot \sum_{i=1}^{N} \left\lceil \dfrac{M_i}{H} \right\rceil}{TA(D)}, & \text{dedicated} \\[2ex] \dfrac{x \cdot y \cdot \left\lceil \dfrac{M}{H} \right\rceil}{TA(D)}, & \text{randomized} \end{cases} \qquad (2)$$

where

$x =$ lane/unit-load width

$y =$ unit-load depth

$z =$ unit-load height

$M_i =$ maximum number of units of SKU i

$M =$ maximum number of units of all SKUs

$N =$ number of different SKUs

$D =$ number of rows

$TS(D) =$ total 3-D *space* (given D rows of storage).

$TA(D) =$ total 2-D *area* (given D rows of storage).

Although not a cube, 2-D "cube" utilization is often easier to use and is equivalent to 3-D utilization as long as the height of storage is, and will remain, fixed. In (2), $CU(\text{2-D}) = (stack\ area)/(total\ area)$, where the stack area is the product of the 2-D footprint of each stack of H items, xy, and the total number of stacks, which is $\lceil M/H \rceil$ for randomized storage. The total area is given by (4).

Defining the *effective lane depth* as the depth of the lane plus half of the width of the down aisle in front of the lane, the total space required, as a function of lane depth, is

$$\text{Total space (3-D):} \quad TS(D) = X \cdot \underbrace{\left(Y + \frac{A}{2}\right)}_{\text{Eff. lane depth}} \cdot Z = xL(D) \cdot \left(yD + \frac{A}{2}\right) \cdot zH\,, \tag{3}$$

where

$X =$ width of storage region (row length)

$Y =$ depth of storage region (lane depth)

$Z =$ height of storage region (stack height)

$A =$ down aisle width

$L(D) =$ number of lanes (given D rows of storage)

$H =$ number of levels.

In most cases, only the 2-D area of a storage region is needed since the height of the region is fixed (see Figure 5). To convert the total 3-D space to 2-D area:

$$\text{Total area (2-D)} = TA(D) = \frac{TS(D)}{Z} = X \cdot Y^{\text{eff}} = xL(D) \cdot \left(yD + \frac{A}{2}\right) \tag{4}$$

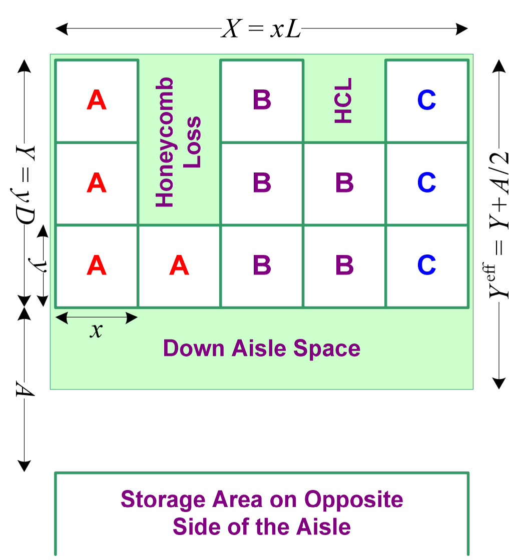


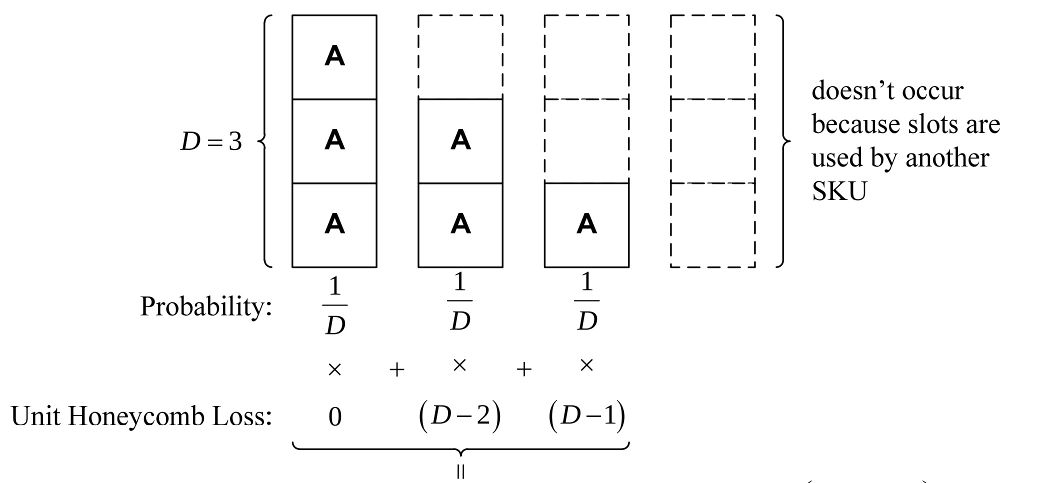
Figure 5. Total area of a storage region.

Given D, the total number of lanes required for storage in the region can be estimated as follows:

$$\text{Number of lanes:}\quad L(D)=\begin{cases}\displaystyle\sum_{i=1}^{N}\left\lceil \frac{M_i}{DH}\right\rceil, & \text{dedicated}\\[2ex] \left\lceil \dfrac{M+NH\left(\dfrac{D-1}{2}\right)+N\left(\dfrac{H-1}{2}\right)}{DH}\right\rceil, & \text{randomized } (N>1)\end{cases}, \qquad (5)$$

Note: in practice, there should be at least two lanes for each item to facilitate stock rotation so that all of the older units in one lane can be picked even after newer units are stored in the other lane.

For dedicated storage, the honeycomb loss can be directly determined for each item via the ceiling operation $\lceil \bullet \rceil$ in (5), which then determines the corresponding number of lanes required; for randomized storage, since only the total maximum number of units of items, M, is known and not the specific the number of each SKU that comprise this total at the exact time that the total reaches its maximum (unless the SKU's inventory levels are not perfectly correlated), the honeycomb loss can only be estimated by assuming that, at the maximum inventory level, the number of items in the partially filled lane and/or stack for each SKU is equally likely (see Figure 6).



$$\text{Expected Loss: } \frac{1}{D}\big[(D-2)+(D-1)\big]=\frac{1}{D}(1+2)=\frac{1}{D}\sum_{i=1}^{D-1} i=\frac{1}{D}\left(\frac{(D-1)D}{2}\right)=\frac{D-1}{2}=1$$

Figure 6. Expected honeycomb loss for dedicated storage.

If the SKUs' inventory levels are uncorrelated and items are either stored or retrieved at a constant rate so that, on average, half of the M_i items of SKU i are likely to be present at any given time, then

$$M=\left\lfloor \sum_{i=1}^{N}\frac{M_i}{2}+\frac{1}{2}\right\rfloor. \quad \text{(uncorrelated, constant demand)} \qquad (6)$$

This estimate can be increased to include safety stock for each item, SS_i. For example, if the order size of each of three different products is 50 units and 5 units of each item are held as safety stock, then

$$M = \left\lfloor \sum_{i=1}^{N} \left(\frac{M_i - SS_i}{2} + SS_i \right) + \frac{1}{2} \right\rfloor = \left\lfloor 3\left(\frac{50}{2} + 5 \right) + \frac{1}{2} \right\rfloor = 90 . \qquad (7)$$

Given the number of lanes L, the (3-D) honeycomb loss is:

$$\text{Honeycomb loss} = \begin{cases} xyz\left(L(D)DH - \sum_{i=1}^{N} M_i \right), & \text{dedicated} \\ xyz\left(L(D)DH - M \right), & \text{randomized} \end{cases} . \qquad (8)$$

An estimate of (3-D) honeycomb loss for randomized storage that is used to determine the expected number of lanes in (5) is

$$\text{Expected honeycomb loss} = N\,x\,y\,z \left[\underbrace{H\left(\frac{D-1}{2} \right)}_{\text{Partial lane loss}} + \underbrace{\left(\frac{H-1}{2} \right)}_{\text{Partial stack loss}} \right] \qquad (9)$$

Given the number of lanes of storage, the corresponding (3-D) down aisle space is

$$\text{Down aisle space} = xL(D) \cdot \frac{A}{2} \cdot zH . \qquad (10)$$

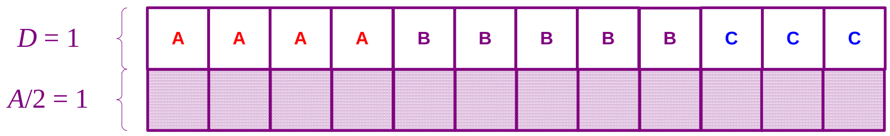
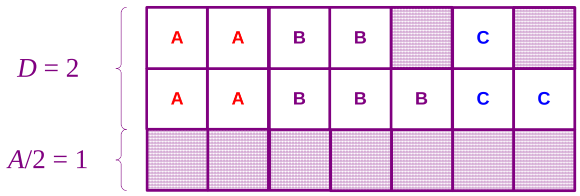
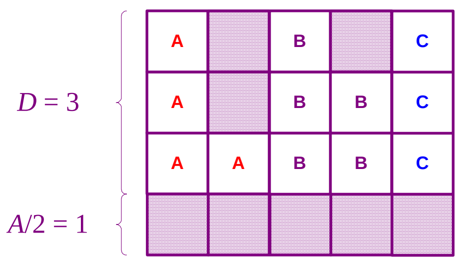
Optimal Lane Depth

The lane depth that maximizes cube utilization corresponds to best compromise between honeycomb loss (8) and down-aisle space loss (10) (see, also, Figure 7).

Example: Dedicated Storage

The optimal value for dedicated storage can be determined by calculating the utilization associated with each stack using for D ranging from 1 to $\max\{M_i'\}$. In this example for SKUs A, B, and C (see Table 3), $x = 1$, $y = 1$, $z = 1$, $M_A = 4$, $M_B = 5$, $M_C = 3$, $N = 3$, $A = 2$, and $H = 1$. Starting with a lane depth of $D = 1$, which results in 12 lanes of storage and a cube utilization of 50%, the value used for D is increased until either the cube utilization starts to decrease or D reaches the maximum number of units required for any of the SKUs, $\max\{M_i\}$ (at which point there would be a single lane for each SKU). In the example, the cube utilization is still increasing at $D = 3$, so $D = 4$ would need to be considered next. At $D = 3$, the honeycomb loss is 3 units and the down-aisle space loss is 5 units, for a total loss of 8 = 20 – 12 units.

Table 3. Cube Utilization for Dedicated Storage

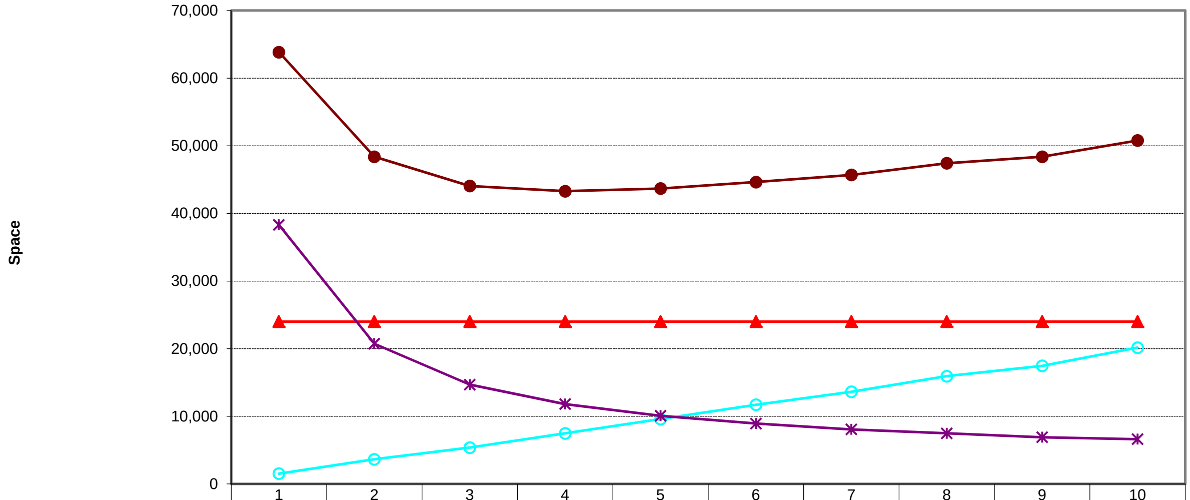
Storage Area at Different Lane Depths	Item Area	Lanes	Total Area	Cube Util.
	12	12	24	50%
	12	7	21	57%
	12	5	20	60%

Example: Randomized Storage

Unlike dedicated storage, where the optimal lane depth corresponding to the maximum cube utilization is determined by value checking each different value of D, the optimal lane depth, D^*, for randomized storage can be determined by direct calculation using an analytical approximation formula. Since the item space is constant in (2), cube utilization can be maximized by minimizing total space. Minimizing (3) (ignoring the ceiling operation in (5)) by solving for D in $dTS(D)/dD = 0$ results in the following expression to determine D^*, the lane depth (in rows) that maximizes cube utilization:

$$\text{Optimal lane depth for randomized storage (in rows):} \quad D^* = \left\lfloor \sqrt{\frac{A(2M-N)}{2NyH}} + \frac{1}{2} \right\rfloor . \qquad (11)$$

Taking the floor of $\lfloor \bullet + 0.5 \rfloor$ in (11) forces the result to the nearest integer. Equation (11) provides only an approximation of the optimal lane depth because the ceiling operation in (5) is ignored; to calculate the optimal depth, actual $TS(D)$ values should be directly calculated for several D values close to D^*.



	1	2	3	4	5	6	7	8	9	10
Item Space	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
Honeycomb Loss	1,536	3,648	5,376	7,488	9,600	11,712	13,632	15,936	17,472	20,160
Aisle Space	38,304	20,736	14,688	11,808	10,080	8,928	8,064	7,488	6,912	6,624
Total Space	63,840	48,384	44,064	43,296	43,680	44,640	45,696	47,424	48,384	50,784

Figure 7. Total space associated with different lane depths for deep-lane randomized storage.

In this example, $x = 4$, $y = 4$, $z = 3$, $M = 500$, $N = 20$, $A = 12$, and $H = 4$. Figure 7 shows the total space associated with D ranging from 1 to 10. Also shown are the components of total space: item space, honeycomb loss, and down-aisle space. Using (11) or finding the minimum total space in Figure 7, the optimal lane depth is $D^* = 4$. D^* is then used in (5) to determine the number lanes, $L(4) = 41$, which is then used in (3) to determine the total space, $TS(4) = 43{,}296$. The corresponding maximum cube utilization is as follows:

$$\text{Max cube utilization} = \frac{\text{item space}}{\text{total space } (D = 4)} = \frac{x \cdot y \cdot z \cdot M}{TS(4)} = \frac{4 \cdot 4 \cdot 3 \cdot 500}{43{,}296} = 0.5543 = 55.43\% .$$

Estimating Handling Costs

Minimizing handling costs usually increases building costs, where the cost of racks, etc., are included as part of the building costs. Warehouse design involves determining the best compromise between these issues. Handling costs can be estimated by determining:

1. Expected time required for each move based on an average of the time required to reach each slot in the region.
2. Number of vehicles needed to handle a target peak demand for moves, e.g., moves per hour.
3. Operating costs per hour of vehicle operation, e.g., labor, fuel.
4. Annual operating costs based on annual demand for moves.

5. Total handling costs as the sum of the annual capital recovery costs for the vehicles and the annual operating costs.

Storage and Retrieval Cycle

A storage and retrieval (S/R) cycle is one complete roundtrip from an I/O port to slot(s) and back to the I/O. The type of cycle depends on load carrying ability of the material handling device. Most fork trucks can carry only one pallet load at a time, while a cart used for piece order picking can carry multiple loads at the same time.

- Carrying one load at-a-time:

  Single command

  Storage: carry one load to slot for storage and return empty back to I/O port, or

  Retrieval: travel empty to slot to retrieve load and return with it back to I/O port.

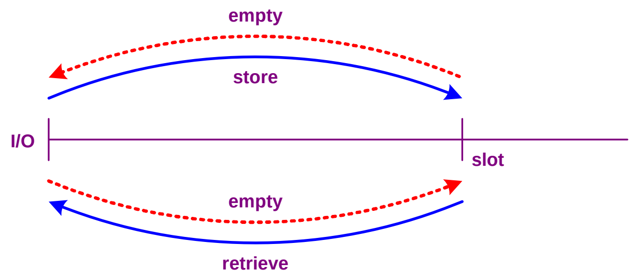


Figure 8. Single-command S/R cycle.

  Dual command

  Combine storage with a retrieval: Store load in slot 1, travel empty to slot 2 to retrieve load. Can reduce travel distance by a third. Also termed task “interleaving.”

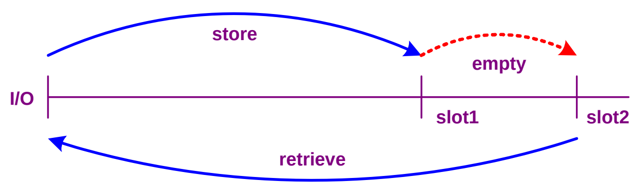


Figure 9. Dual-command S/R cycle.

- Carrying multiple loads:

  Multiple command

  Multiple loads can be carried at the same time. Used in case and piece order picking.

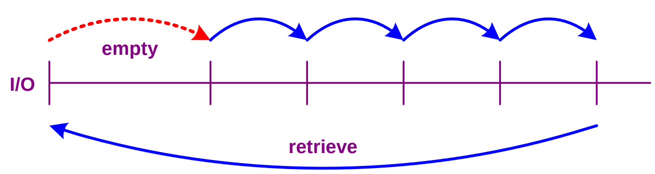


Figure 10. Multiple command S/R cycle.

Expected Time per S/R Cycle

The expected time for each single-command (SC) S/R cycle is

$$\text{Single-command:} \quad t_{SC} = \frac{d_{SC}}{v} + t_L + t_U = \frac{d_{SC}}{v} + 2t_{L/U}\,, \qquad (12)$$

where

d_{SC} = expected distance per SC cycle

v = average travel speed (e.g.: 2 mph = 176 fpm walking; 7 mph = 616 fpm riding)

t_L = loading time

t_U = unloading time

$t_{L/U}$ = loading/unloading time, if same value

The expected time for each dual-command (DC) S/R cycle is

$$\text{Dual-command:} \quad t_{DC} = \frac{d_{DC}}{v} + 2t_L + 2t_U = \frac{d_{DC}}{v} + 4t_{L/U} \tag{13}$$

Estimating Expected Distance

It is helpful to consider determining the expected distance for a storage region consisting of just a single row of slots (i.e., a 1-D region as shown in Figure 11) because the result for a 2-D region, assuming rectilinear distances, is the same as the 1-D result for each dimension. The following results assume (1) all S/R cycles are single-command, (2) rectilinear distances, and (3) each slot is region used with equal frequency (i.e., randomized storage). For dedicated or class-based storage, the expected distance for each SKU or class would be determined separately. Similar formulae can be developed for dual-command S/R cycles.

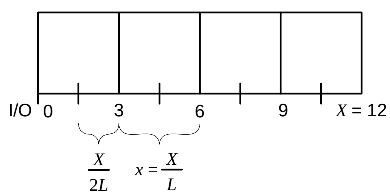


Figure 11. 1-D expected distance.

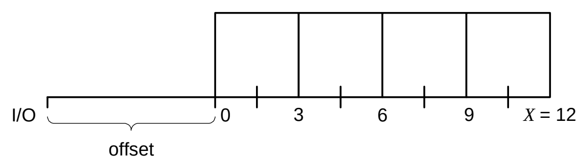


Figure 12. Off-set from I/O port.

1-D Expected Distance

In the 1-D region shown in Figure 11, the expected distance is the average distance from I/O port to midpoint of each slot; e.g., [2(1.5) + 2(4.5) + 2(6.5) + 2(10.5)]/4 = 12, which corresponds to $d_{SC} = X$ =12 as determined in (14).

$$TD_{\text{1-way}} = \sum_{i=1}^{L} \left(i\frac{X}{L} - \frac{X}{2L} \right) = \frac{X}{L} \left(\sum_{i=1}^{L} i - \frac{1}{2} \sum_{i=1}^{L} (1) \right)$$

$$= \frac{X}{L} \left(\frac{L(L+1)}{2} - \frac{L}{2} \right) = \frac{XL + X - X}{2} = \frac{XL}{2}$$

$$ED_{\text{1-way}} = \frac{TD_{\text{1-way}}}{L} = \frac{X}{2}$$

$$d_{SC} = 2(ED_{\text{1-way}}) = X \tag{14}$$

In the handling cost example shown in Figure 16, below, the I/O point was located along the perimeter of the storage region. In many cases, the I/O point is not adjacent to the storage region and each move involves travel between the I/O point and the perimeter of the storage region (see Figure 12). The area between the I/O and the storage region may be a different storage region. If the I/O port is off-set from the storage region, then 2 times the distance of the offset is added the expected distance within the slots:

$$d_{SC} = 2(offset) + X \tag{15}$$

2-D Expected Distance

Since dimensions *X* and *Y* are independent of each other for rectilinear distances, the expected distance for a 2-D rectangular region with the I/O port in a corner is just the sum of the distance in *X* and in *Y*:

$$d_{SC}^{rect} = X + Y \tag{16}$$

For a triangular region with the I/O port in the corner (see Figure 13), let $X = Y$ and $L = D$, so that

$$TD_{\text{1-way}} = \sum_{i=1}^{L} \sum_{j=1}^{L-i+1} \left[\left(i\frac{X}{L} - \frac{X}{2L} \right) + \left(j\frac{X}{L} - \frac{X}{2L} \right) \right] = \quad \cdots$$

$$= \frac{X}{6}\left(2L^2 + 3L + 1\right)$$

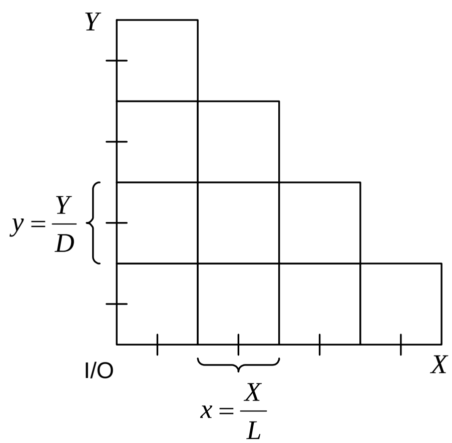


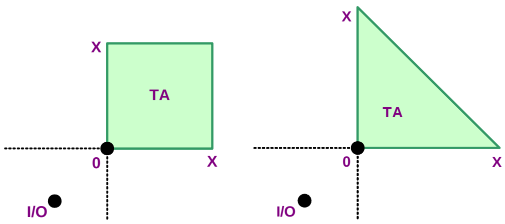
Figure 13. 2-D triangular region.

The expected distance result for a triangular region is an approximation that becomes exact as the number of slots in the region increases:

$$ED_{\text{1-way}} = \frac{TD_{\text{1-way}}}{\frac{L(L+1)}{2}} = \frac{2}{3}X + \frac{X}{3L} = \frac{2}{3}X, \quad \text{as } L \to \infty$$

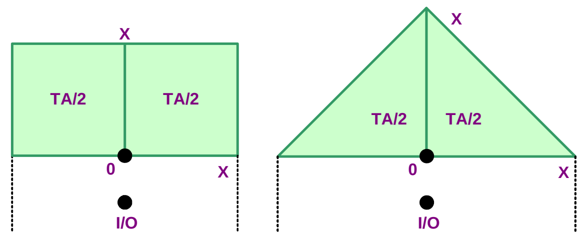
$$d_{SC}^{tri} = 2\left(\frac{2}{3}X\right) = 2\left(\frac{1}{3}X + \frac{1}{3}Y\right) = \frac{2}{3}(X + Y). \tag{17}$$

The expected distance for two region shapes, rectangular and triangular, and two different I/O point configurations will be considered. In Figure 14, the I/O point is assumed to be located off to a side of the region; in Figure 15, it is assumed to be offset from the middle of a side of the region. The expected distances for each configuration are as follows:



(a) Rectangular (b) Triangular

Figure 14. I/O-to-side configurations.



(a) Rectangular (b) Triangular

Figure 15. I/O-at-Middle configurations.

$$\textit{Rect. I/O-to-Side:}\quad TA = X^2 \Rightarrow X = \sqrt{TA} \Rightarrow d_{SC} = \boxed{2\sqrt{TA}} \tag{18}$$

$$\textit{Tri. I/O-to-Side:}\quad TA = \frac{1}{2}X^2 \Rightarrow X = \sqrt{2TA} = \sqrt{2}\sqrt{TA} \Rightarrow d_{SC} = \frac{4}{3}\sqrt{2}\sqrt{TA} = \boxed{1.886\sqrt{TA}} \tag{19}$$

$$\textit{Rect. I/O-in-Middle:}\quad \frac{TA}{2} = X^2 \Rightarrow X = \sqrt{\frac{TA}{2}} = \frac{\sqrt{TA}}{\sqrt{2}} \Rightarrow d_{SC} = \sqrt{2}\sqrt{TA} = \boxed{1.414\sqrt{TA}} \tag{20}$$

$$\textit{Tri. I/O- in-Middle:}\quad \frac{TA}{2} = \frac{1}{2}X^2 \Rightarrow X = \sqrt{TA} \Rightarrow d_{SC} = \frac{4}{3}\sqrt{TA} = \boxed{1.333\sqrt{TA}} \tag{21}$$

Given the opportunity to select a shape for a storage region where the I/O point is to be located off to a side of the region (Figure 14), a square and an isosceles right triangle are the shapes that minimize the expected distance for rectangular and triangular regions, respectively. In both cases, $X = Y$, and the expected distance can be determined in terms of the total storage area, *TA*. The distance does not include I/O offset. Thus, given the same *TA* for both the rectangular and triangular regions, the triangular region provides a (2 – 1.886)/2 = 5.7% reduction in expected distance as compared to a rectangular region. If the region is not a square or an isosceles right triangle, then the formulae on the previous slide can be used.

Given the opportunity to select a shape for a storage region where the I/O point is assumed to be offset from the middle of a side of a region (Figure 15), a rectangle with as aspect ratio of 2 (side-by-side squares) and side-by-side isosceles right triangles are the shapes that minimize the expected distance for rectangular and triangular regions, respectively. In both cases, $X = Y$, and the expected distance can be determined in terms of the total storage area, *TA*. The distance does not include I/O offset. Given a square rectangular region (as on the previous slide) with the same *TA* as a rectangular region with as aspect ratio of 2, the latter region provides a (2 – 1.414)/2 = 29.3% reduction in expected distance as compared to the square region.

Handling Cost Example

The storage region in this example has a total area of TA = 20,000 square feet and thousands of slots (see Figure 16). The expected distance for a single-command S/R cycle from the I/O point (e.g., loading dock) to all of the slots is 200 feet. The formula used to determine the expected distance depends on the shape of the storage region and the location for the I/O point relative to the region. The expected time per S/R cycle is determined by converting the expected distance to time, assuming a travel speed of 200 fpm, and adding the time required for loading (30 s) and unloading (30 m) for the single-command cycle.

In this example, the peak demand is 75 moves per hour. If the warehouse operates for 2,000 hours per year, then the annual demand of 100,000 moves corresponds to 50 moves per hour, thus the peak demand is 50% greater than the average demand. The investment related cost of \$7,500 per year for all of the trucks is proportional to the peak demand, while the operating cost of \$33,333 per year for labor is proportional to the average demand. The only operating cost considered is labor cost (\$10 per hour), which is usually the largest such cost (fuel is typically one-tenth the cost of labor). Labor cost is determined based only on the total hours spend performing the required moves. If the three truck operators needed for the peak periods of demand were solely dedicated to performing these moves and each was available for 2,000 hours per year, then the labor cost would be 3 × 10 × 2,000 = \$60,000 per year. The lower cost (\$33,333) assumes that it is possible for the operators to perform other tasks during the off-peak periods.

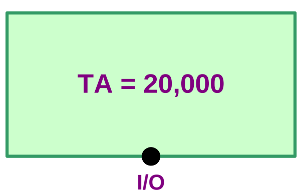


Figure 16. Handling cost example.

$$\text{Expected Distance: } d_{SC} = \sqrt{2}\sqrt{TA} = \sqrt{2}\sqrt{20,000} = 200 \text{ ft}$$

$$\text{Expected Time: } t_{SC} = \frac{d_{SC}}{v} + 2t_{L/U}$$

$$= \frac{200 \text{ ft}}{200 \text{ fpm}} + 2(0.5 \text{ min}) = 2 \text{ min per move}$$

$$\text{Peak Demand: } r_{\text{peak}} = 75 \text{ moves per hour}$$

$$\text{Annual Demand: } r_{\text{year}} = 100,000 \text{ moves per year}$$

$$\text{Number of Trucks: } m = \left\lfloor r_{\text{peak}} \frac{t_{SC}}{60} + 1 \right\rfloor = \lfloor 3.5 \rfloor = 3 \text{ trucks}$$

$$\text{Handling Cost: } TC_{\text{hand}} = mC_{\text{truck}} + r_{\text{year}} \frac{t_{SC}}{60} C_{\text{labor}}$$

$$= 3(\$2,500 / \text{truck}) + 100,000 \frac{2}{60} (\$10 / \text{hr})$$

$$= \$7,500 + \$33,333 = \$40,833 \text{ per year}$$

Estimating AS/RS

An automated storage/retrieval system (AS/RS) consists of an integrated computer-controlled system that implements the storage/warehousing elements (e.g., storage medium, transport mechanism, and controls) with various levels of automation for fast and accurate random storage of products and materials. One of the unique aspects of an AS/RS with respect to its design is the mode of operation of the S/R machines. In the design of most storage systems, rectilinear distances can be used to represent the movement of the transport mechanisms; in an AS/RS, the S/R machines can move a load in the horizontal direction along an aisle and lift the load in the vertical direction simultaneously (and, typically, at different speeds), so that the use of rectilinear distances would overestimate the distance (or time) the load travels.

Letting v_x and v_z be the horizontal (X) and vertical (Z) speeds, respectively, of an S/R machine, then the time required for the machine to move from (x_0, z_0) to (x, z), assuming instantaneous acceleration, can be represented by the Chebychev "distance":

$$\max\left\{\frac{|x-x_0|}{v_x},\frac{|y-y_0|}{v_y}\right\} \tag{22}$$

For each aisle of an AS/RS, the I/O port for the aisle is typically at the end the aisle and at the bottom level of the racks in the aisle; thus, assuming (x_0, z_0) = (0, 0) as the location of the I/O port (and ignoring the horizontal movement (Y) of the S/R machine's shuttle into the racks), the time required to travel from the I/O port to location (x, z) is

$$\max\left\{\frac{x}{v_x},\frac{y}{v_y}\right\}. \tag{23}$$

Dedicated Storage Assignment Problem (DSAP)

In this section, items are assigned to the slots so that the total cost of material flow is minimized.

Given a layout with N items, the following Dedicated Storage Assignment Problem (DSAP) can be used to determine slot assignments:

DSAP SOLUTION PROCEDURE

1. *Order Slots:* Compute the expected cost for each slot and then put into nondecreasing order.
2. *Order Items:* Put the flow density (flow per unit of volume) for each item i into nonincreasing order

$$\frac{f_{[1]}}{M_{[1]}s_{[1]}} \ge \frac{f_{[2]}}{M_{[2]}s_{[2]}} \ge \cdots \ge \frac{f_{[N]}}{M_{[N]}s_{[N]}}$$

3. *Assign Items to Slots:* For $i = 1, \ldots, N$, assign item $[i]$ to the first slots with a total volume of at least $M_{[i]}s_{[i]}$.

where,

f_i = flow (i.e., moves per period) of item i

s_i = storage space per unit of item i

M_i = maximum number of units of item i

The *volume* of storage space needed for an item i is $M_i s_i$. If the handling costs are identical for all moves between slots and I/O ports, then slot cost can be viewed as the expected distance traveled between the slot and all of the I/O ports. The cube-per-order index (COI), which is the reciprocal of the flow per unit volume, is sometimes used instead, and items are then stored in nondecreasing order.

Assumptions

The following assumptions must be satisfied in order to be able to use the DSAP procedure:

1. All storage/retrieval (S/R) operations are performed as single-command cycles.
2. For item i, the probability of a move to/from each slot assigned to the item is the same.
3. The *factoring assumption*:
   (a) Handling costs and distances (or times) are identical for all items
   (b) The percent of S/R moves of an item stored at slot j to/from I/O port k is identical for all items.

If the factoring assumption is not satisfied and the storage space per unit of each item is the same, then the DSAP can be solved as a Transportation Problem. Transportation problems can be solved relatively easily using commercial software packages.

Due to Assumptions 1 and 2, the slots do not interact with each other; if some of the S/R operations were dual command or part of case or piece order picking (see the slotting discussion in Section 0), then the cost of assigning a slot to an item would depend on what items were assigned to the other slots. If the probabilities of using slots for an item were not all equal (e.g., if the slots that are nearer an I/O port had a higher probability of being used), then the cost for a slot would depend on what other slots are assigned to the item.

Assumption 2 would be valid if, for example, both a FIFO retrieval policy is used for all items, and the slot assigned to item *i* that has remained empty the longest is always the next slot used for storage. In practice, these conditions would be approximately satisfied if all storages (retrievals) took place in a short time period (e.g., receiving (shipping) of truck loads of material) and the slots were emptied (filled) before the next storages (retrievals) took place.

Assumption 3 is termed the *factoring assumption* because it allows the total cost to be factored into the product of two terms, one based only on the slot cost and one based only on the cube per order. In practice, Assumption 3(a) would be satisfied if, for example, the same MHE is used for all items and the handling characteristics (including loading/unloading times) are the same for all items. Assumption 3(b) would be valid if, for example, there is only one I/O port, or there are two ports and one is used only for input and the other port is used only for output and the ratio of flow into a slot to flow out of a slot is identical for all items; the assumption would need to be verified in other situations.

1-D DSAP Example

The DSAP procedure is used to assign items A, B, and C to dedicated 1-D storage regions:

Step 1. The cost of each slot is its distance from the I/O point; thus, from left to right, slots are in nondecreasing order.

Step 2. Items are ordered C-A-B, which corresponds to ranking their flow density values in nonincreasing order 7.00, 6.00, and 1.40.

Step 3. Item C is assigned to the 3 leftmost slots; item A to the next 4 leftmost slots; and item B to the next 5 leftmost slots.

The data for the example is given in Table 4, and is a continuation of the example given in Table 2. The assignment C-A-B minimizes the total distance (436) required to complete the 24, 7, and 21 single-command S/R cycles for items A, B, and C, respectively. The total distance is calculated by summing together the product of the expected distance and flow for each item. The expected distance is calculated as $d_{SC} = 2(offset) + X$. The storage region for item A is offset 3 units from the I/O point because of the slots occupied by item C, and item B is offset 7 units because of the slots occupied by items C and A.

Table 4. Data for 1-D DSAP Example

		Dedicated			Random	Class-Based		
		A	B	C	ABC	AB	AC	BC
Max units	M	4	5	3	9	7	7	8
Space/unit	s	1	1	1	1	1	1	1
Flow	f	24	7	21	52	31	45	28
Flow Density	$f/(M \times s)$	6.00	1.40	7.00	5.78	4.43	6.43	3.50

Table 5. 1-D DSAP Example

Flow Density	1-D Slot Assignments	Expected Distance		Flow		Total Distance
$\frac{21}{3} = 7.00$	I/O C C C _ _ _ _ _ _ _ _ _ (0, 3)	2(0) + 3 = 3	×	21	=	63
$\frac{24}{4} = 6.00$	I/O _ _ _ A A A A _ _ _ _ _ (-3, 0, 4)	2(3) + 4 = 10	×	24	=	240
$\frac{7}{5} = 1.40$	I/O _ _ _ _ _ _ _ B B B B B (-7, 0, 5)	2(7) + 5 = 19	×	7	=	133
	I/O C C C A A A A B B B B B (0, 3, 7, 12)					436

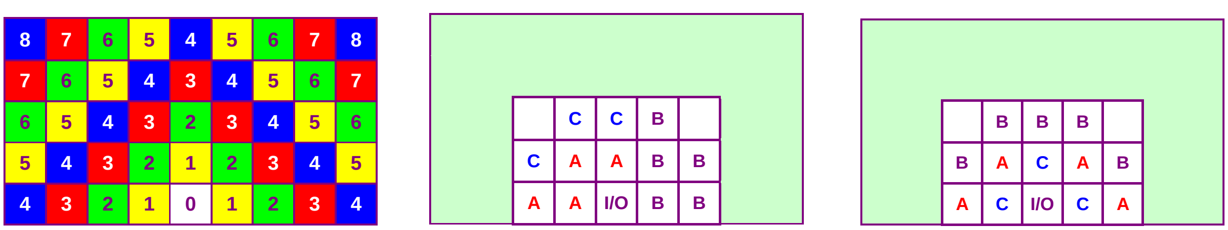
The optimal assignment C-A-B, which corresponds to ranking the flow density values in nonincreasing order, results in the minimum total distance as compared to all other possible dedicated slot assignment. One possible alternative is to rank the just the flow values in nonincreasing order (24, 21, and 7), which results in the assignment A-C-B with a total distance greater than the optimal assignment (460 vs. 436). The optimal class-based assignment (C-AB) and randomized storage (ABC) both have greater total distances than dedicated storage but require a less space, illustrating the trade-off between building costs and handling costs in warehouse design.

Table 6. Comparison of Different Storage Policies

	1-D Slot Assignments	Total Distance	Total Space
Dedicated (flow density)	I/O C C C A A A A B B B B B	436	12
Dedicated (flow only)	I/O A A A A C C C B B B B B	460	12
Class-based	I/O C C C AB AB AB AB AB AB AB	466	10
Randomized	I/O ABC ABC ABC ABC ABC ABC ABC ABC ABC	468	9

2-D DSAP Example

This example is the same as the 1-D Slotting example except that the slots are ordered based on their 2-D rectilinear distance from the I/O port as shown in Figure 17 (a). Distances are determined from the center of the I/O square to the center of each slot, and each slot is assumed to include a portion of aisle space. The contours of equal distance slots have a triangular shape because distances are rectilinear, as opposed to the circular-shaped contours that would be formed is distances were Euclidean (i.e., straight-line). In the optimal assignment shown in Figure 17 (c), item C is assigned to the slots of the contour closest to the I/O.



(a) Distance from I/O to Slot (b) Original Assignment (TD = 215) (c) Optimal Assignment (TD = 177)

Figure 17. 2-D DSAP example.

3. Warehouse Operations

Typical Warehousing Functions

In most warehouses (see Figure 18 and Figure 19), products are received and, if they cannot be cross-docked and immediately shipped out, are putaway into storage until they are needed to fill a customer's order, at which time they are picked from storage, packed, sorted, and unitized, if necessary, and then shipped to customers. A separate forward picking storage area can be used to enable more efficient order picking. It is replenished from a reserve storage area. Periodically, partially filled storage locations containing the same type of item are consolidated into a single location to improve space utilization, items are moved to different storage locations to improve handling efficiency in a process termed rewarehousing, and the contents of storage locations are counted in order to verify the accuracy of inventory records in a process termed *cycle counting*. Storage for pallet and case picking occupies the majority of space in a typical warehouse.

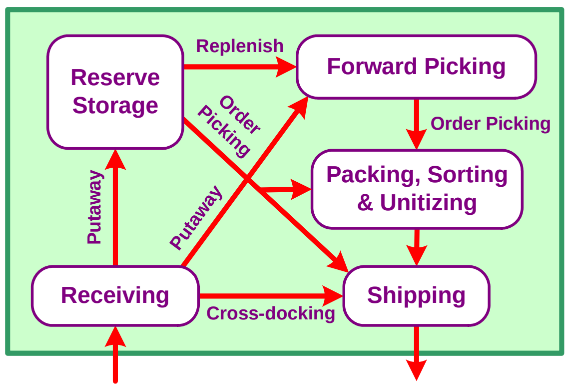


Figure 18. Typical warehousing functions.

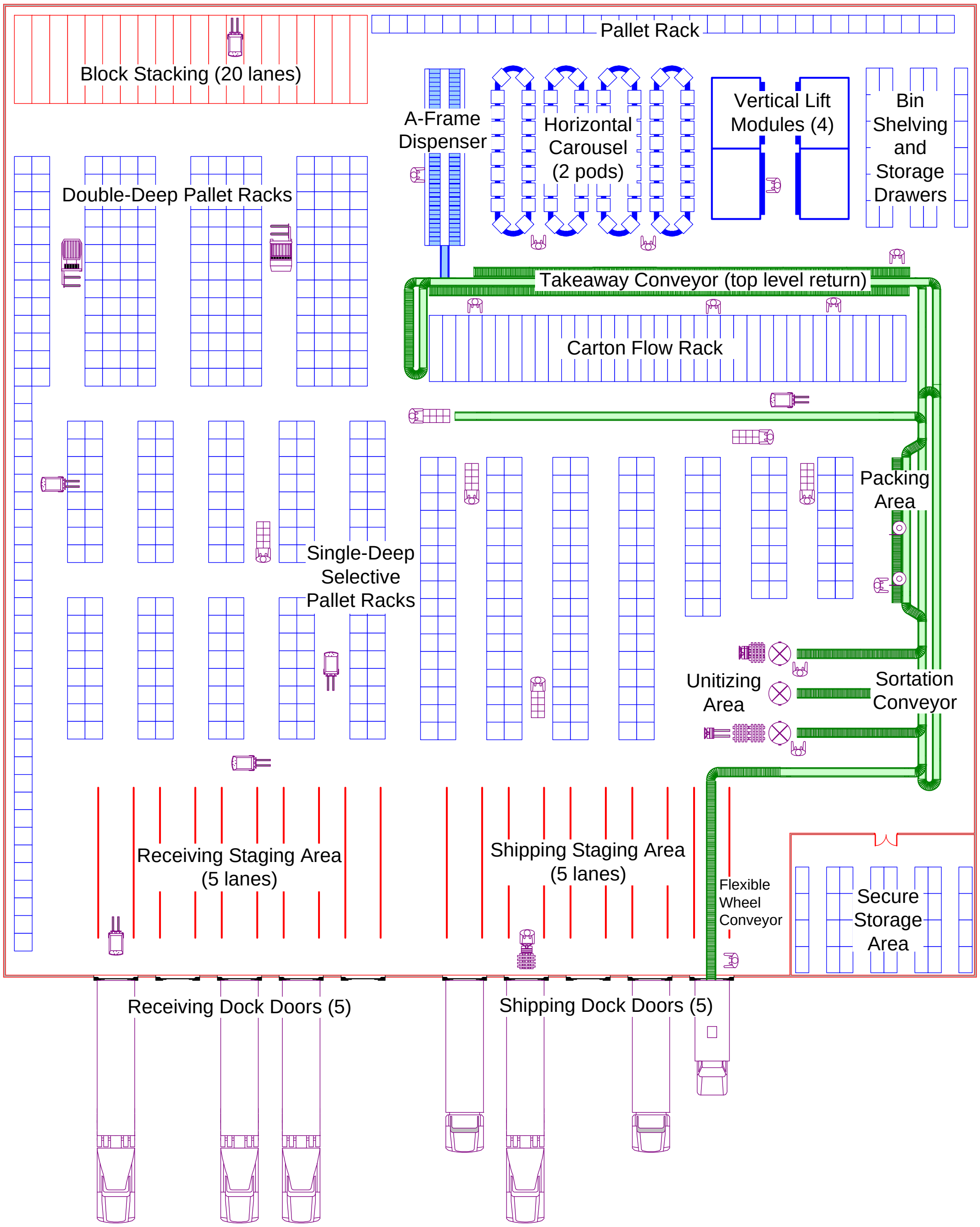


Figure 19. Example distribution center.

Warehouse Control

Warehouse control involves the interplay between inventory control and location management. The warehouse management system (WMS) is the software system that enables real-time, paperless control of warehouse operations. As shown in Figure 20, the WMS of a single warehouse interfaces with the corporation's enterprise resource planning (ERP) software where item, carrier, and customer master files common to all of the firm's warehouses reside. This information is used to create and maintain an inventory master file and a location master file. The WMS uses these files along with control logic to execute the required warehouse operations, which include interfacing with the various automated material handling equipment subsystems and generating pick lists for order picking. Advance shipping notices (ASNs) are sent to the WMS from suppliers as part of the receiving function, and the WMS sends ASNs to customers as part of the shipping function of a warehouse. A separate transportation management system (TMS) is typically used to determine shipping details.

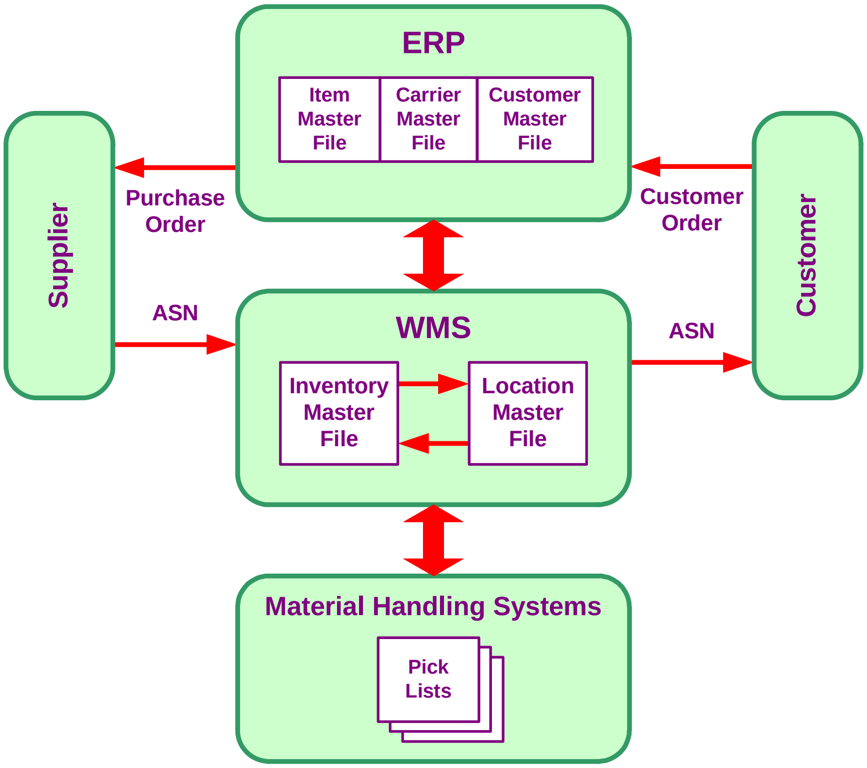


Figure 20. Warehouse management system.

At its lowest level, warehouse operations involve the storage of an object at a location or the movement of an object between locations. Inventory is the quantity of each item stored in the warehouse, and the inventory master file acts as the repository for all inventory in the warehouse. It contains the total quantity and storage locations of each item stored in the warehouse and is used together with the location master file to control material transport operations. The location master file provides the link between the WMS's logical representation of the warehouse and the physical layout of the warehouse. The item master file is used to identify valid items that are handled in the warehouse, and includes information about the item that is need for picking purposes (see Figure 26 for an example). The carrier master file includes transportation-related information (e.g., rate schedules) that is used for shipping completed orders, and the customer master file is used to store customer preferences for how orders are to be shipped so that it does not need to be included in each order.

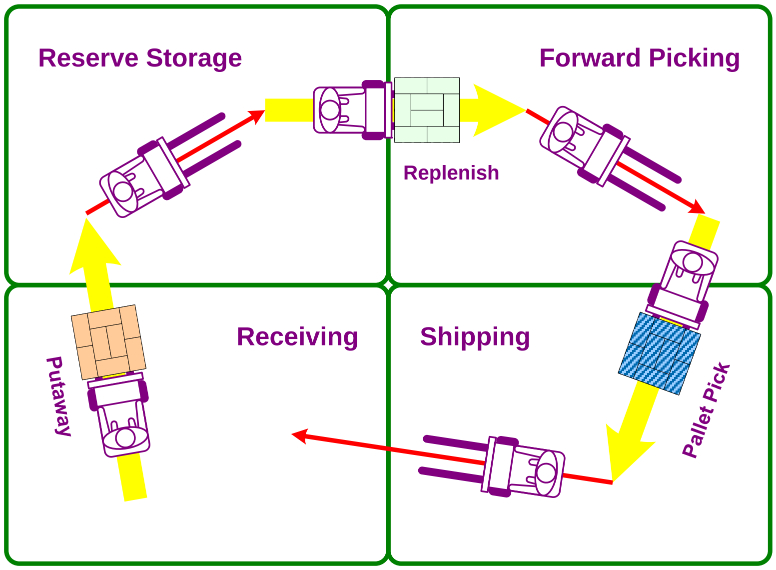


Figure 21. Task interleaving.

Inventory Master File

Item	On-Hand Balance	In-Transit Qty.	Locations
A	2	1	11,21
B	4	0	12,22

Location Master File

Location	Item	On-Hand Balance	In-Transit Qty.
11	A	1	0
12	B	3	0
21	A	1	1
22	B	1	0

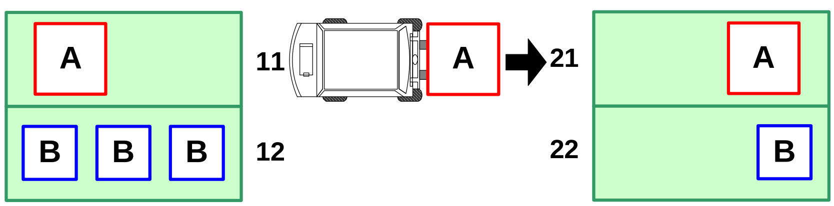


Figure 22. Validation.

In order to improve the efficiency of transport operations in a warehouse, a WMS and RF communications can be used to dispatch material handlers from one task to another in real time based on their proximity, resulting in the interleaving of putaway, replenishment, and picking operations (see Figure 21).

Validation

Validation is the verification that an inventory movement was performed correctly. Independent data is collected concerning the identity of the movable unit and the beginning and ending locations of the move. This is then matched to the record of the move maintained in the WMS. Any discrepancies are singled out for immediate correction in order to maintain the accuracy of the inventory records. In Figure 22, although three units of item A are in the warehouse, one unit is in transit from location 11 to location 21 and will not be available for picking until the WMS is notified that it has been delivered at location 21, at which time the on-hand balance at location 21 will increase to 2 and the in-transit quantity will decrease to 0.

Logistics-related Codes

Table 7 lists the three major categories of codes that are used in logistics-related activities. In warehousing, item-level SKU codes are used for inventory control, while unit-level RFID tags are just starting to be used to track each individual unit of an item in a warehouse, thereby facilitating FIFO stock rotation, for example. The use of a globally unique code allows products to move through the supply chain from firm to firm without the need to apply firm-specific codes when product is received at the warehouse door. The use of commodity codes is most useful for procurement activities where, for example, a similar item from multiple vendors is being sought and each vendor has a different SKU number.

Table 7. Logistics-Related Codes

	Commodity Code	Item Code	Unit Code
Level	Category	Class	Instance
Description	Grouping of similar objects	Grouping of identical objects	Unique physical object
Function	Product classification	Inventory control	Object tracking
Names	—	Item number, Part number, SKU, SKU + Lot number	Serial number, License plate
Codes	UNSPSC, GPC	GTIN, UPC, ISBN, NDC	EPC, SSCC, GLN

Common codes used in logistics include the following:

- UNSPSC (United Nations Standard Products and Services Code). A hierarchical 8-digit code that can used to classify all products and services at the segment, family, class, and commodity levels.
- GPC (Global Product Catalogue). A directory of product attributes that allows independent data repositories to be synchronized for global, multi-industry supply chain messaging and reporting.
- GTIN (Global Trade Item Number). All-numeric system for assigning globally unique codes to trade items (products and services). GTIN includes UPC, ISBN, and NDC.
- UPC (Universal Product Code). The standard bar code for retail items in North America.
- ISBN (International Standard Book Numbering). An international standard code for books.

- NDC (National Drug Code). A code maintained by the FDA for identifying prescription drugs and some over the counter drugs.
- EPC (Electronic Product Code). A globally unique serial number for physical objects identified using RFID tags.
- SSCC (Serial Shipping Container Code). A globally unique serial number for identifying movable units (carton, pallet, trailer, etc.).
- GLN (Global Location Number). A globally unique serial number for identifying physical places and legal entities. A location can refer to a physical place, such as a building or a storage area within a building (including a specific shelf in a warehouse), or a legal entity such as a company or a division of a company.[1]

Receiving

Receiving introduces inventory into the warehouse and prepares it for storage or customer order fulfillment. It is the process of unloading, verifying, inspecting, and staging of material transported to a warehouse in preparation for putaway or cross-docking, sometimes including sorting and repackaging of the material. Purchase orders (including shop orders and return authorizations) are sent to suppliers to authorize the shipment of material to the warehouse. In response to a purchase order, a supplier sends an advance shipment notice (ASN) to the WMS. The ASN contains information about the material contained in each movable unit (case, carton, pallet, etc.) contained in the shipment. Using SSCC, unique serial numbers can be assigned to each component at the time of its manufacture so that re-labeling is not required as part of the receiving function even when the material is not stored in the top-level container in which it is received.

The basic steps in receiving are the following:

1. Unloading of material from trailer.
2. Identify supplier with ASN, and associate material with each moveable unit listed in ASN.
3. Assign inventory attributes to movable unit from the item master file, possibly including repackaging material into new movable unit and assigning new serial number.
4. Inspect material to ensure that specifications are satisfied, possibly including holding some or all of the material for testing, and report any variances.
5. Stage units in preparation for putaway.
6. Update item balance in inventory master and assign units to a receiving area in location master.
7. Create receipt confirmation record.
8. Add units to putaway queue.

Putaway

Putaway is the process of moving material from the receiving area to a storage location or, in the case of cross-docking, directly to the shipping area. A putaway algorithm is used in the WMS to search for and validate locations where each movable unit in the putaway queue can be stored. The efficiency of all subsequent warehouse operations depends on performance of the putaway algorithm. The following inventory and location attributes are used in the algorithm to make the selection:

- *Environment*—used to restrict the locations where an item can be stored; e.g., refrigerated storage, caged area for high-value or controlled substances, quarantine area for units being held for inspection.
- *Container type* (pallet, case, or piece)—location can hold container type matching unit's type; a piece can be stored in a case or pallet location, and a case can be stored in a pallet location if necessary.
- *Product processing type*—specifies locations in processing area (e.g., floor, conveyable, nonconveyable) best suited for picking item.
- *Velocity* (A, B, or C)—matches turnover of item (A, fast; B, medium; C, slow) with the ease of storage and retrieval to/from location.
- *Preferred putaway zone*—item should be stored in location in the same zone as related items in order to, for example, improve picking efficiency.

An example putaway algorithm is as follows:

1. If moveable unit already allocated to a customer order, then it is moved (cross-docked) to shipping area.
2. If unit is being held for inspection, then it is moved to a location whose environment attribute is designated for quarantine storage; if no location found, then keep unit at its current location.
3. If unit not being cross-docked or held for inspection, then:
   (a) Search for available location that matches unit's environment, container type, product processing type, velocity, and preferred putaway zone attributes.
   (b) If no location found, drop preferred putaway zone attribute and repeat search.
   (c) Until location found, use next best velocity value and repeat search.
   (d) If no location found, restore original velocity value and, until location found, use next best product processing type and repeat search.
   (e) If no location found, report exception to operator.

4. Order Picking[2]

Basic Concepts

Order picking is the process of removing material from storage in response to specific customer orders or shop orders. Order picking is at the intersection of warehousing and order processing (see Figure 23): it includes the physical material handling processes associated with retrieving (or picking) items efficiently, and the information processing associated with searching and updating inventory records as orders are filled.

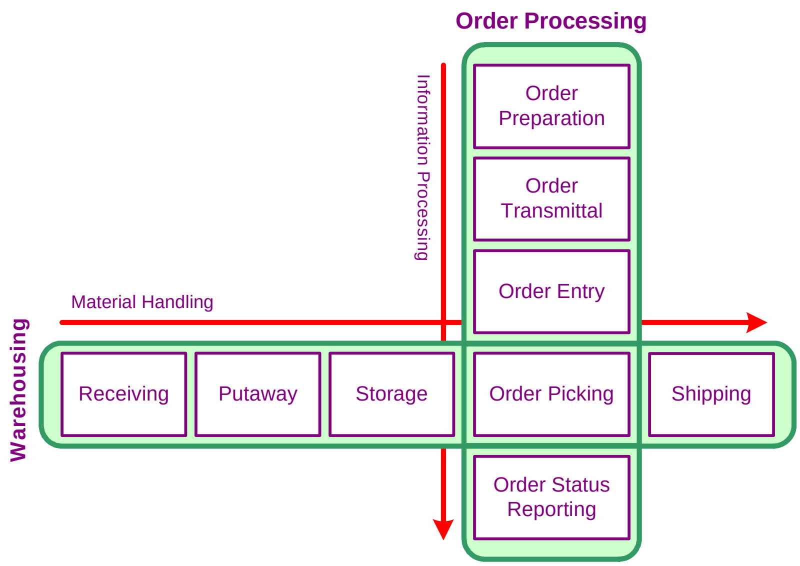


Figure 23. Order picking in relation to warehousing and order processing.

Order picking is the most critical activity in most distribution operations because it is the point at which customer expectations are actually filled. While the process of placing the fewer large unit loads into a warehouse is usually mechanized, the process of picking the many small items from a warehouse is often very labor intensive. This makes order picking the most costly warehousing activity, representing 55% of all operating costs in a typical warehouse.

An *order* indicates the type and quantity of items required. Each distinct type of item is termed a *SKU*. A *unit* is an instance of a SKU. Each SKU-quantity pair in an order is termed a *line*. A *pick list* indicates the sequence at which the storage locations of SKUs are to be visited along with the number of units to be picked from each location for one or more orders. Groups of orders are picked during planning periods termed *waves*. There can be one or more waves during each shift. Multiple waves are used to coordinate picking with other material flows in the facility and shipping schedules.

Table 8. Methods of Order Picking

Method	Pickers per Order	Orders per Picker
Discrete	Single	Single
Zone	Multiple	Single
Batch	Single	Multiple
Zone-Batch	Multiple	Multiple

Methods of Order Picking

There are three basic methods for order picking (see Table 8), with zone-batch picking being a combination method:

- *Discrete picking*. A single picker picks all of the items for a single order. Although an entire order can be packed while it's being picked, with no need for sortation and consolidation, travel time can be excessive if there is a low number of picks per order and congestion in aisles can occur if there are a large number of orders being picked.
- *Zone picking*. Each picker picks only the items of an order that are located in an assigned zone. This allows different techniques and equipment to be used in each different zone, and can reduce travel time as long as fast moving SKUs are located in the most accessible locations, but can be difficult to balance the amount of work in each zone (the "bucket-brigade" technique[3] can be used to dynamically balance each zone). Two variations of zone picking are *simultaneous picking*, where items for an order are picked simultaneously in each zone and then consolidated, making it possible to minimize the total picking time required for an order (which is useful if there are multiple waves per shift); and *progressive assembly*, where an order is passed from one zone to the next, eliminating the need to consolidate the order but increasing its total picking time (a.k.a. pick-and-pass).
- *Batch picking*. A single picker picks all of the items for multiple orders. This can reduce travel time (as long as the batched orders have items located in close proximity) and can reduce search time if multiple orders visit common locations, but items must be sorted into individual orders (sorting can occur during or after picking), and it might take a long time to accumulated enough orders that have items that are located in close proximity.
- *Zone-batch picking*. Combination of zone and batch picking, where multiple pickers each pick portions of multiple orders. This provides more opportunities for batching since items in the same zone are in close proximity and more orders with larger size items can be batched since picker does not carry full orders, but it requires the highest degree of coordination (e.g., can require both consolidation and sortation).

Levels of Order Picking

There are three major levels of order picking based on the size of the unit being picked (see Figure 24):

- *Pallet picking*, where full pallets of cartons or layers of cartons are retrieved (a.k.a. *unit-load picking*).
- *Case picking*, where full cartons of items are retrieved (termed *split-case picking* if inner packs of items from cartons are retrieved).
- *Piece picking*, where the individual units of issue to the customer of an item are retrieved (a.k.a. *broken-case picking*).

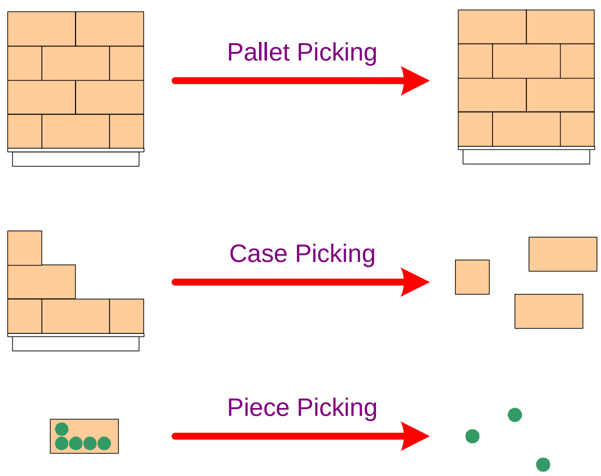


Figure 24. Levels of order picking.

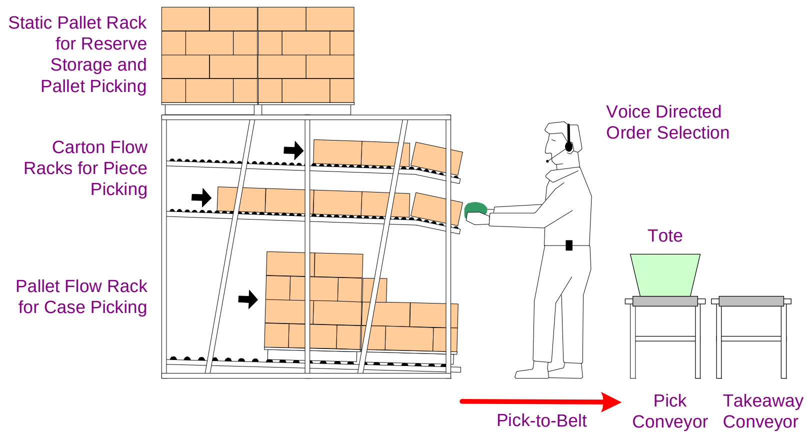


Figure 25. Example order picking operation.

Storage for pallet and case picking occupies the majority of space in a typical warehouse (see Figure 19); while piece picking is the most labor intensive and is typically the largest component of total order picking operating costs. One goal in designing an efficient picking operation is to try to pick the largest unit load size possible that will fulfill a customer's order; picking, for example, one case instead of several pieces or one pallet instead of several cases. Figure 25 illustrates an order picking operation where all three levels of order picking occur in a single rack structure: using hands-free verbal transmission of pick instructions and pick confirmations, pieces are picked from inside a case on carton flow rack into tote on pick conveyor, and single cases are picked from pallet bottom-level flow rack directly onto the conveyor. Carton and pallet flow racks provide pick storage areas that minimize operator travel, and the takeaway conveyor transports completed orders and full totes.

Activity Profiling

Activity profiling is the systematic analysis of the items and orders handled in a warehouse in order to improve its design and operation. In the design of an order picking system, a representative set of customer orders are used together with the item master file to generate parameters that are used for a variety of different warehousing decisions, including equipment and method selection and slotting. If available, the previous three months to one year of customer orders provide a reasonable representative set of orders.

Item Master

SKU	Length	Width	Depth	Cube	Weight
A	5	3	2	30	1.25
B	3	2	4	24	4.75
C	8	6	5	180	9.65
D	4	4	3	32	6.35
E	6	4	5	120	8.20

Customer Orders

Order: 1	
SKU	Qty
A	5
B	3
C	2
D	6

Order: 2	
SKU	Qty
A	4
C	1

Order: 3	
SKU	Qty
A	2

Order: 4	
SKU	Qty
B	2

Order: 5	
SKU	Qty
C	1
D	12
E	6

Total Lines = 11

Lines per Order = 11/5 = 2.2

Cube per Order = 493.2

SKU	Flow per Item	Lines per Item	Cube Movement
A	11	3	330
B	5	2	120
C	4	3	720
D	18	2	576
E	6	1	720

Demand Correlation Distibution					
SKU	A	B	C	D	E
A		0.2	0.4	0.2	0.0
B			0.2	0.2	0.0
C				0.4	0.2
D					0.2
E					

Figure 26. Activity profiling example.

An example of activity profiling is presented in Figure 26. Each customer order in composed of one or more lines, where each line represents an item–quantity pair (e.g., Order 1 has five lines, with the first line indicating five units of item A have been ordered). In this example, the five customer orders along with the item master file are used to create the following warehouse design parameters:

- *Total Lines*—the total number of lines for all items in all orders over some period of time (representative of total picking activity); used to select piece-picking methods.
- *Lines per Order*—the average number of different items (i.e., lines or SKUs) in an order; used to select piece-picking method.
- *Cube per Order*—the average total cubic volume of all of the units (i.e., pieces) in an order; used to select piece-picking methods.
- *Flow per Item*—the total number of storage and retrieval operations performed for the item over some period of time; used to select pallet-picking equipment.
- *Lines per Item* (a.k.a. *popularity*)—the total number of lines for the item in all orders over some period of time (representative of picking activity for item); used to select case- and piece-picking equipment and for slotting.
- *Cube Movement*—the total unit demand of the item over some period of time times the cubic volume of each unit (representative of the cube in storage for the item); used to select pallet-, case-, and piece-picking equipment.
- *Demand Correlation*—the percent of orders in which both items appear; used for zoning and slotting (see below), but not for batching because that is an operational decision.

In Figure 26, the item master file includes the dimensions, cubic volume, and weight of each item. Note that an item’s cube can be less than the product of its dimensions (e.g., items C and D). In addition, the unit of measure (UOM) is typically included. The UOM is a description of whether the quantity of inventory for an item refers to individual units (eaches or pieces), cases, or pallets. A conversion ratio is used whenever multiple units of measure are used for the same item.

Slotting

Slotting refers to the assignment of items to storage locations so that subsequent picking operations are best supported. Slotting for pallet picking differs from case and piece picking because only a single pallet can be picked at a single location. As a result, the DSAP covered in Section 0 is only appropriate for (single-command) pallet picking. For case and piece picking, the basic idea behind the DSAP, which is to use assign frequently picked (fast) items to the most convenient pick locations, is combined with demand correlation information in order to assign items that are picked together to locations that are close together (using). Flow per item measures pick frequency for pallets, and lines per item measures the number of times multiple units of item will be picked from locations where cases and pieces are stored. As shown in Figure 27, the most convenient pick locations are those that are in the “golden zone” and those that are close to the takeaway conveyor.

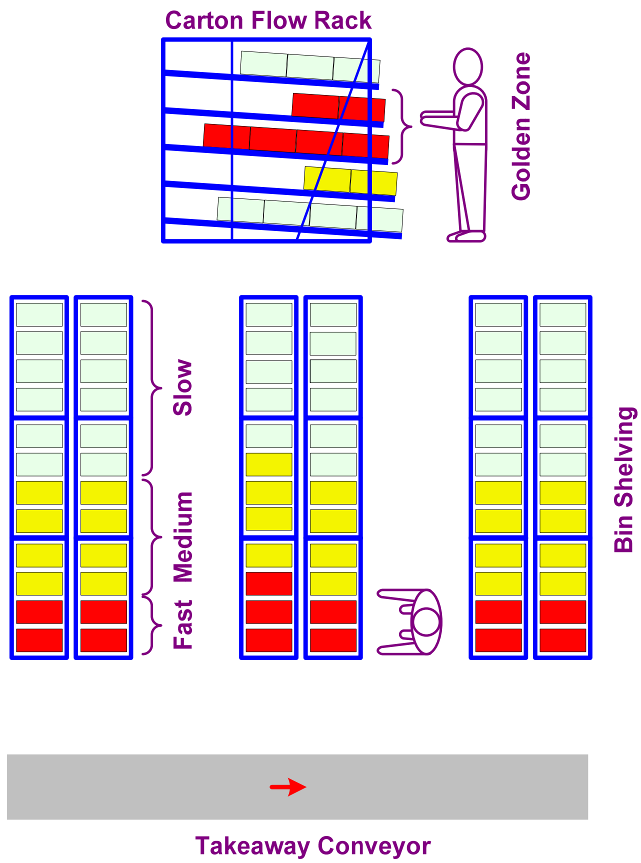


Figure 27. Slotting.

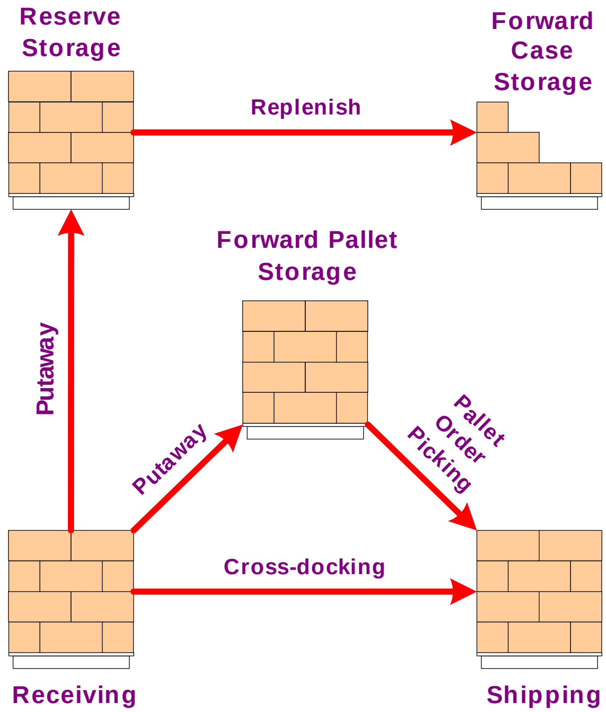


Figure 28. Pallet picking.

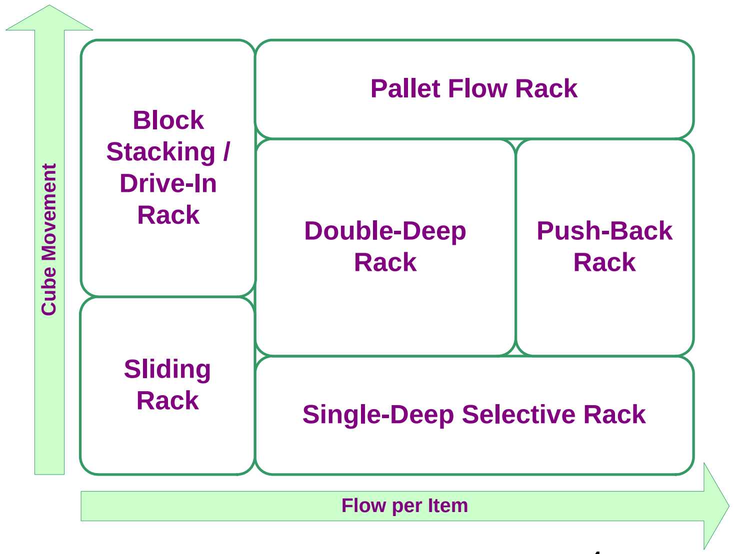


Figure 29. Pallet storage equipment.[4]

Pallet Picking

The transport of full pallet loads is used for putaway, replenishment, and cross-docking operations in a warehouse in addition to pallet order picking (see Figure 28). As shown in Figure 29, cube movement and flow per item can be used to select an appropriate type of equipment to store pallet loads of an item. Additionally, high labor costs can favor the use of a unit-load AS/RS.

Case Picking

Case order picking involves the retrieval of full carton loads of each item or inner packs of items from cartons. As shown in Figure 30, pallet loads of cases of the same item are transformed into pallet loads of mixed items through case order picking, sortation, and unitizing. Although much of the same storage equipment is used, case picking is more complex than pallet picking. As a result, a greater variety of case-picking techniques are available. As shown in Figure 31, cube movement and flow per item can be used to select an appropriate type of equipment for case picking.

Both manual and automated case picking is used. Pallet racks are used for all types of manual case picking, while automated picking uses specialized equipment. Also, carton flow racks can sometimes be used for case picking. The methods of manual case picking include pick to pallet, pick to belt, and pallet pick with sort.

Automated case picking equipment can provide high picking rates with no cost for labor. Replenishment and unitizing may or may not be fully automated. Two types of automated equipment are available: *flow delivery lanes*, where cases of each item are pushed from parallel merge chutes onto a sortation conveyor from which they are consolidated into individual orders and unitized, providing a high pick rate for fast moving items; and, for smaller cases, *case dispensers*, where cases are dispensed into larger containers that form each load.

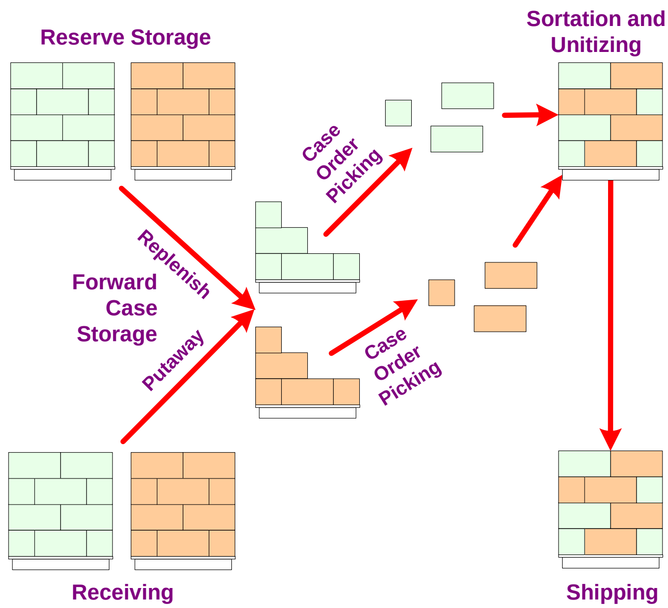


Figure 30. Case picking.

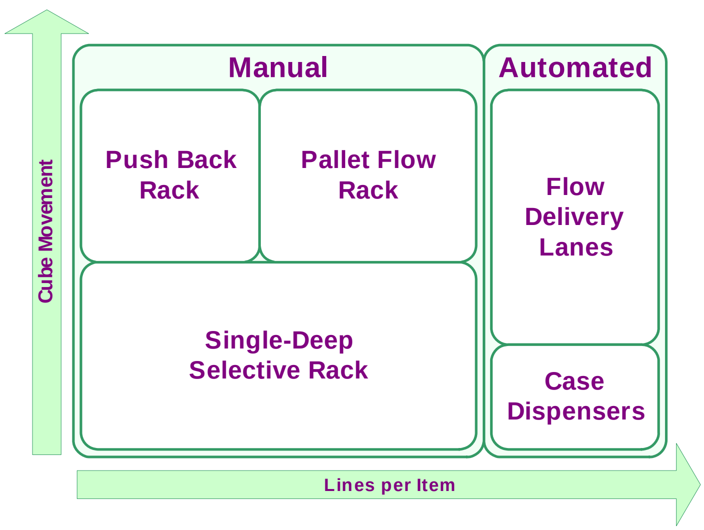


Figure 31. Case picking equipment.

Pick to Pallet

Pick to pallet is the simplest and most common type of case picking technique and it has the lowest equipment costs. Several variations are possible: floor- vs. multi-level, and discrete vs. batch.

Floor- vs. Multi-level Pick to Pallet

In floor-level picking (see Figure 32), only the bottom level of the pallet rack is used for picking and is replenished from pallets stored at higher levels. It is used for picking fast moving items since it is quicker to pick from the floor and replenish from above, and it is easy to combine pallet picking with case picking.

In multi-level picking (see Figure 32), all levels of the pallet rack are used for picking and are replenished from a separate reserve storage area. It is used to pick a large number of different slow moving items since entire rack is used for pick storage, and requires an order picker truck to lift picker to pallet (unless mezzanines are provided at each level, in which case pick to belt can be used on each level).

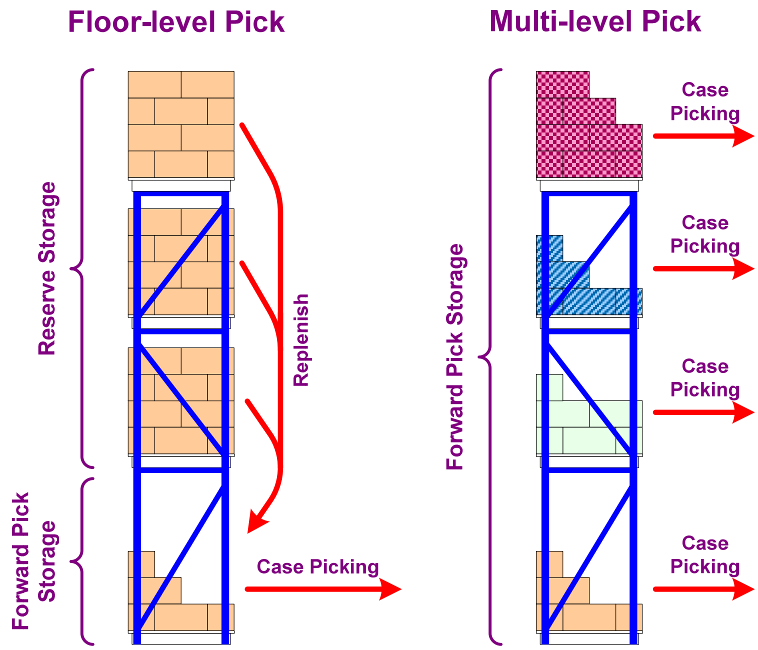


Figure 32. Floor- vs. multi-level pick to pallet.

Discrete vs. Batch Pick to Pallet

In discrete pick to pallet (see Figure 33), all of the cases in an order are picked onto the same pallet in which they will be shipped, thereby combining picking with unitizing. The picking can be floor-level or multi-level.

In pure batch picking, the cases needed for several orders are picked onto a single pallet and then sorted into individual orders. It is used when each order is much less than a pallet load.

In zone-batch picking (see Figure 34), cases are simultaneously picked to several pallets and then inducted onto a sortation conveyor from which they are consolidated into individual orders and unitized. This provides a high pick rate, but requires both a sortation conveyor and that each case has a label so that it can be scanned during subsequent sortation. The recirculation loop of the conveyor is used to control loading sequence onto shipping pallet.

Pick to Belt

In pick to belt picking (see Figure 35), cases for a batch of orders are simultaneously picked and inducted onto a sortation conveyor from which they are consolidated into individual orders and unitized. This provides a higher pick rate than pick to pallet because picking is combined with induction and it does not require the picker to travel. Replenishment does not interfere with picking when using pallet flow racks are used, but it does require a sortation conveyor and labeled cases.

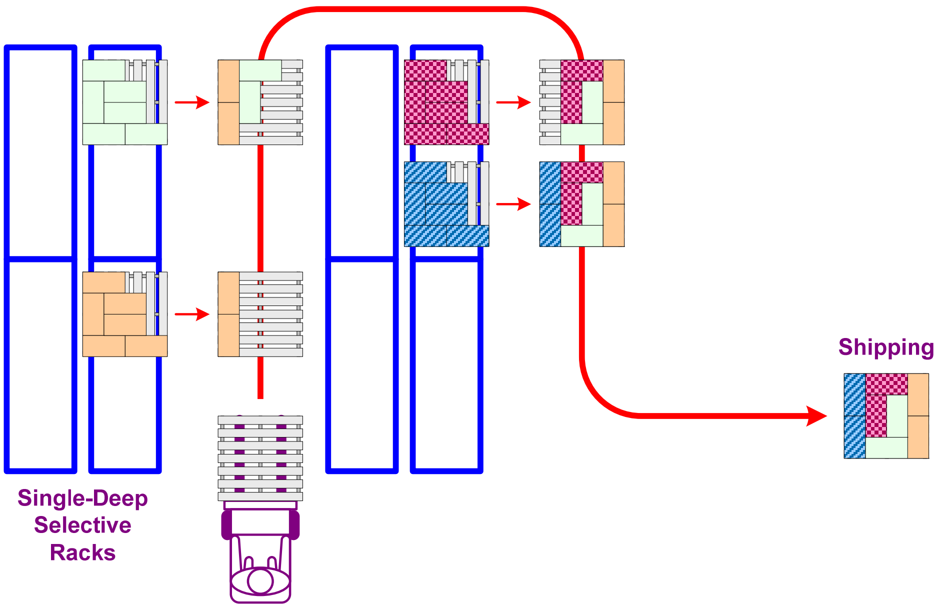


Figure 33. Discrete pick to pallet.

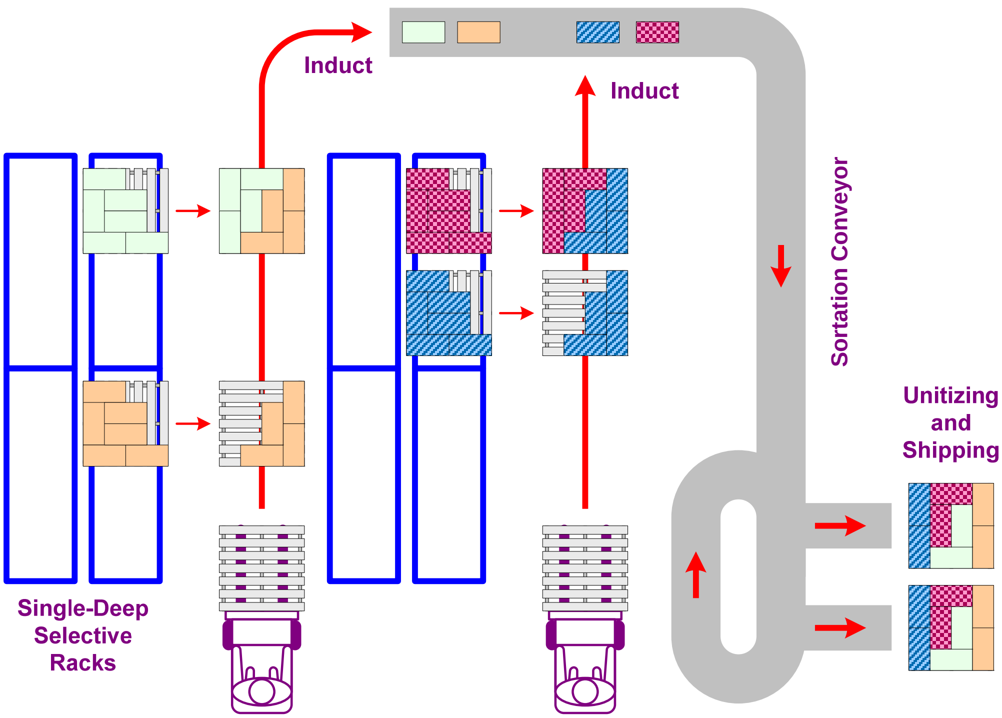


Figure 34. Zone-batch pick to pallet.

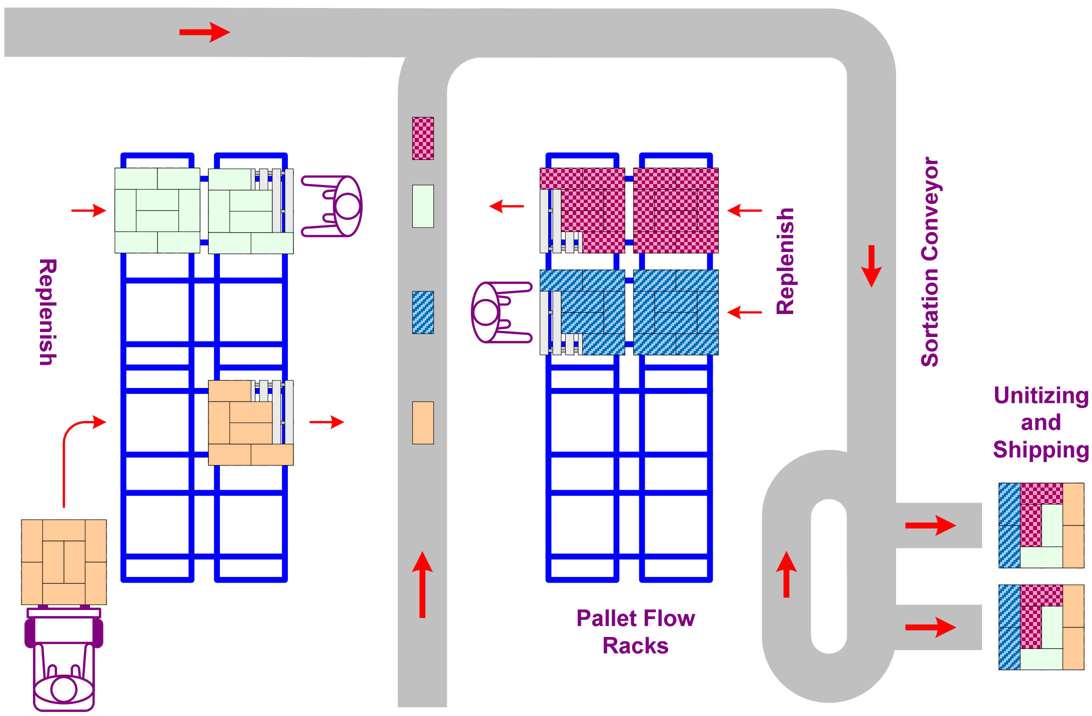


Figure 35. Pick to belt.

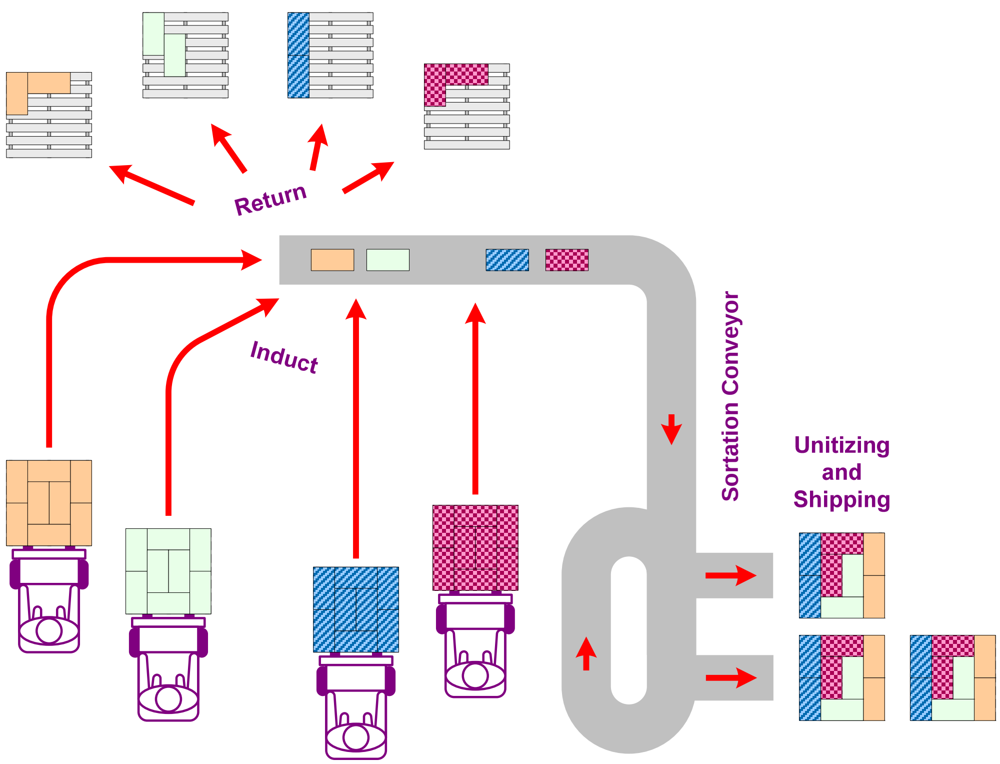


Figure 36. Pallet pick with sort.

Pallet Pick with Sort

In pallet pick with sort case picking (see Figure 36), full pallet loads of the items needed for a batch of orders are brought to a sortation conveyor where a portion of the cases from each pallet are inducted onto the conveyor and consolidated into individual orders and unitized. The partially full pallets are then returned to storage. This provides a high pick rate for fast moving items because pallets can be picked from reserve storage (i.e., no replenishment) , but it does require a sortation conveyor and labeled cases. Pallet pick with sort is similar to *putting*, and can be combined with pick to pallet for slower moving items.

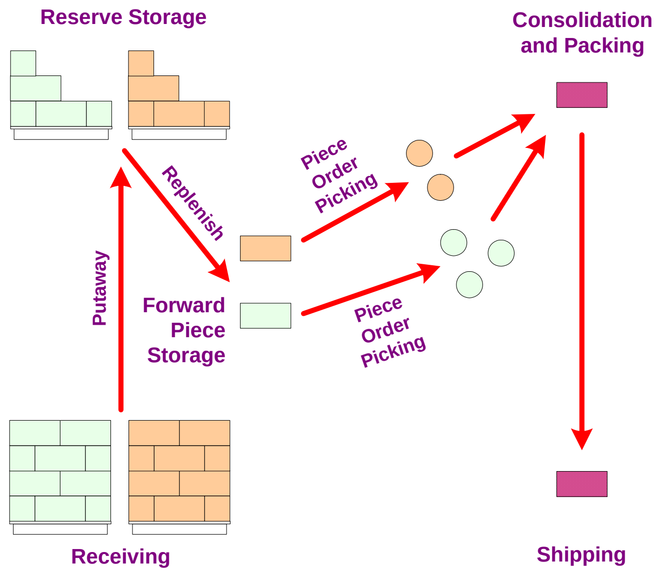


Figure 37. Piece picking.

Piece Picking

Piece order picking involves the retrieval of individual units of an item, where each piece picked (a.k.a. an *each*) is the unit of issue to the final customer. As shown in Figure 37, for each order, pieces are picked from cases of the same item and then packed into a container that is shipped to the customer. Piece picking is more complex than either case or pallet picking and, as a result, a variety of specialized piece-picking techniques and equipment have been developed. are available. As shown in Figure 38, cube movement and flow per item can be used to select an appropriate type of equipment for piece picking. Mini-load storage and retrieval machines can be used to enable fully automated replenishment of carton flow racks. Automation allows more frequent replenishment to better support picking operations and allows the item mix to be easily changed.

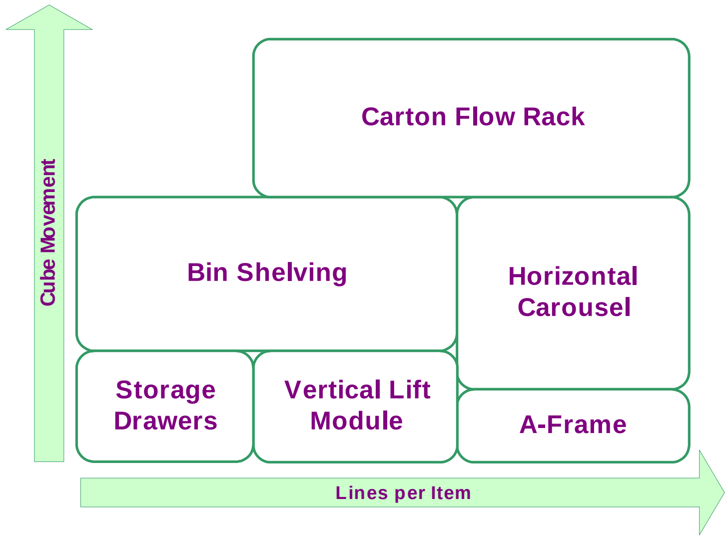


Figure 38. Piece picking equipment.[5]

As shown in Figure 39, an appropriate method for piece picking can be selected using the parameters lines per order, cube per order, and total lines. Discrete picking is infrequently used pick pieces (or cases). In the following, an example of how each method can be implemented for piece picking is presented.

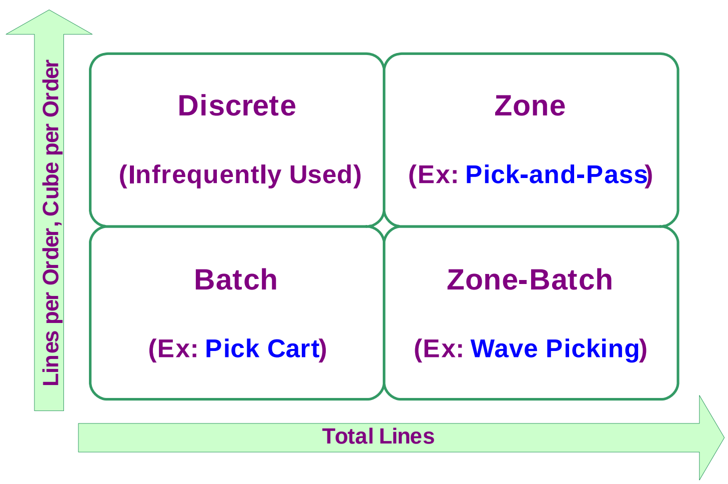


Figure 39. Methods of piece picking.

Batch Example: Pick Cart

In pick-cart batch piece picking, separate cartons or totes for each order are placed on a cart. Packing can occur either during or after picking:

- *Pick-and-pack*—shipping carton used during picking
- *Pick-then-pack*—reusable tote sent to packing station after picking (see Figure 40)

Although the use of a pick cart provides a low-cost, low-tech means for piece picking, poor pick-tour generation can result in excessive travel for picker. Pick carts can also be used for pick-and-pass zone-batch picking, where carts are passed from zone to zone.

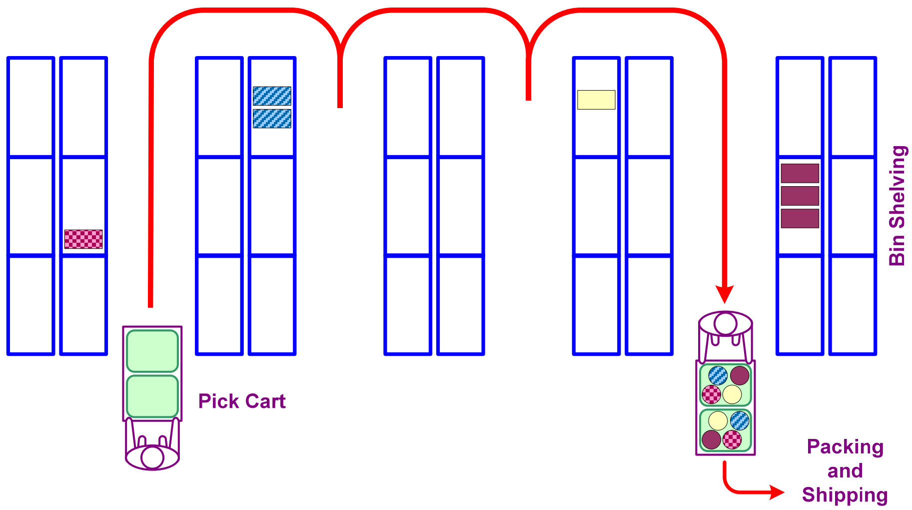


Figure 40. Pick-cart batch piece picking.

Zone Example: Pick-and-Pass

Items from each zone picked to tote and then tote is passed to the next zone. Cartons can be used instead of totes to allow pick-and-pack. Two different configurations used:

- *All zones visited*—if pick conveyor is attached to rack (see Figure 41), then tote is scanned at first zone and then visits each zone (totes maintain fixed sequence).
- *Skip zones*—if pick and takeaway conveyors are offset from racks, then takeaway conveyor can be used to move totes only to the zones with picks (requires tote scanning at each zone).

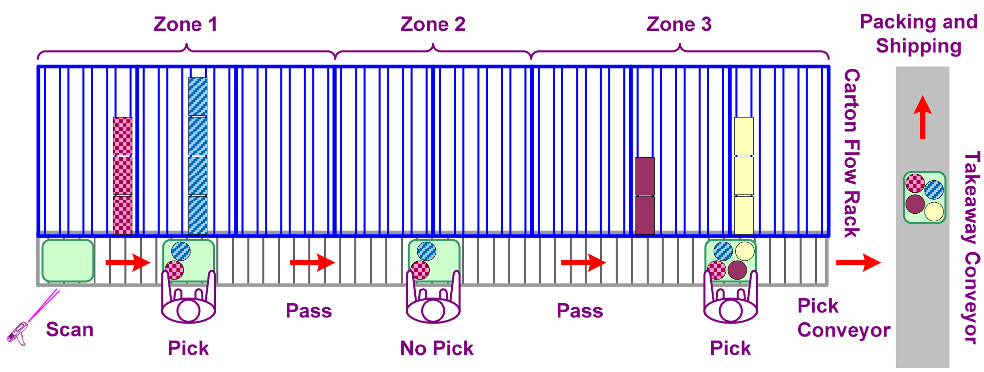


Figure 41. Pick-and-pass zone piece picking.

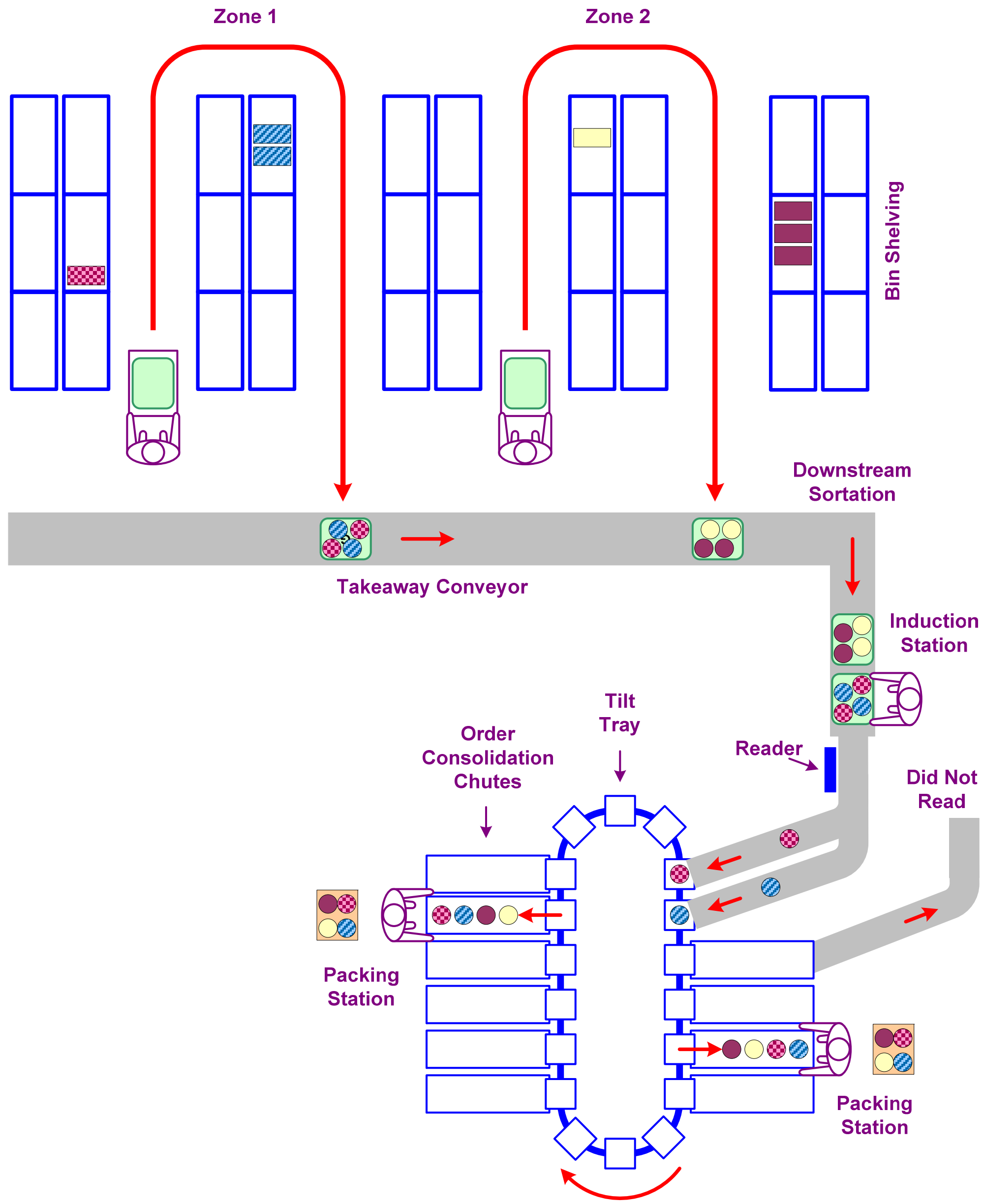
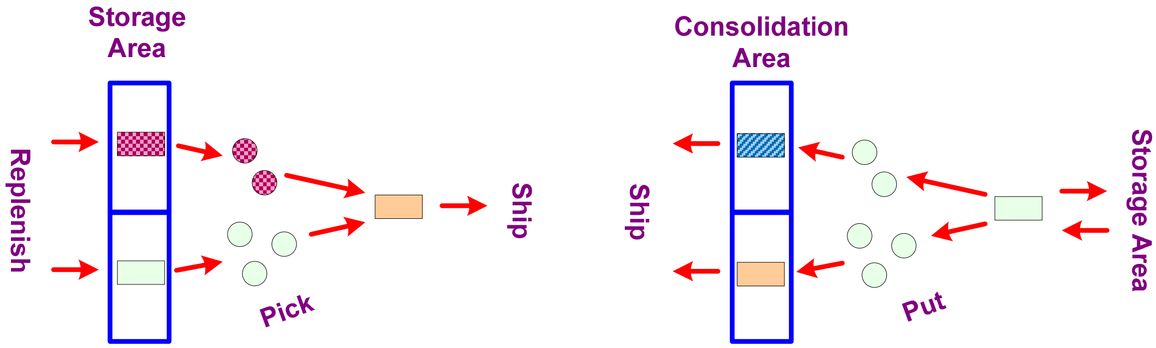


Figure 42. Wave zone-batch piece picking, including downstream tilt-tray-based sortation.

Zone-Batch Example: Wave Picking

Groups of orders are picked during a short period of time (a wave) in order to coordinate picking with shipping schedules or because downstream sortation has limited order capacity. Although wave picking enables a very high pick rate, it requires each piece picked to have a label so that it can be scanned during subsequent sortation. As shown in Figure 42, in each zone, all of the units of each item needed for all of the orders in the wave are picking into a tote. The totes from each zone are then sent downstream for sortation and packing. Pieces are then unloaded from totes, scanned, and then inducted onto sortation conveyor from which they are consolidated into individual orders and packed. Two different types of sorters are typically used:

- *Tilt-tray sorter* (pictured)—each piece slides onto a tray, which subsequently tilts to send the piece into its consolidation chute; sorting rates of over 10,000 units per hour are possible, but items cannot be fragile; the number of consolidation chutes limits the number of orders in each wave, and one operator can be used to pack multiple chutes.
- *Cross-belt sorter*—similar to a tilt-tray sorter except that a short belt conveyor is used in place of a tray; sorting rates of over 20,000 units per hour are possible.



(a) Picking Operation (b) Putting Operation

Figure 43. Picking vs. putting.

Picking vs. Putting

In some situations, it is more efficient to put instead of pick. In putting (see Figure 43(b)), a single carton or pallet load of an item is brought to a consolidation area and used to fill many orders at the same time. Picking consolidates many items into one order, while putting distributes (multiple units of) one item to many orders. Putting reverses the typical picking process:

- *Pick*—many items to one order
- *Put*—one item to many orders

Putting can be used to efficiently pick a large number of orders. In putting operations, shelves, carts, or carousels can be used for consolidation.

Picking Process

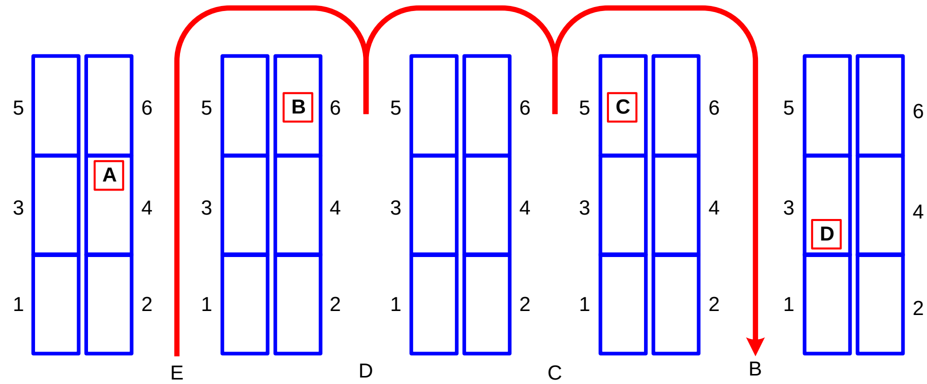
Most order picking processes involve the following basic steps:

1. Identifying the location of each pick.
2. Confirming the pick.
3. Indicating any shortage of product.

A variety of different identification and communications equipment can be used to implement the picking process. A communications link between the WMS and the pickers enables real-time rebalancing of the pick line during the picking process.

Line	Loc	SKU	Qty	UOM
1	E4	A	4	ea
2	D6	B	3	ea
3	C5	C	1	ea
4	B3	D	12	ea

(a) Paper pick list



(b) Picking tour

Figure 44. Pick-to-paper.

Pick-to-Paper

The basic pick-to-paper process is as follows (see Figure 44):

1. Paper pick list given to picker. List includes the location, SKU ID, quantity, and units of measure (UOM) of all items and in the sequence that they should be picked.
2. Weight scale on a pick cart might be used to (indirectly) confirm each item as it is picked, and any shortage can be noted on pick list.

The WMS generates the pick tour. Sometimes, location address sequence is used to determine tour, resulting travel up or down each aisle. Better algorithms (or picker modification) can generate shorter distance tours. The advantages of pick-to-paper are that it is reasonably fast, low-cost, low-tech, and an experienced picker can see entire tour and can often modify inefficient tours that have generated by the WMS tour-generation algorithms. The disadvantages are that the paper list held by the picker can interfere with picking, resulting in slower pick rates, and there is no direct pick confirmation. Also, because of the lack of a communications link to the WMS, it is not possible to perform real-time rebalancing of the pick line and shortages are only communicated at end of tour, thereby delaying the updating of the WMS.

Bar Code Scanning

The basic bar code scanning picking process is as follows:

1. Location, quantity, and SKU ID of an item to pick are presented to the picker on the display of the portable data terminal.
2. Picker then scans or keys-in the check digit to confirm the location.
3. Picker scans the unit or keys-in confirmation of the pick, noting any shortage.

4. Return to 1 if more picks.

Although scanning provides real-time pick confirmation and shortage indication, and the bar code labels and readers are low cost, it can slow down picking and the portable data terminal sometimes interferes with picking; also, the entire pick tour is usually not displayed to picker, which makes it difficult for the picker to modify the tour to improve its efficiency (cf. pick-to-paper).

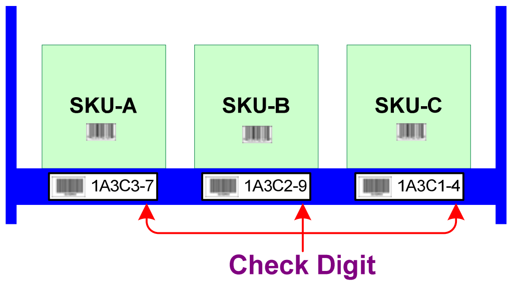


Figure 45. Location labels for bar code scanning.

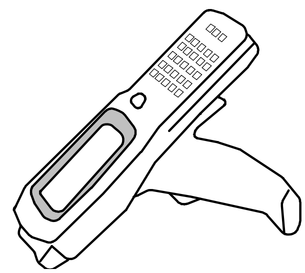


Figure 46. Portable data terminal.

As shown in Figure 45, each location label includes a bar code and a printed address that includes a check digit. The check digit is typed using the keypad on the portable data terminal and provides a fast means of location identification in situations where it is not feasible to scan the location label (e.g., from a long distance). The portable data terminal can be handheld (see Figure 46), arm-mounted, or vehicle-mounted and is used for scanning bar code labels and communicates with the WMS via a radio frequency (RF) link.

Figure 47. Bar codes used in warehousing.[6]

A variety of bar codes are used in warehousing. Numeric bar codes are smaller in size than alphanumeric codes and are used when space is at a premium. The most common codes are the following (see Figure 47):

- Interleaved 2 of 5—used in warehouse for pick location labels.
- Code 39—used in warehouse to mark storage locations.

- Code 128—used in warehousing for shipping labels since it can represent all 128 ASCII characters instead of Code 39's 43.
- UPC/EAN—used for retail merchandise marking.

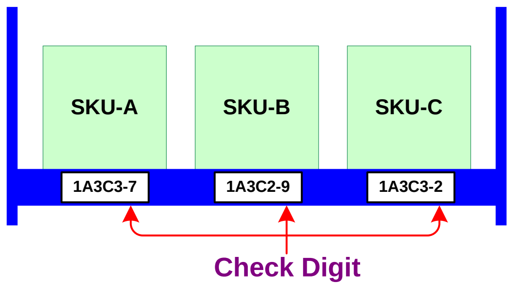


Figure 48. Location labels for pick-to-voice.

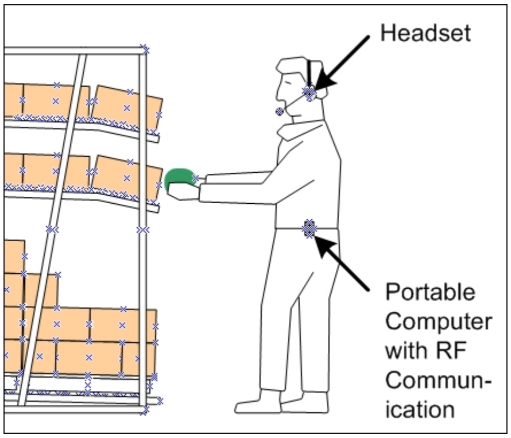


Figure 49. Portable computer and headset used in pick-to-voice.

Pick-to-Voice

The basic pick-to-voice process is as follows:

1. SKU ID and quantity of an item to pick are spoken to picker through a headset.
2. Picker then says the check digit to confirm the location (see Figure 48).
3. Picker says quantity picked followed by the word "picked" to confirm the pick, indirectly noting any shortage.
4. Return to 1 if more picks.

Although voice provides hands-free real-time pick confirmation and shortage indication, and location labels are low cost, speaking may slow down picking and it difficult for the picker to modify a pick tour to improve its efficiency since the entire tour is not known to the picker (cf. pick-to-paper). As shown in Figure 49, a portable computer used for voice processing and RF communications. Speaker-dependant and speaker-independent voice recognition available.

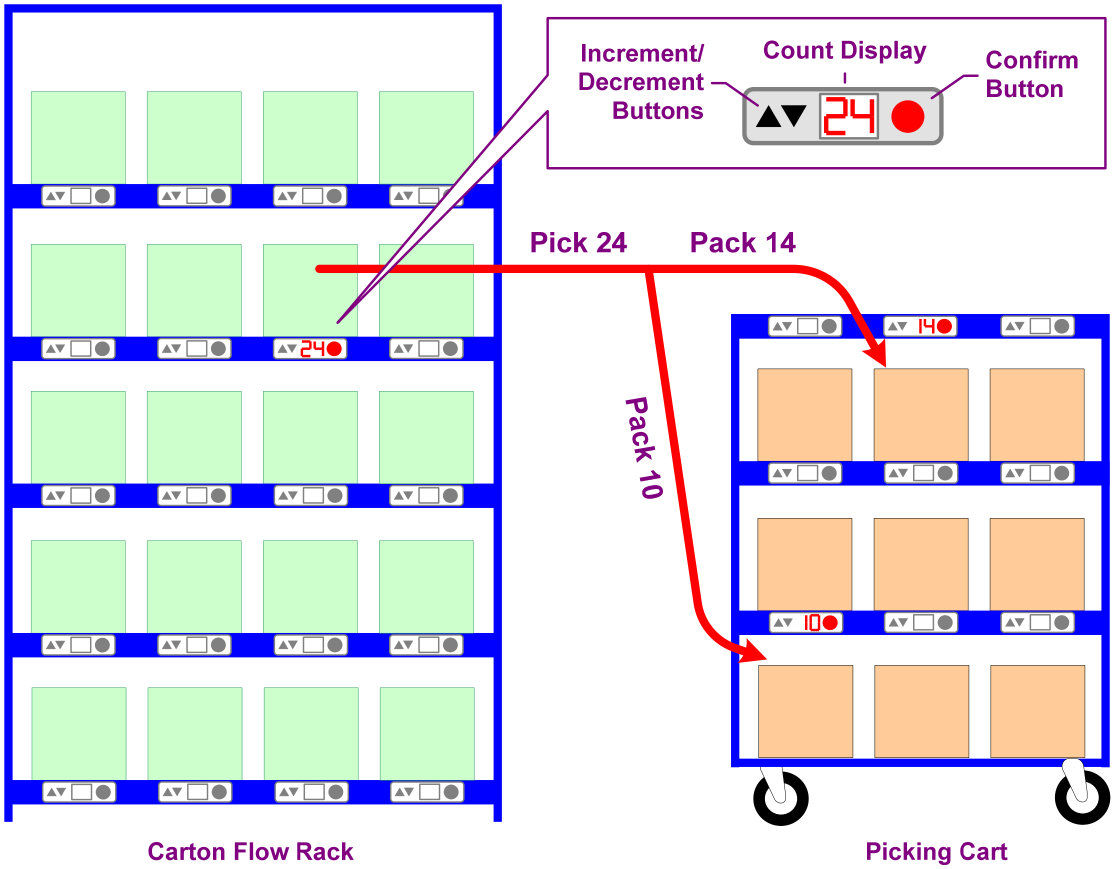


Figure 50. Pick-to-light.

Pick-to-Light

The basic pick-to-light process is as follows (see Figure 50):

1. Quantity of pick indicated by LED on display at the pick location.
2. Picker then hits button on display to the confirm location and pick, using decrement button to note shortage.
3. In batch picking, displays can also be used to indicate and confirm packing.
4. Return to 1 if more picks.

The main advantage of pick-to-light is that it can enable very fast picking and packing. Also, it provides real-time pick confirmation and shortage indication. Its main disadvantage is that display cost is proportional to the number of pick locations, as compared to the portable data terminal and voice recognition equipment used in bar code scanning and pick-to-voice, respectively, that are proportional to number of pickers (which is much less than the number of pick locations). The increment button on the display is only used for cycle counting. Displays communicate with the WMS via a wire network in the rack.

5. Warehousing Glossary

Activity profiling. The systematic analysis of the items and orders handled in a warehouse in order to improve its design and operation.

Advance shipping notice (ASN). Electronic information concerning a single shipment of movable units sent to a WMS from suppliers and sent from a WMS to customers.

Batch picking. An order picking method where a single picker picks all of the items for multiple orders.

Broken-case picking. Alternate term for piece picking.

Case picking. Retrieval of full carton loads of each item or inner packs of items from cartons (the latter a.k.a. split-case picking).

Consolidation. The process of (a) combining material from several partially filled storage locations containing the same item into a single location, (b) combining several orders into a single shipment, or (c) combining several portions of an order at a single location.

Cross-docking. The process of moving material from a receiving area directly to a shipping area without long-term storage of the material.

Customer order. Request that indicates the type and quantity of SKUs to be shipped to a customer; each SKU–quantity pair in the order is termed a line (cf. purchase order and shop order).

Cycle counting. The process of counting the contents of storage locations in order to verify the accuracy of inventory records.

Discrete picking. An order picking method where a single picker picks all of the items for a single order.

Each. An individual unit picked during piece picking.

ERP (Enterprise resource planning) system. Software system that control the entire operations of a firm. The item, carrier, and customer master files are maintained by an ERP system and are used as a common data source for orders and ASNs.

Forward picking. A storage area designed for efficient piece and case order picking that is usually replenished from reserve storage but sometimes directly from receiving.

Inner pack. Package used inside of a carton to allow more efficient split-case picking instead of individual piece picking when a less-than-carton-size number of units are to be picked.

Inventory master file. File maintained by a WMS that contains the total quantity and storage locations of each item stored in the warehouse. Used together with the location master file to control material transport operations.

Inventory. The number of units of each item stored in a warehouse.

Item. Grouping of identical objects, i.e., a class or collection of units; inventoried items are usually referred to as stock-keeping units (or SKUs).

Item master file. File that includes the dimensions, cubic volume, weight, and unit of measure of each item; used along with representative customer orders in activity profiling.

Line. An item–quantity pair in an order.

Location master file. File maintained by a WMS that contains the quantity of the item available at each storage location in the warehouse. Used together with the inventory master file to control material transport operations.

Movable unit. A single identifiable unit load (e.g., carton, pallet, trailer, etc.) that is moved between and stored at a location.

Order picking. The process of removing material from storage in response to specific customer orders or shop orders (cf. putting).

Order. Request to ship, receive, or transport material as indicated in a customer order, purchase order, or shop order, respectively.

Packing. The process of preparing a container for shipment.

Pallet picking. Retrieval of full pallets of cartons, or layers of cartons from a pallet (a.k.a. unit-load picking).

Pick conveyor. A non-powered conveyor (e.g., wheel or roller) used in piece picking to support a tote or other container while it is being filled.

Picking. Short for order picking (cf. putting).

Pick list. Request to a picker that indicates the sequence in which the storage locations of SKUs are to be visited along with the quantity of units to be picked from each location for one or more orders.

Pick-and-pass. Alternate term for progressive assembly picking.

Piece picking. Retrieval of individual units (or "eaches") of an item, where each piece picked is the unit of issue to the final customer (a.k.a. broken-case picking).

Progressive assembly picking. Variation of zone picking where an order is passed from one zone to the next, eliminating the need to consolidate the order but increasing its total picking time (a.k.a. pick-and-pass).

Purchase order. Request that indicates the type and quantity of items to be received from a vendor; each item–quantity pair in the order is termed a line (cf. customer order and shop order).

Putaway. The process of moving material from a receiving area to a storage location.

Putting. Putting reverses the typical picking process: in picking, units of many items are picked into one order; in putting, units of one item are put into many orders.

Receiving. The process of unloading, verifying, inspecting, and staging of material transported to a warehouse in preparation for putaway or cross-docking, sometimes including sorting and repackaging of the material.

Replenishment. The process of moving material from reserve storage to a forward picking area.

Reserve storage. An area intended for the storage of material in full pallet load sizes from which both forward picking areas are replenished and pallet orders and some case orders are picked.

Rewarehousing. The process of moving items to different storage locations to improve handling efficiency.

Shipping. The process of staging, verifying, and loading orders to be transported from a warehouse.

Shop order. Request that indicates the type and quantity of SKUs to be transported from a warehouse to a production area; each SKU–quantity pair in the order is termed a line (cf. customer order and shop order).

Simultaneous picking. Variation of zone picking where the items for an order are picked simultaneously in each zone and then consolidated, making it possible to minimize the total picking time required for an order (which is useful if there are multiple waves per shift).

Slot. Alternate term for a storage location.

Sortation. The process of merging, identifying, inducting, and separating material to be conveyed to specific destinations.

Split-case picking. Variation of case picking where inner packs of items from cartons are retrieved.

SSCC (Serial Shipping Container Code). A globally unique serial number for identifying a movable unit (e.g., a pallet).

SKU (Stock-keeping unit). An inventoried item.

Storage location. An identifiable location in a warehouse assigned a unique address and used to store a single item, where the capacity of the location corresponds to the maximum number of units of the item that can be stored at the location (a.k.a. slot).

Takeaway conveyor. A powered conveyor (e.g., belt or live roller) used in piece and case picking to transport completed orders.

Unit load. Either a single unit of an item, or multiple units so arranged or restricted that they can be handled as a single entity and maintain their integrity.

Unit. Instance of an item, i.e., a unique physical object.

Unitizing. The process of combining multiple smaller containers into a larger container that can be handled as a single unit load.

Unit-load picking. Alternate term for pallet picking.

Unit of measure (UOM). A description of whether the quantity of inventory for an item refers to individual units (eaches or pieces), cases, or pallets. A conversion ratio is used whenever multiple units of measure are used for the same item.

Wave. A planning period for picking groups of orders that can be used to coordinate picking with shipping schedules or because downstream sortation has limited order capacity; there can be multiple waves during each shift.

WMS (Warehouse management system). Software system that enables real-time, paperless control of the operations of a single warehouse.

Zone picking. An order picking method where each picker only picks the items of an order that are located in the portion of the storage area assigned to the picker for picking; simultaneous picking and progressive assembly picking are two variations of zone picking.

Zone-batch picking. A combination of zone and batch picking, where multiple pickers each pick portions of multiple orders.

6. References

The following sources are recommended for further study:

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Bartholdi, III, J.J., and Hackman, S.T., 2014, *Warehouse & Distribution Science*, version 0.96, www2.isye.gatech.edu/~jjb/wh/book/editions/wh-sci-0.96.pdf.

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Piasecki, D., 2005, "Order Picking: Methods and Equipment for Piece Pick, Case Pick, and Pallet Pick Operations," InventoryOps.com, www.inventoryops.com/order_picking.htm.

Notes

[1] GS1, 2011, "The value and benefits of the GS1 system of standards, http://www.gs1.org/docs/GS1_System_of_Standards.pdf (accessed March 2011).
[2] Much of the material in this section is based on web-based order picking training modules developed for the Material Handling Industry of America, www.mhia.org/et/et_mhi_elessons_home.cfm.
[3] Bartholdi, J., and Eisenstein, D., 1996, "A production line that balances itself," *Operations Research*, 44(1):21–34.
[4] Adapted from Fig. 5-11 in Frazelle, *World-Class Warehousing*.
[5] Adapted from Fig. 2-12 in Frazelle, *World-Class Warehousing*.
[6] Barcodes made using the online Barcode Label Printer, http://www.barcodesinc.com/generator/.