CHAPTER 81

Warehouse Management

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1. INTRODUCTION

Modern warehouses operate with sophisticated equipment for storage, handling, data capture, and communication. A competitive environment requires warehouse managers to have tight control over inventories and orders shipped, with rapid response being the norm. At the same time, efficient strategies for storage and retrieval offer significant operating savings. To satisfy these objectives, an effective warehouse management system (WMS) is essential. A WMS may be a combination of paper-based systems together with computerized inventory records, but the trend clearly is toward an integrated, computer-based system that handles management and automatic identification. The major benefits of a WMS are typically the following:

Handbook of Industrial Engineering: Technology and Operations Management, Third Edition.
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- Improved inventory accuracy, which allows for higher order-fill rates and faster response times
- Increased efficiency as a result of eliminated operations, reduced deadhead travel of workers and vehicles, and sharing of workers across departments
- More timely replenishments of forward pick areas, which result in higher order fill rates
- Better pick wave planning and execution in zone pick systems, which result in better worker utilization and earlier completion of the picking activity

This chapter presents the main concepts of warehouse management. First, there is a functional description of a typical warehouse operation, with emphasis on order picking because that is where most of the labor costs in a warehouse are incurred. This is followed by a discussion of strategic and tactical factors for warehouse operation, and then a discussion of database considerations for WMS. The last part of the chapter describes how users interact with a WMS and what functions they should expect it to perform. The purpose here is not to describe how the WMS is structured, since that varies with the software vendors, but rather to present a user's viewpoint of the major aspects of the system.

A distinction should be made among three different aspects of use of a WMS: planning, executing, and reporting (Rouwenhorst et al. 2000). Once a system is installed, effective reporting feeds back to planning. Although most users focus on the execution aspect, the planning aspect is just as important since that involves strategic (more than six months in the future) and tactical decisions (one to six months in the future) that affect operational effectiveness just as much as short-term planning and execution do.

2. FUNCTIONAL DESCRIPTION OF WAREHOUSE OPERATIONS

2.1. Functional Structure of Warehouse Operations

A functional structure of a warehouse with order-picking activities, as shown in Figure 1, consists of at least 8 functional areas (departments) and more than 15 material flows (represented by arrows) with various load types (Yoon and Sharp 1996). This functional structure is a road map, and not all facilities will contain all departments and flows. The major departments can be categorized as breakdown or consolidation area, based on major functions, and as storage or transfer area, based on the duration of product stay:

- *Receiving area:* incoming shipments are unloaded, and inspected if necessary (transfer area).
- *Pallet reserve area:* an area where products are stored and retrieved in whole pallet quantities, without pallet breakdown (storage area).
- *Carton pick area:* an area from which products are retrieved in carton quantities. Incoming loads and storage units are usually pallets, but may also be cartons and mixed unit loads (storage area).
- *Item pick area:* an area from which products are retrieved in item (less-than-carton) quantities. Incoming loads and storage units are often cartons, but may also be totes and items (storage area).
- *Sorting area:* an area where different items of an order are consolidated, if this function is needed because of orders being split into suborders for picking efficiency (transfer area).
- *Consolidation area:* an area where the different items, cartons, and totes belonging to an order are unitized, such as into a shrink-wrapped pallet (transfer area).
- *Shipping area:* an area where outgoing items are checked and loaded onto vehicles (transfer area). Consolidation and shipping areas are often combined.
- *Auxiliary areas:* may include labeling, repackaging, and processing of items returned from customers.

Material flows can be classified as order and replenishment flows. For replenishment the relevant flows are from receiving to pallet reserve, carton pick, and item pick areas; from pallet reserve to carton pick area; from carton pick to item pick area. The other flows, for customer orders, are relatively more frequent. Consider the flow of a typical high-activity product, which is received in pallets and stored in the pallet reserve area (e.g., the upper levels of pallet rack). It is then moved to the carton pick area (e.g., the lower levels of pallet rack). Individual cartons are removed from the carton pick area and placed in the item pick area (e.g., a gravity flow rack holding cartons). The order pickers selectively retrieve items from the flow racks and place them on conveyors, which carry the items to the sorting area. There the items of each order are sorted into totes, which are then sent to the consolidation area and then to shipping. Some customers may order this product in carton quantities, which may be retrieved directly from the carton pick area. If an order requests a quantity equivalent to 4.2 cartons, then 4 cartons may be retrieved from the carton pick area and the remaining

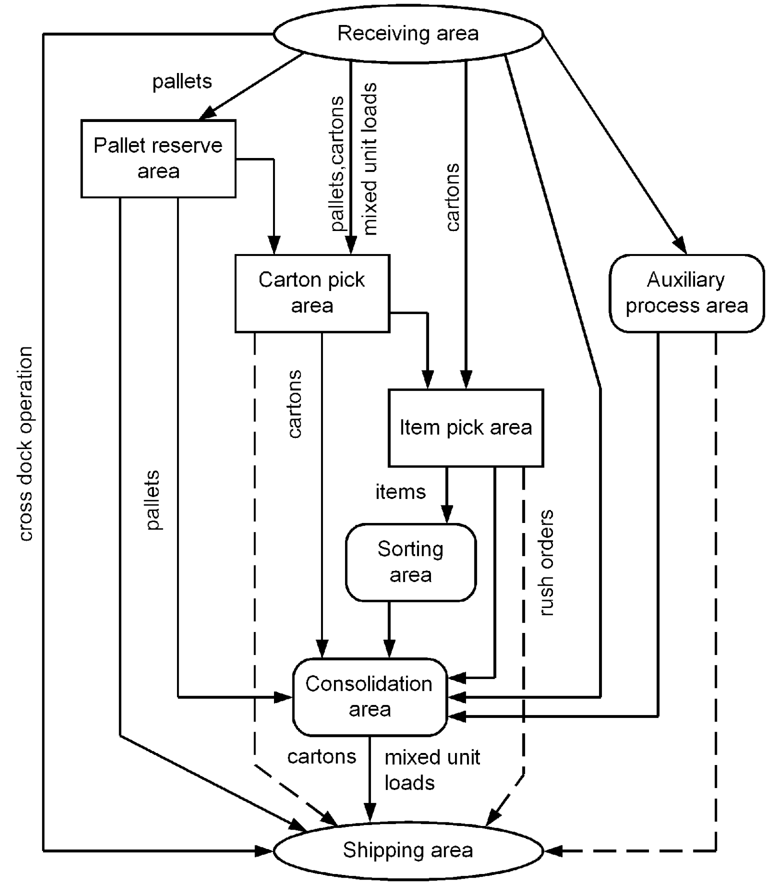

Figure 1 Functional Structure of a Warehouse with Order Picking.

item quantity from the item pick area. Similar logic applies to full pallet quantities of a product on an order.

2.2. Classification of Warehouses Based on Mission

Warehouses differ greatly in purpose and size, even within the same organization, so it is useful to examine some popular types. The purpose and size of a warehouse influence the factors that are important to the user of a WMS in the facility.

2.2.1. Factory Warehouse

A factory warehouse supplying wholesalers might process a small number of large orders daily with advance information about the composition of orders. The definition of "small number of orders" is based on the number of consolidation/shipping lanes: if during a process cycle, such as a shift, a packing/shipping lane can be dedicated to an order, we say the number of orders is "small." The definition of "large order" refers to the number of different products on an order: if there are 10 or more different products, we say the order is "large." The operating criteria in such a facility are usually cost and accuracy. Response time is often dependent on production scheduling in the factory and thus isusually beyond the control of the warehouse operator. The type of picking is usually pallet retrieval and carton picking, with emphasis on pallets.

2.2.2. Retail Distribution Warehouse

A warehouse serving captive retail units usually has advance information about the composition of orders. Typically, there are more orders per shift than consolidation/shipping lanes. Picking is usually

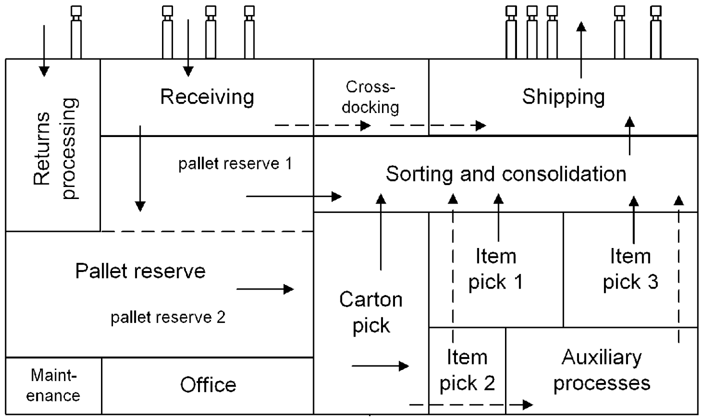

Figure 2 Example Layout of a Retail Distribution Warehouse.

carton and item picking, and usually there is a forward pick area (see Figure 2). Criteria are usually cost, accuracy, and fill rate (fraction of items requested that are actually shipped with the main part of the order). Response times are usually fixed and heavily dependent on truck routing schedules. If the retail units are not captive (not constrained to order from the particular warehouse), then response time becomes an important criterion.

2.2.3. Catalog Retailer

A catalog retailer typically processes a large number of small orders. While the definition of "small order" refers to fewer than 10 products, in the catalog retail business it is often closer to 2 or even 1 product per order. The number of orders per day may in the hundreds or even thousands. During the early part of the shift the composition of orders is usually known. Orders that arrive late during the shift may also be rushed through the system. For planning labor and replenishment of the forward pick area there is only statistical information available on these late-arriving orders. The primary criterion is often cost, but response time is also important. The picking here is usually item picking, with some carton picking.

2.2.4. Support for Manufacturing Assembly

A stockroom serving a manufacturing facility might process many small order with perhaps only statistical information about the composition of orders. If the response time is on the order of 30 minutes, then in effect any daily planning must be based on statistical information. The primary criterion is often response time, with cost a secondary criterion. The major types of picking may include item picking and carton picking.

Precise definitions of the descriptors "small" and "large" are not possible. For example, order size can be determined by cubic volume and/or number of different products on the order (number of line items). It is suggested that a small order be defined as one that contains fewer than 10 line items. If the quantity per line item results in a cubic volume less than 0.01 m^3 (0.35 ft^3), then a small order is also limited roughly to 0.1 m^3 (3.5 ft^3). A large order, containing 10 or more line items, would often have a volume greater than 0.1 m^3. In some situations, a large order might fill a truck. These definitions allow for some awkward, in-between situations. The demarcation based on the number of line items may be more useful because it relates more to operating strategies than a demarcation based on cubic volume.

The difference between advance and statistical information relates to the ability to process the order data for more efficient operation. In the example of a stockroom serving a manufacturing facility, the requirement for fast response (such as 30 minutes) probably would preclude the types of batching strategies used by a catalog retailer, who usually has several hours at night for data processing and a late-afternoon shipping deadline. If there is adequate time for preprocessing, we say there is advance information. Otherwise, the information is statistical. The information availability is directly related to the control rules in the operation of the OPS, since planning and execution based on statistical information may be different from that based on advance information.

2.2.5. Some Terminology

The language used by warehouse designers and operators contains some commonly used terms that need to be defined:

SKU: stock-keeping unit, the type identification of a product for purposes of distribution; for example, Coca-Cola Classic may be sold in 2-liter bottles packed 6 to a carton, 1-liter bottles packed 12 to a carton, 12-ounce cans packed 24 to a carton, 12-ounce cans arranged as 4 6-can inner packs in a carton, and 12-ounce cans packed 24 to a flat; these would all be different SKUs.

Item: the smallest unit of a product sold by the distribution center if many items are contained in a carton; sometimes called piece or each; examples are a 1-liter bottle of soft drink, a 12-pack of inexpensive ball-point pens, a 4-pack of spark plugs, a carton of cigarettes (containing 200 cigarettes in 10 packs of 20 each), a gift pack of stationery and envelopes.

Carton: a paperboard container holding identical product; usually of a size and weight allowing manual handling; example dimensions are $14 \times 10 \times 20$ in. and $300 \times 200 \times 400$ mm; recent trends in some industry sectors are towards a flimsier container, often called a flat, where the upper portion is plastic wrap.

Inner pack: several units of a product secured together (usually by paper or cellophane wrap) and sold by the distribution center as a unit if many items are contained in a carton and purchase quantities per item are large; a carton contains several inner packs.

Pallet: a set of cartons or totes of identical product arranged in a cubical pattern and usually supported by a base that may be of wood or plastic; example dimensions are $40 \times 48 \times 54$ in. and $800 \times 1200 \times 1000$ mm.

Mixed unit load: a set of cartons or totes of different products arranged in a cubical pattern similar to a pallet, often wrapped or strapped for stability.

Overpack: a large carton or tote containing different products; smaller than a pallet but larger than a carton so that manual handling may be difficult.

Tote: a container usually made of plastic and often used for storing and handling different products; usually similar in size to a carton; may be nestable or collapsible, with or without lid.

Order: a document from a customer requesting specific SKUs in specific quantities.

Line item: a ‘‘line’’ on an order document relating to a specific SKU and quantity.

Zone: a part of a distribution center to which an order picker is restricted; an example is a 40-aisle system divided into four zones of 10 aisles each, or an aisle-captive person-aboard system with 6 aisles and thus six zones.

Suborder: the portion of a customer order relating to a zone in the distribution center.

Batch: a set of suborders in a zone assigned to an order picker.

Time window: a portion of a day during which an order is processed; for example, an eight-hour day may be split into four two-hour time windows such that an order is processed completely during one of the time windows.

Pick wave: the set of orders processed during a time window; waves are often associated with zone picking.

Order class: a subset of the daily orders with some common characteristic, such as the same customer type, same size of order, or same shipping method.

Product group: a subset of the products in a distribution center with some common characteristic, such as vendor, product type, activity, or brand.

I/O point: the input/output point of a system.

S/R: storage/retrieval.

ASN: advance shipping notice, issued by a supplier to inform the warehouse operator of a shipment to arrive in the near future, usually transmitted electronically.

3. STRATEGIC AND TACTICAL FACTORS IN WAREHOUSE OPERATION

3.1. Classification by Implementation Time

We define strategic factors as those with implementation six or more months in the future. Usually these involve design changes in the physical or operating system where procurement and installation take that much time. Examples include:

- Changing the holding capacity and processing capacity of a functional area
- Changes in hardware for storage, vehicles, conveyors, control system

Tactical factors are defined as those with implementation one to six months in the future. Examples include:

- Modifications to existing storage and handling equipment and major movements of products to new storage or pick positions that cannot be performed with in-house labor on nights and weekends
- Changes in operational rules for storage, retrieval, sorting, and merging that require software modifications
- Negotiating changes in labor mix, that is, the balance between permanent and temporary employees, the balance between regular and overtime

3.2. Operational Planning

In addition to these strategic and tactical factors above, operational planning must be performed on a monthly or more frequent basis. This includes the examples below:

- Reclassification of products based on activity and inventory requirements, including the phase-in of new products and deletion of obsolete ones
- Restructuring of pick zones
- Changing operational settings in the WMS to accommodate a change in volume or change in the mix of orders
- Volume forecasting and labor planning
- Retraining of employees based on performance measures, such as productivity and quality

3.2.1. Space-Planning and Space-Adjustment Factors

The determination of storage space requirements is one of the most fundamental functions in warehouse management. Space utilization in a storage system is affected by several factors:

- *Volumetric efficiency,* F_a, in placing a product load in a storage compartment. This may result from undersized loads and from obstructions in the rack area, such as columns and sprinkler pipes.
- *Utilization,* F_b, of a set of storage compartments by a product lot as withdrawals are made. Deep-lane storage systems are particularly affected by this phenomenon, although it also affects single-deep pallet rack and shelving systems when withdrawals are in small quantities.
- Number of *storage compartments not assigned* for operational flexibility, such as performing dual-command S/R operations. It is usually impossible to occupy every storage position and maintain any type of operational discipline. Some fraction of the spaces, say 5–10%, need to be empty to provide opportunities for activity-based storage when incoming loads arrive. The resulting factor, F_c, will be 90–95% when applied to maximum product storage requirements. For average product storage requirements the factor usually does not apply and can be set to 100%.
- *Cyclical fluctuations* in storage requirements, resulting in factor F_d. Most businesses experience inventory peaks at a particular time(s) of the year. If one designs for the peak (or 90% of the peak) requirement, then at other times of the year the system will be underutilized. One can minimize this effect by renting space from third-party providers during peak inventory periods, by smoothing out deliveries and shipments with incentives, and by more frequent inventory replenishments during peak inventory periods.

The volumetric efficiency, F_a, depends on the matching of load sizes with storage compartment sizes. The storage compartment size must allow for clearances and some load deformation; thus, 100% utilization of the storage compartment would reflect the minimum clearances.

In one case study, pallets in a manufacturer's warehouse were limited in height to 127 cm (50 in.) based on rack spacing, but the average pallet height was 112 cm (44 in.) (Sharp et al. 1994). This gave a factor value of

$$F_a = \frac{112}{127} = 0.88$$

In addition, 50% of the pallets in storage required a height less than 102 cm (40 in.), so for these the factor was

$$F_a = \frac{102}{127} = 0.80$$

Partial pallets that are received and stored without consolidation contribute to low factor values. Columns and other obstructions may cause a loss of 5% or more of the available space. This factor applies to the maximum product storage requirement.

The utilization of a set of storage compartments by a product lot depends on the number of compartments assigned and the withdrawal pattern. For example, if an incoming lot consists of three pallets of identical product, the product is stored in a single-deep rack system, and carton withdrawals occur uniformly, then the average compartment utilization is calculated as shown in Table 1. The calculations assume the ability to reassign empty spaces immediately to other products. The result here is a utilization of 75%, based on the average product storage requirement. If we were to calculate the utilization factor based on maximum product storage requirement, it would be 1.5/3.0 = 50%.

For deep-lane systems the calculations are similar but more involved. Often there is a mismatch between an incoming product lot and the available slots, despite the best efforts of the warehouse designer. One first needs to calculate the optimum lane depth, assuming that empty lanes can be reassigned to other products immediately. Table 2 shows a typical situation in floor stacking, where an incoming lot of 15 pallets may be assigned to a lane depth up to 5, with a stacking height of 3. The best situation requires a floor space of 6.3 m^2, which corresponds to floor space occupied by product (not counting aisle space) of either 3.6 or 4.2 m^2. The incoming lot of 15 pallets requires 5 floor spots of 1 m^2 each, or 5 m^2. The average inventory is 8 pallets (the time for zero inventory is assumed to be negligible), and these require an average of 8/3 = 2.67 m^2. Thus, the utilization based on average product storage requirement is 2.67/3.6 = 74% (for the 2-deep lanes), and 2.67/5 = 53% based on maximum product storage requirement (Tompkins et al. 1996). This underutilization of deep-lane systems is called honeycombing.

The cyclical fluctuations work together with the method (or lack) of shared storage. Consider the forecasts of inventory requirements (in pallets) over eight time periods for 10 products shown in Table 3. The 10 products have been classified into two groups based on chemical compatibility, and within each group any pallet may occupy any storage position (shared storage). If there is no reorganization of the storage system over the eight time periods, then the positions needed for the groups are 32 and 20, respectively, for a total of 52 pallet positions, as shown in column 15 of Table 4. If the spaces are reorganized every two time periods, then the requirements decrease to a total of 44, for savings of 15%. In this example the reorganization might require some special cleaning to avoid chemical incompatibilities with residues left in the storage compartments. For the case of reorganizing every 8 periods, the sum, over products, of the average storage requirement is 36.75. So the utilization, based on average product storage requirement, is 36.75/52 = 71%; for reorganization every 2 periods, the factor is 36.75/44 = 84%. This dependence of utilization based on reorganization interval is examined in Sharp et al. (1999).

TABLE 1 Method of Calculating Average Storage Compartment Utilization

Col. 1 Number of Spaces Occupied	Col. 2 Percent of Time Number Occupied	Col. 3 (col.1)(col.2)	Col. 4 Average Product Quantity in Storage	Col. 5 (col.4)(col.2)
3	0.333	1.000	2.500	0.833
2	0.333	0.667	1.500	0.500
1	0.333	0.333	0.500	0.167
	Total	2.000	Total	1.500

Average utilization, F_b = 1.500/2.000 = 0.75

TABLE 2 Lane Depth Analysis, Incoming Lot Size = 15 Pallets
Stacking height = 3, pallet dimensions are 1 × 1m, including horizontal clearances

Lane Depth		Modular Width		M^2 per	Lanes Needed		Average m^2	Floor Space
Pallets	Meters	Pallets	Meters	Lane	Maximum	Average	Occupied	Product
1	2.5	1	1	2.5	5	3	7.5	3
2	3.5	1	1	3.5	3	1.8	6.3	3.6
3	4.5	1	1	4.5	2	1.4	6.3	4.2
4	5.5	1	1	5.5	2	1.2	6.6	4.8
5	6.5	1	1	6.5	1	1	6.5	5

Explanation of averages, assuming smooth reduction of inventory:
For 1-deep, each of the 5 situations has equal probability, so average = 3.
For 2-deep, 3 lanes occurs 20% of the time, 2 lanes occurs 20 + 20 = 40% of time.
and 1 lane occurs 20 + 20 = 40% of time. So average is (3)(0.2) + 2(0.4) + 1(0.4) = 1.8.
For 3-deep, 2 lanes occurs 20 + 20 = 40% of time, 1 lane 60%, so average = 1.4.
For 4-deep, 2 lanes occurs 20% of time, 1 lane 80%, so average = 1.2.
For 5-deep, we always need the entire lane.
The time when no lanes are needed is assumed to be negligible.

The overall effect of these four factors can be quite shocking. Using values similar to those in the examples, we might have an overall utilization of storage space, based on average product storage requirements, equal to

$$F_a * F_b * F_c * F_d = 85\% * 75\% * 100\% * 80\% = 51\%$$

Based on maximum product storage requirements, the overall value would be much lower, depending on the method of shared storage. The above examples point to the need for the WMS to report information that enables the warehouse manager to estimate space requirements in a manner consistent with the ability to reallocate that space. Although these types of decisions are often thought of as being part of warehouse design, the ever-changing business conditions in the economy imply that they are also part of warehouse management.

3.2.2. Individual Product Assignment to Storage Positions

A storage rule is defined as a rule for assigning each SKU to storage locations. A primary objective of warehouse design and operation is to minimize the average process time per storage/retrieval (S/R) activity or per order. Even if the total cost of order picking may be the ultimate concern, a significant portion of the total cost is usually proportional to S/R time. Storage rules can be grouped into two broad classifications:

TABLE 3 Example Forecast, 10 Products in Two Groups

		Period							
Product	Group	1	2	3	4	5	6	7	8
1	1	4	5	6	7	9	0	3	4
2	1	7	9	11	0	1	3	5	6
3	1	9	10	0	1	2	5	7	8
4	1	12	0	2	3	4	7	8	10
5	1	0	6	6	4	3	3	2	1
6	2	4	0	0	1	1	2	3	4
7	2	0	1	1	2	3	4	7	9
8	2	0	1	2	2	3	4	5	0
9	2	2	3	4	5	6	7	0	0
10	2	1	2	2	3	3	3	0	1

TABLE 4 Analysis of Data in Example

col.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
			Period		Max.	Period		Max.	Period		Max.	Period		Max.	Max.		Average
Row	Product	Group	1	2	1, 2	3	4	3, 4	5	6	5, 6	7	8	7, 8	1–8		1–8
1	1	1	4	5	5	6	7	7	9	0	9	3	4	4	9	Total	4.75
2	2	1	7	9	9	11	0	11	1	3	3	5	6	6	11	of max.	5.25
3	3	1	9	10	10	0	1	1	2	5	5	7	8	8	10	values	5.25
4	4	1	12	0	12	2	3	3	4	7	7	8	10	10	12		5.75
5	5	1	0	6	6	6	4	6	3	3	3	2	1	2	6	48	3.13
			Subtotals		Max.	Subtotals		Max.	Subtotals		Max.	Subtotals		Max.	Max. 1–8		Subtotal
6	sum of rows 1–5:		32	30	32	25	15	25	19	18	19	25	29	29	32		24.13
7	6	2	4	0	4	0	1	1	1	2	2	3	4	4	4	Total	1.88
8	7	2	0	1	1	1	2	2	3	4	4	7	9	9	9	of max.	3.38
9	8	2	0	1	1	2	2	2	3	4	4	5	0	5	5	values	2.13
10	9	2	2	3	3	4	5	5	6	7	7	0	0	0	7		3.38
11	10	2	1	2	2	2	3	3	3	3	3	0	1	1	3	28	1.88
			Subtotals		Max.	Subtotals		Max.	Subtotals		Max.	Subtotals		Max.	Max. 1–8		Subtotal
12	sum of rows 7–11:		7	7	7	9	13	13	16	20	20	15	14	15	20		12.63
			Subtotals		Total	Totals		Total	Totals		Total	Totals		Total	Total	Total	Total
13	sum of rows 6 + 12:		39	37	39	34	28	38	35	38	39	40	43	44	52	76	36.75

1. *Dedicated storage:* Each product is assigned a set of storage compartments that no other product is allowed to occupy.
2. *Shared storage:* Each product group is assigned a set of storage compartments that no product in another group is allowed to occupy.

For dedicated storage, the most popular assignment rule is to assign the SKUs with the highest activity (fast movers) to the locations near the input/output (I/O) point(s). The motivation is to reduce average S/R time. This assignment of individual products to storage positions, called slotting, is usually supported by the WMS. The major principles were outlined in the 1960s (Heskett 1963); a more accessible reference is Tompkins et al. (1996). The activity level of a product is measured by its cube-per-order-index (COI), defined as:

$$\text{Cube per order index} = \frac{\text{access trips per period}}{\text{maximum storage space needed}} \tag{1}$$

A shared storage system where any product in any group may occupy a storage compartment is characterized as pure random storage. However, products are usually grouped by size, environmental requirements (temperature, humidity, hazard level, etc.), value, and chemical compatibility, so pure random storage systems are rare. More popular are class-based systems, where products are grouped by activity level in addition to the factors of size, environmental requirements, etc. A typical class-based system allocates products into three classes, usually called A, B, and C, following the principles of Pareto analysis (Tompkins et al. 1996). The left portion of Figure 3 shows a typical result of such ABC analysis for a pallet S/R system, where the 20% most active storage spaces account for 60% of movements, the next 20% of spaces account for 20% of movements, and the remaining 60% of least active spaces account for 20% of movements. The right portion of Figure 3 shows a corresponding grouping of storage compartments in a single-deep pallet system and the resulting assignment of product groups.

A major benefit of shared storage is reduced space needs. Although textbook formulas suggest savings on the order of 45% (Tompkins et al. 1996), in reality the savings are diminished by common seasonality among products, inbound transport consolidation, inherent variability of product inventory, and inability of the warehouse manager to reallocate space. Typical savings for a three-class system with monthly reallocation of space are 20-30% (Sharp et al. 1999).

Referring to Table 4, if the five products in group 1 were stored in a dedicated system, with space needs based on the forecast for eight periods, then a total of 48 spaces would be required (sum of the individual values in column 15). With shared storage for group 1, only 32 spaces are needed, for a savings of (48 − 32)/48 = 33% just within group 1.

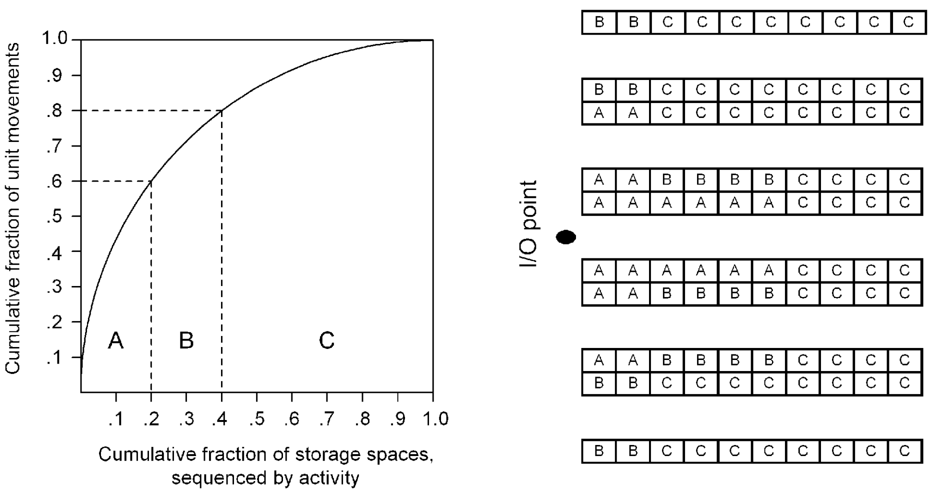

Figure 3 Pareto Analysis and Assignment of Product Groups to Storage Spaces.

A more refined version for pallet storage systems is based on the expected time in storage for each individual pallet (Goetschalckx and Ratliff 1990). For item pick areas a more refined measure is the viscosity of a product (Hackman and Rosenblatt 1990), defined as:

$$\text{Viscosity index} = \frac{\text{retrieval visits per period}}{(\text{cubic volume of product retrieved per period})\wedge 0.5} \tag{2}$$

The concept of family-based storage is sometimes applied in an effort to reduce picker travel time and to simplify order consolidation. The idea is based on identifying items that are likely to be ordered together and then to locate these items near each other. The method has been applied successfully in at least two situations: 1) selecting items based on bills-of-material for manufacturing, and 2) selecting clothing based on size in a catalog retailer operation (Frazelle 1989; Sadiq et al.1996; Amirhosseini and Sharp 1996).

3.2.3. Forward–Reserve Allocation

Referring to Figure 2, one of the crucial decisions in operational planning is deciding which products should occupy positions in the forward pick area and how space should be allocated to each. Depending on the storage technology used in the forward pick area, the total space allocated to it may be a strategic, design decision or a tactical, operational decision. The most commonly used methods use product activity to select products for the forward area and allocate an equal time value of inventory per product. This method, however, is inferior to the recommended method for making these decisions as described in Bartholdi and Hackman (1998). The concept of the viscosity index presented above is used in a recursive algorithm, using the following formula:

$$\text{Fraction of space for product } i = \frac{\sqrt{\text{cubic demand of product } i}}{\sum_j \sqrt{\text{cubic demand of product } j}}\,(V) \tag{3}$$

Dynamic reallocation of products to the forward pick area is practiced by some operators. Using this method, when a pick slot in the forward area becomes empty, it may be reassigned to another product that was previously being picked from the reserve area. Other operators periodically move slow-moving items from the forward area back to reserve.

3.2.4. Zoning and Batching, Order Retrieval

Order retrieval in large and/or busy systems is often characterized by zone picking, where the pick area is divided into smaller areas and a picker is restricted to a zone. An order that requests items from more than one zone is split into suborders, and the picker(s) in each zone selects the respective items. In a grocery distribution center an order may consist of a truckload, and this would be divided into perhaps 20 suborders. In this situation the zone picking would be simultaneous; otherwise it would take too long to complete the order. In a pharmaceutical distribution center the total cubic volume would be less, and the items might be picked into totes. In that situation the zone picking might be progressive, where the picker in the first zone starts the order and passes the partially filled tote to the picker in the next zone, and so forth. Figure 4 illustrates these concepts.

Zone picking is motivated by necessity in the case of large orders and efficiency in terms of operator training with equipment and familiarity with the products. When part-to-picker equipment is used, such as carousel, vertical storage column, and miniload, it is preferable to keep an operator at the retrieval station for that equipment to reduce operator idle time, and thus zones are usually defined by the equipment units.

When the orders or suborders are small relative to the zone size, batch picking is often used: each picker is assigned a set of suborders in the zone, and the items are selected in the most effective manner to reduce picker travel (in picker-to-part systems) or machine travel (in part-to-picker systems). If the pick vehicle has compartments that allow the picker to keep separate the items of the orders (maintain order integrity), then the method is sort-while-pick. Otherwise, downstream sorting is used to reestablish order integrity. The travel time savings from batch picking are discussed in (Armstrong et al. 1979; Choe et al. 1993).

Considering all these options, these are the following logical ways to process orders:

- *Single-order-pick:* One picker works on one order at a time until the order is filled.
- *Sort-while-pick, no zoning:* One picker works on several orders at time with a vehicle that has compartments for maintaining order integrity.

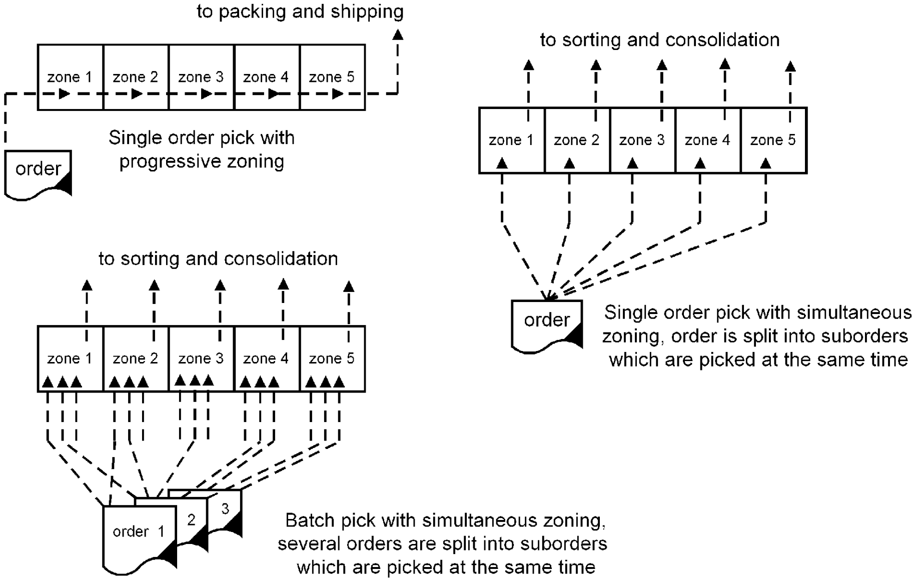

Figure 4 Zoning and Batch Picking.

- *Batch picking with downstream sorting, no zoning:* Several orders are picked by one person completely, often applied with conveyor transport of items to the sorting area.
- *Single-order-pick with zoning:* An order is split into suborders by zone and a picker in each zone fills the corresponding suborder; may be applied with progressive or simultaneous zoning.

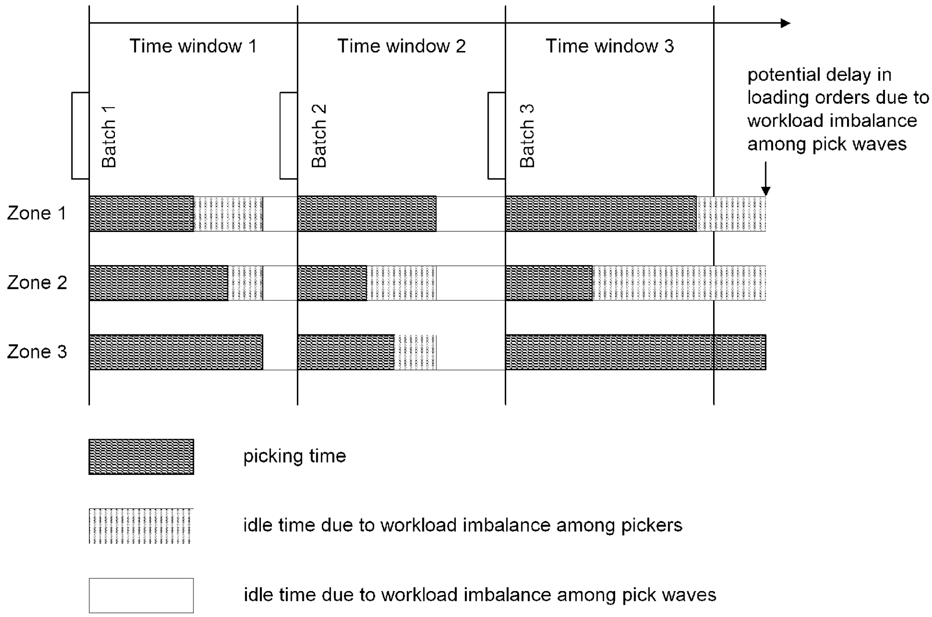

Figure 5 Workload Imbalances among Picker Zones.

TABLE 5 Picker Productivity as a Function of Zone Size and Time Window

Line Items per Consolidated Pick List	Number of Pick Waves	Time Window Duration, hr	Average Number of Orders in Process*	Productivity, Line Items per hr	Relative Productivity
50	12	0.5	25	64.6	65.3%
100	12	0.5	25	67.7	68.5%
50	6	1	50	72.7	73.5%
100	6	1	50	76.7	77.6%
200	6	1	50	79.7	80.6%
50	4	1.5	75	75.9	76.7%
100	4	1.5	75	80.2	81.1%
50	3	2	100	77.6	78.5%
100	3	2	100	82.2	83.1%
200	3	2	100	85.7	86.7%
50	2	3	150	79.4	80.3%
100	2	3	150	84.2	85.1%
200	2	3	150	87.9	88.9%
100	1	6	300	98.8	99.9%
200	1	6	300	98.9	100.0%

*Line items per order distributed Poisson with mean of 4.0.

- *Sort-while-pick with zoning:* An order is split into suborders by zone and a picker in each zone fills the corresponding suborders using a set of containers or a vehicle that has compartments for maintaining order integrity.
- *Batch picking with downstream sorting and zoning:* Several orders are split into suborders and the suborders for each zone are filled by the picker(s) operating in that zone, usually applied with simultaneous zoning.

3.2.5. Pick Wave Planning

When there are many orders to be processed daily, it may be desirable to split them into groups, called pick waves. The time for processing a pick wave in the pick area is called a time window. Pick waves may be necessary for one or more of the following reasons:

- Downstream sorting is used, and the design of the sorting system limits the number of orders that may be in process at one time. Note that the number of orders in process can often exceed the number of output chutes of a conveyor sorter (Bozer et al. 1988).
- The capacity of the forward pick area is insufficient to allow the daily orders to be filled without replenishment, and it is desirable to stop the pick process and replenish, for reasons of safety and/or efficiency.

There are some fundamental trade-offs among the size of a pick wave, picking efficiency, and size of the downstream sorting operation. The smaller the time window, the greater the workload imbalances among zones and across time windows. Depending upon the WMS and conveyor accumulation capacity, a picker who finishes early may or may not have to wait until all pickers are finished with the wave. Figure 5 illustrates this phenomenon of induced idle time. Also, smaller pick waves imply more travel per item selected. On the other hand, a small pick wave allows for a smaller and less expensive sorting system and allows for earlier completion of some orders. In the situation where items are sorted according to loading dock doors, the number of doors may limit the size of the wave. For a more complete discussion of these issues see (Choe 1991; Amirhosseini 1999). Table 5 shows some results for picker productivity and number of orders in process at a time for the situation where pickers must work in synchronized mode (pickers who finish early must wait for all to finish the wave).

4. DATABASE CONSIDERATIONS

Although the detailed structure of a WMS varies according to vendor, the WMS will typically be represented by a number of databases and protocols (methods) that reflect operating rules. In this section an overview of the more important databases is given, as well as some of the linkages among them. Further details may be found in Huffman (1985) and Lin (2000).

TABLE 6 Example Item Master Table for Products

Item SKU	Parent SKU	Vendor	Date Introduced	Vendor Part Number	Lot Control Logic	Perish Date, Months	Alternate Vendors	Substitute Items	Pricing Schedule
4539056512-1	none	153	99.10.14	23331175	none	24	none	4539056513	153-427
4539056512-2	4539056512-1	153	00.02.08	23331175	none	24	none	4539056513	153-427
4540076423	none	28	00.02.15	8004550034	none	24	29	4540076431	29-080

Description	Major Product Group	Minor Product Group	Status	Current Reserve Zones	Current Reserve Slots	Current Forward Zones	Current Forward Slots	Hazard Class	Item Weight, kg	Item Cube, liters
Speaker set, for PC	12	4	active	P1, P3	0958, 0129	C2	2583	none	5.680	3.00
Speaker set, for PC	12	4	active	P2	0125	C2	2583	none	5.680	3.00
Voltage adapter, general	12	7	active	P1	1018	C2	2674	none	0.6	0.60

Item L, cm	Item W, cm	Item H, cm	Items Per Carton	Carton L, cm	Carton W, cm	Carton H, cm	Cartons per Tier	Items per Tier	Tiers per Pallet	Cartons per Pallet	Items per Pallet	Pallet L, cm	Pallet W, cm	Pallet H, cm
20.0	15.0	10.0	8	40.0	30.0	20.0	8	64	5	40	320	120	80	100
20.0	15.0	10.0	8	40.0	30.0	20.0	8	64	7	56	448	120	80	140
12.0	10.0	5.0	16	24.0	20.0	20.0	20	320	5	100	1600	120	80	100

Total Sales Last 6 Months	Pallet Requests Last 6 Months	Sales, Pallet Requests, Last 6 Months	Carton Requests Last 6 Months	Sales, Carton Requests, Last 6 Months	Item Requests, Last 6 Months	Sales, Item Requests, Last 6 Months	Retail Items per WH Item	Retail Item L, cm	Retail Item W, cm	Retail Item H, cm
317	0	0	17	204	49	113	1	20.00	15.00	10.00
							1	20.00	15.00	10.0
2893	0	0	87	2352	78	541	1	12.0	10.0	5.0

4.1. Products and Orders

Two important databases relate to products and orders, respectively. The item master defines the products that are handled by the warehouse. Included in this database are product identification, physical characteristics, vendor sources, replenishment and safety stock levels, service level, and so forth (see Table 6). The order master contains the records of customer orders (see Table 7). In addition, closely related tables include a vendor master, a customer master, and an inventory master. The last table should reflect not only quantities and locations of products on hand, but also back-ordered quantities and quantities reserved for customers or other reasons.

4.2. Flow Control

Another series of database tables is used to track the flow of material: advance shipping notice (ANS) table for those receipts that are expected soon, putaway tables for items received that are to be stored, replenish tables for forward pick areas, pick tables for pick waves in each area, load consolidation tables, truck manifest tables, and additional move tables for other moves not specified above. There may be more than one version of each table, one as planned and another as executed, or these characteristics may be captured in one table. These tables, which are often subdivided by priority, are particularly important when automatic identification, such as bar code, is used to control flow. In the situation of batch picking with zoning the pick table needs to contain details on zone, picker, pick wave, sorting area, packing method, and so on. (see Table 8).

4.3. Building, Equipment, and Personnel Assets

The equipment master contains information on the physical characteristics of storage and transport equipment, speeds, compatibilities with respect to products and containers by size, and access times

TABLE 7 Example Order Master Table

Date	Order	Customer	Address	PO Number	Ship Date
00.10.25	392457	ABC Mfg. Co.	12 Main Street, Anytown, State	00100479	00.10.27

Purch Agent	Sales Rep	Tel Ref	Fax Ref	E Ref
Mary Doe	Jane Dowling	201.456.3333	201.456.3339	mdoe@abc-mfg.com

Ship Address	Ship Method	Preferred Carrier	Freight Charges	Ship Short	Split Shipment	Billing	Credit Status
14 Main Street, Anytown, State	LTL	Fast Truck Co.	customer	yes	no	30 2% 10	1

SKU	Quantity	Unit Price	Discount Logic
3092874101	4	34.00	2
3092874217	7	122.00	2
3092921004	1	345.00	3

Date	Order	Customer	Address	PO Number	Ship Date
00.10.25	392458	XYZ Dist. Co.	1 Little Lane, Smalltown, State	04005682	00.10.28

Purch Agent	Sales Rep	Tel Ref	Fax Ref	E Ref
Ron Howard	Linda Cabot	715.233.8700	715.233.8710	ronnie@xyzdistn.com

Ship Address	Ship Method	Preferred Carrier	Freight Charges	Ship Short	Split Shipment	Billing	Credit Status
1 Little Lane, Smalltown, State	package	Zip Express	customer	no	no	30 net	1

SKU	Quantity	Unit Price	Discount Logic
5200346721	8	55.00	1

TABLE 8 Example Pick Table for Batch Picking with Zoning

Date 8	01.03.0	Wave	2-08	Zones C1		Release Time 1030		
Empl	31	Method 2	Order Picker	Packin g Lane 7		Standa rd Time 30		
Stop	Slot	SKU	Description	Package	Total	Quantity	Customer	Notes
1	1005	6540049423	PCV valve, GM 98 type 5	carton	3	3	Right tune #47	
2	1008	6840052109	tune-up kit, 6G, platinum	carton	7	2	J Discount #2	label 2 in from bottom
						1	AAFES TX	
						4	AAFES SF	export label, US mfg
3	1017	7134458302	oil filter, N30	carton	9	5	AAFES SF	export label, US mfg
						2	Right tune #47	
						2	J Discount #2	label 2 in from bottom
4	1024	6424083023	transmission filter, F28	carton	4	3	L&M Service	
						1	Right tune #47	

TABLE 9 Example Equipment Master Table

Type	Class	Parent	Date	Mfg.	Desc.	Qty.	W. cm	D, cm	H, cm	Aisle cm	Max. Lift, cm	Level	Levels	Deep	Wide	Flow
storage	010	none	96.05.08	ABC	pallet rack	450	320	280	530	300	0	1	1	2	3	B-B
	011	10	96.05.09	ABC	pallet rack	450	320	280	530	300	420	2–4	3	2	3	B-B
	012	10	96.05.10	ABC	pallet rack	350	320	280	530	300	540	5	2	2	3	B-B, Top thru
	015	none	96.05.11	ABC	p flow rack	55	110	500	300	300	180	1–2	2	4	1	
	021	none	96.05.12	DEF	shelf	120	120	65	200	150		1–6	6	1	1	B-B

Surface	Sprinkler	Std Load W, cm	Std Load D, cm	Std Load H, cm	Min. Load W, cm	Min. Load D, cm	Min. Load H, cm	Max. Load W, cm	Max. Load D, cm	Max. Load H, cm	Comments
floor	2,4	80	120	110	60	120	20	300	130	110	
none	2,5	80	120	110	60	120	20	300	130	110	
mesh	2,6	80	120	110	60	120	20	300	130	220	
roller	2,7	80	120	110	80	120	50	80	120	110	pallet QC
metal		30	30	27	10	10	10	110	35	30	

Type	Class	Mfg.	Date	Desc.	Power	Duration, hr	W, cm	L, cm	H, cm	Pick Aisle	Cross-Aisle	Max. Lift. cm	Max. wt, kg	Velocity H, m/sec
Vehicle	100	GHI	98.02.10	pallet jack	none	NA	80	110	130	200	200	8	800	0.6
	102	JKL	98.03.02	pallet jack	battery	8	85	120	115	220	220	10	1000	1.2
	201	GHI	98.05.04	fork lift, CB	propane	14	105	170	255	300	320	610	1500	2.8
	202	GHI	98.06.10	fork lift, CB	propane	14	105	170	255	300	320	640	1800	3.0
	251	JKL	99.03.02	order picker 1	battery	6	120			180	380	640	1400	2.0

Velocity V, m/sec	Std Load W, cm	Std Load D, cm	Std Load H, cm	Min. Load W, cm	Min. Load D, cm	Min. Load H, cm	Max. Load W, cm	Max. Load D, cm	Max Load H, cm	Permitted Accessories	IDs
0	80	120	110	60	120	10	100	140	140	container 1	100-01, 100-02
0	80	120	110	60	120	10	105	160	140	container 1	102-09, 102-11
1.3	80	120	110	60	120	10	120	120	220	container 1	201-04
1.3	80	120	110	60	120	10	120	120	220	container 1	202-07
1.2	80	120	130	40	80	10	80	120	160	container 1	251-01
										container 3	251-02

TABLE 10 Example Personnel Master Table

ID	Name	Taxpayer ID	Date Hired	Phone	Pager	Pay Classification	Level
22	Cyril Bezukhov	123 45 6789	86.11.02	201.055.6000	201.055.6000	Manager 2	120
26	Ilya Rostov	087 65 4321	89.03.15	201.055.7000	201.055.7000	Manager 1	110
29	Mary Bolkonskaya	010 79 2468	84.05.22	201.055.7575	201.055.7575	Regular 4	130
31	Helene Kuragina	021 54 9876	93.01.08	201.055.8888	201.055.8888	Regular 2	115
36	Anna Drubetskaya	064 29 7531	98.07.14	201.055.9999	201.055.9999	Regular 1	100
40	Valentin Berg	004 02 3856	00.06.27	201.055.4444	201.055.4444	Clerical 1	100

Assignment Priorities											Other Shift Schedules		
A1	A2	R1	R2	P1	P2	I1	I2	L1	L2	Primary Shift			
2	1			3						1	2	3	4
1	2			3						1	2	3	
		3		2	1					1	2		
				1	2			3		2	1	4	
		1						2		3	none		
	1					2	5	3	4	1	2		

TABLE 11 Example Zone Master Table

Zone ID	Parent	Desc.	Primary Function	Other Functions	Storage Equip. ID	Quantity	Description	Vehicle Class	Description	ConvID	Description	Employee Type	Start Location	End Location
0	none	system												
1	0	Rec-1	Receiv	PalStor	010	30	p rack floor	100	pallet jack	301	skatewheel, extendible	R1		
					011	30	p rack	201	fork lift, CB	310	belt, 8m	R2		
2	0	Rec-2	Receiv	QuarInv	010	20	p rack floor	100	pallet jack	302	skatewheel, extendible	R2		
					011	20	p rack	201	fork lift, CB					
10	0	Pal-1	PalStor	QuarInv	010	120	p rack floor	201	fork lift, CB			R2		
					011	120	p rack	202	fork lift, CB			R2		
11	10	Pal-1A	PalStor	Cpick	010	120	p rack floor	102	pallet jack			P1		
								202	forklift, CB			R2		
12	10	Pal-1B	PalStor	QuarInv	011	120	p rack	202	forklift, CB			R2		
20	0	Pal-2	PalStor	QuarInv	010	150	p rack floor	201	fork lift, CB			R2		
					011	150	p rack	202	fork lift, CB			R2		
					012	150	p rack top	202	fork lift, CB			R2		
21	20	Pal-1A	PalStor	CPick	010	150	p rack floor	103	pallet jack			P1		
								202	fork lift, CB			R1		
22	20	Pal-1B	PalStor		011	150	p rack	202	forklift, CB			R2		
23	20	Pal-1B	CPick		011	150		251	order picker			P3		
24	20	Pal-1C	PalStor	QuarInv	012	150	p rack top	251	order picker			P3		
211	21	Pal-1A-A	CPick	Transient	010	30	p rack floor	103	pallet jack			P1	1131	1160
212	21	Pal-1A-B	CPick	Transient	010	50	p rack floor	103	pallet jack				1161	1210
213	21	Pal-1A-C	CPick	Transient	010	70	p rack floor	103	pallet jack				1001	1060
													1211	1220
30	0	Pal-3	CPick		015	55	p flow rack	201	fork lift, CB				1901	1950
40	0	Item-3	ItPick		070	1	carousel					P2	3201	3800
50	0	Item-4	ItPick		80	22	carton flow	401	belt+2			P3	4201	4222

(see Table 9). This table is usually subdivided into storage media (e.g., racks, shelving), automated storage/retrieval systems, vehicles, and conveyors. This type of information is accessed when decisions on product storage are made. Racks and conveyors are usually divided into zones, and this information is reflected in the tables. Compatibility of storage media with vehicles is also recorded.

The personnel master contains information on the skills of employees, availability by shift, and sometimes their performance (productivity and quality) ratings (see Table 10).

The most important table for building and equipment is the zone master. This table relates building space and equipment units in a logical manner, and it provides the links for inventory, product storage assignment, product retrieval, and flow control. In some applications the table is hierarchical, with overlapping zones. Zone overlap may occur when some areas of a building are used for one purpose, such as single-order-pick during one part of the shift, and another purpose, such as batch-picking-with-zoning, during another part. Table 11 shows some information in an example zone master table.

4.4. Operating Rules

A series of protocols is used to drive the functions in a warehouse according to specified rules. There is an umbrella protocol, called the function flow map, that defines the functions that are allowed to occur in the different zones (areas) of the warehouse. This protocol may be in the form of a table that can be controlled by the warehouse operator, or it may be coded directly into the WMS software. Table 12 is an example where the allowable functions are prioritized. In addition, there are tables that prescribe putaway rules and inventory allocation rules. The rules for picking flow path must reflect the zone structure: one zone, progressive zone picking, or simultaneous zone picking. Rules for picking method reflect single-order-pick and batch-picking. Picking control may be by paper labels, container license plate (e.g., bar code), or radio frequency (RF). Another set of rules applies

TABLE 12 Example Function Flow Map

Function number	Description	Origin Zone	Destinaion Zone, First Choice	Destination Zones, Other
101	receiving, general	none	1	2
102	receiving, R1 only	none	1	
103	receiving, R2 only	none	2	
201	putaway to pallet storage	1	10	20, 30
202	putaway to pallet storage	2	20	10, 30
203	putaway to pallet storage	1	10	
204	putaway to pallet storage	1	20	
205	putaway to pallet storage	1	30	
206	putaway to pallet storage	2	10	
207	putaway to pallet storage	2	20	
208	putaway to pallet storage	2	30	
221	move to cross dock operation	1	90	100
299	putaway to quarantine storage	1	10	20
301	putaway to item pick	1	40	50
302	putaway to item pick	1	50	40
303	putaway to item pick	2	50	40
401	pallet pick	10	100	90
402	pallet pick	20	100	90
501	replenish carton forward area	22	211	
502	replenish carton forward area	22	50	
601	carton picking, one zone only	211	100	
602	carton picking, multiple zones	211	80	
701	item pick, single-line orders	40	95	
702	item pick, single-line orders	50	95	
703	item pick, multi-line orders	40	85	90
704	item pick, multi-line orders	50	85	90
801	carton sorting	80	100	
901	item sorting	85	100	
950	packing	95	100	
960	outbound hold	95	98	
990	loading	100	none	

to consolidation, packing, and loading of orders. If value added functions are performed, such as labeling, pricing, or repackaging for retail display, then rules must be established for them.

4.5. Links to Hardware Controllers

Mechanized and automated equipment units will have their own hardware controllers, and these must be linked to the WMS. The hardware controllers are typically coded in C language in a UNIX operating system. Besides flow-control logic, information on system integrity, battery voltage, conveyor utilization, equipment malfunction, and so on is reported. Automated storage/retrieval systems, high-speed sorting conveyors, and merge conveyors, if present, must be integrated into the overall software system for the warehouse. Conveyor systems have numerous photo-eye detectors, which can send thousands of signals per hour; such high transaction rates must be handled by separate controllers that are linked to the WMS. The interfaces typically involve the transfer of batch instructions between the WMS and the hardware controllers. The main computing platform for the WMS may be a mainframe system, an IBM AS-400 system, or a Windows NT PC-based system. The major WMS vendors support multiple platforms (Seidl 1997; Hahn-Woernle 2000; IT logistiek 2000).

4.6. Data Backups

Systems that attempt to operate in real time require a hot backup or mirror computer operation, augmented by an emergency power generator. In essence, two computer operations run simultaneously, and either one can control the WMS in case the other fails. Otherwise, or in addition, a system of backup data tables should be maintained on an independent computer, so that they may be printed and used for operation in case the WMS computer fails. These backup tables should be updated once every shift or pick wave.

5. DAILY OPERATIONAL FACTORS IN WAREHOUSE OPERATION

5.1. Receiving Operations

It is logical to think of receiving as the first operation in warehousing. The physical receipt of goods, however, is typically preceded by an ASN. This allows for planned cross-dock operations, which are increasing in popularity. Out-of-stock conditions are flagged, and the corresponding goods go directly to packing and shipping for back-orders. Some goods may go to replenishment of forward pick areas directly from receiving (subject to stock rotation policies). Upon receipt of goods from qualified vendors, the inventory values in destination areas may be adjusted, or the goods may be logged into a transient state. Goods from non-qualified vendors may undergo a quality check and/or count. If this is time-consuming, the goods are held in a quarantine inventory status. If the quality check is based on a sample, it is usually possible to move the bulk of the product to another location and control the quarantine status through the WMS. Figure 6 shows the possible logical flows for receiving operations.

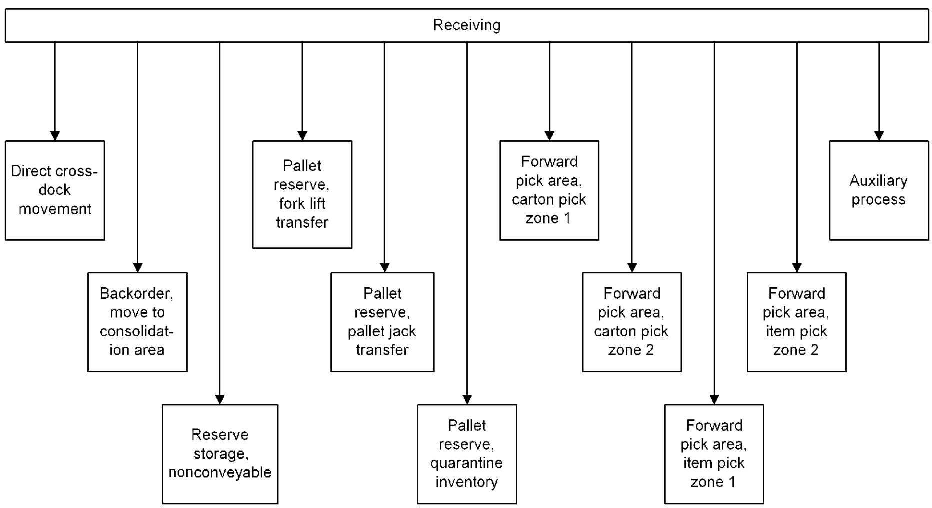

Figure 6 Receiving Operations Material Flows.

There should be the capability to process partial receipts, generate labels for pallets and cartons, and assign storage locations. The assignment of storage locations may follow one of several disciplines:

- *User is completely directed by WMS:* The WMS identifies the location based on product characteristics and available locations. The operator is not allowed to store the item in a different location, except by going through exception routines.
- *User is partially directed by WMS:* An example would be when the WMS directs the user to a zone or a portion of a zone (e.g., an aisle or portion of an aisle), but the user has flexibility within the zone of where to place the item.
- *User has complete flexibility:* The WMS allows the user to place the item in any location, and reports an error only when there is some physical incompatibility, such as compartment too small, compartment contains too much already, etc.

Returns processing is increasingly being assigned to outside operators, but most warehouses still accept some return goods from customers. This is often a labor-intensive operation, involving unpacking, inspecting, repackaging, and labeling. After the last step the goods can be ‘‘received’’ as if they came from a vendor. Manual date entry and error correction are also functions that must be included in receiving.

5.2. Storage and Inventory Control

In addition to the concepts of dedicated vs. shared storage discussed earlier, the WMS should have capability for lot control (typically by date or production run), fractional unit loads, and storage in more than one location. When the incoming quantity of a product is less than a unit load, there is an opportunity for consolidation when the products are stored. Various rules may govern this consolidation, such as same SKU, same SKU and same lot, allow different SKUs in storage compartment, compute remaining compartment capacity by cubic volume, compute remaining compartment capacity by dimensions of items, and so on. When goods that were in a transient state upon receipt are stored, the inventory values are adjusted. In addition, the actual storage location is recorded, or acknowledged in the situation of the user being completely directed by the WMS. Some goods may be reserved for specific customers when they are stored; such stock reservation may also occur later. Cycle counting may be performed when the items are stored; such opportunistic counting helps reduce extra travel for inventory control. Other functions that occur on a regular basis are stock activity reports for fast, medium, slow, and dead stock, and empty location reports. Manual data entry and error correction are also needed.

5.3. Order Processing

The first step in order processing, which is usually performed by the customer service department, is verification of item availability. This is preferably done online, or electronically in the situation of computer-based orders. On-line verification of customer credit status is next, followed by inventory reservation, if appropriate. The pricing structure may reflect quantity restrictions, such as full carton or full pallet, and these are applied at this time. The customer service department should suggest the closest or next quantity multiple, with price breaks if any, to simplify the work in the warehouse. The software used by the customer service department, which may be linked to the WMS, should have flexibility in pricing by customer and order type, flexibility for partial shipments, flexibility in picking and packing orders according to customer needs (including priority class), and flexibility in handling shipping charges (customer pays, price includes transportation, etc.) After the order has been selected, the WMS (or linked software) generates an invoice and bill of lading. Manual date entry and error correction are also included as functions.

5.4. Order Picking

There are several planning functions precede the actual retrieval of products for customer orders. The first of these is to check current inventory levels in the forward pick areas and generate replenishment reports. Most warehouse operators prefer to replenish at the beginning of the shift, for reasons of safety and efficiency. Some replenishments may occur during the pick process, especially if the information about orders is incomplete, or if operators select full cartons from the item pick area when they should be selected from the carton pick area. The WMS should support workload balancing in the pick operation: reflect different picker capabilities according to data in the personnel master (Table 10), and reflect different number of operators according to pick wave and shift. The ability to balance workload over more than one day is desirable, but it is usually not available in the typical WMS.

The WMS must be capable of supporting the different pick methods described in Section 3.2.4, along with estimates of completion times for the major steps, such as the pick waves and sorting and loading operations for waves. For pick wave formation a variety of criteria may apply: group rush orders first, group orders by type (single-order-pick, batch-pick, etc.), group orders by packing method, group orders by loading dock door in reverse sequence based on delivery routes, and group orders by proximity of retrieval locations for sort-while-pick operation (Gibson and Sharp 1992). In zone systems it is desirable to have flexibility for changing the zone configuration, either by pick wave or dynamically. Dynamic adjustment of zones in item-pick operations has proven very effective (Bartholdi and Eisenstein 1996). The routing of pickers in a multi-aisle system is usually accomplished by software according to the number of retrieval stops and the travel metric:

- *Single-command operation:* The operator makes only one stop in the storage system before returning to the I/O point.
- *Dual-command operation:* The operator makes two stops in the storage system before returning to the I/O point. If one stop is for storage and the other for retrieval, as in pallet operations, this method is called interleaving. The rules in the WMS determine the travel savings to be gained by such methods (Graves et al. 1977).
- *Multicommand operation in a sparse system:* The operator makes several stops (more than two) in a system but considerably fewer than the number of pick aisles. For a single block of aisles, called a ladder structure (see Figure 7), an adaptation of the traveling salesman problem may be applied to the routing (Ratliff and Rosenthal 1983). When there are cross-aisles or multiple blocks of aisle, heuristic algorithms are available (Kees 2000).
- *Multicommand operation in a busy system:* When the number of retrieval stops is more than the number of pick aisles, serpentine routing is applied. Here the picker enters each aisle that contains product on the pick document and continues through to the end of the aisle, and then proceeds to the next aisle that contains product to be retrieved. In busy systems, or systems where U-turns or reverse travel in an aisle are not desirable, a one-way flow in each aisle may also be imposed. This may induce unnecessary travel in aisles with no products for the current

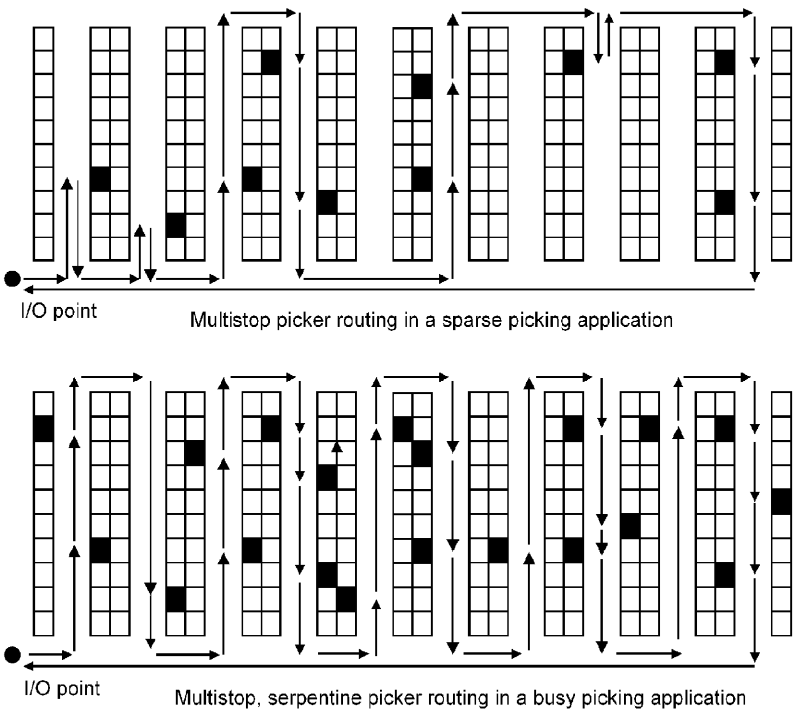

Figure 7 Multistop Picker Routing.

pick document. The expected picker travel in such systems may be obtained using the results in Choe (1991).

- *Multicommand operation with order-picker trucks:* When the vertical travel dimension is added, the picker routing becomes more complicated. Generally, it has been found that the best storage-assignment method is to place the more active items at the lower levels of the rack system. Placing more active items at the end of the aisle doesn't help much, since there is a good chance the picker will travel through the aisle anyway (Krueger 1999).
- *Multicommand operation with automated S/R systems:* In an automated S/R system, the characteristics of the S/R machine usually imply simultaneous movement in the horizontal and vertical dimensions. Most of the technology applications have one S/R machine per aisle. The picker routing then becomes a traveling salesman problem in the Chebyshev metric (Bozer et al. 1990).

The WMS will generate consolidated pick documents for each operator (see Table 8), sequenced by retrieval location. These documents may be paper, electronic, labels or electronic tags, or a combination. They must contain the picker or picker team identification, SKU location, quantity, inner-pack quantity if applicable, zone, wave, packing lane, packing method, and shipping method. Exceptions and interruptions occur frequently in order picking, and a series of protocols must be available to deal with them. The simplest exception decision to execute is to ship an incomplete order: the packing list and invoice are adjusted to reflect actual quantities, and the missing items are placed on back order for the customer if that is the applicable policy. More involved are decisions to substitute items, or to place nearly complete orders temporarily on hold to wait for a missing item. These actions usually require that the products be placed in a temporary storage area, which complicates the sequence of data-processing operations in the flow control tables. The discovery of wrong or damaged items at the loading operation may tie up a loading dock door and disrupt the release of the next pick wave.

5.5. Order Consolidation

After the multiple parts of an order are selected, they must be brought together in one location for packing and consolidation. This may be as simple as consolidating items in a staging lane near the loading dock. In other situations, such as the use of high-speed sorters, accumulation lanes feeding packing lanes are needed. The WMS or linked sorter software controls the flow of goods from picking through sorting and order consolidation and on to packing and loading. Items that differ physically

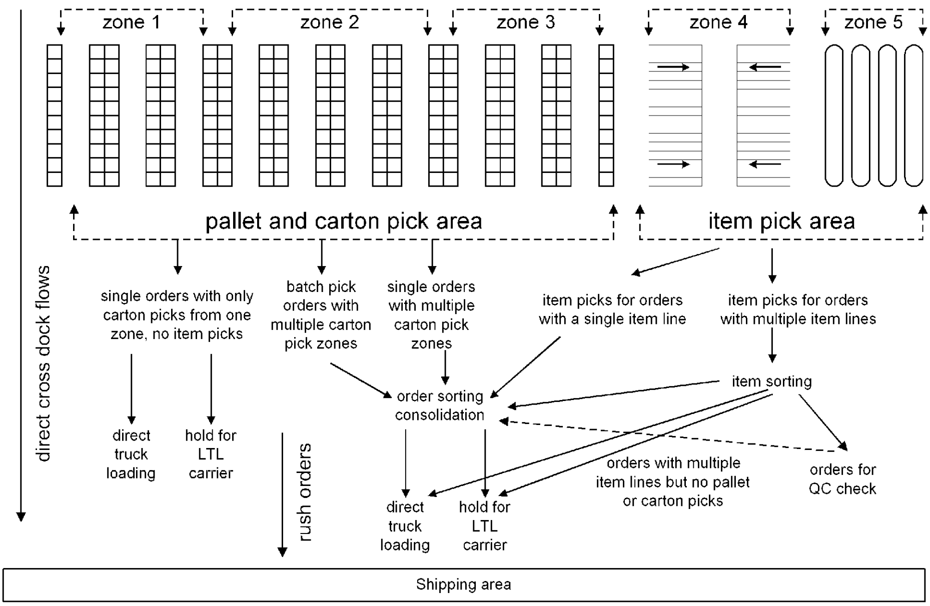

Figure 8 Example of Order-Consolidation Material Flows.

according to shape, such as pallets, nonconveyable items, conveyable items, totes containing multiple items, and so on pose the greatest challenge in this situation. Value-added operations such as labeling, pricing, and repackaging for retail display impose additional tracking and coordination needs. A strict control system, usually involving bar code, and sufficient floor space are necessary ingredients of an effective solution to such problems.

Figure 8 shows some possible flows for order consolidation where pallet and carton picks are sorted manually in a consolidation area and item picks are sorted in a separate area, perhaps with a conveyor.

5.6. Additional Factors

A number of human factor and hardware enhancements are available to increase the productivity and accuracy of order picking, including pick-to-light, voice-guided picking, and voice-recognition systems. Pick-to-light systems (see Figure 9) offer productivity increases of 30–100%, with corresponding error reductions of up to 80% (Sharp et al. 1997). Voice-guided picking allows the operator to use both hands to retrieve products without the need to refer to a paper pick document. Voice-recognition systems enable the picker to interact with the WMS without cumbersome key-entry

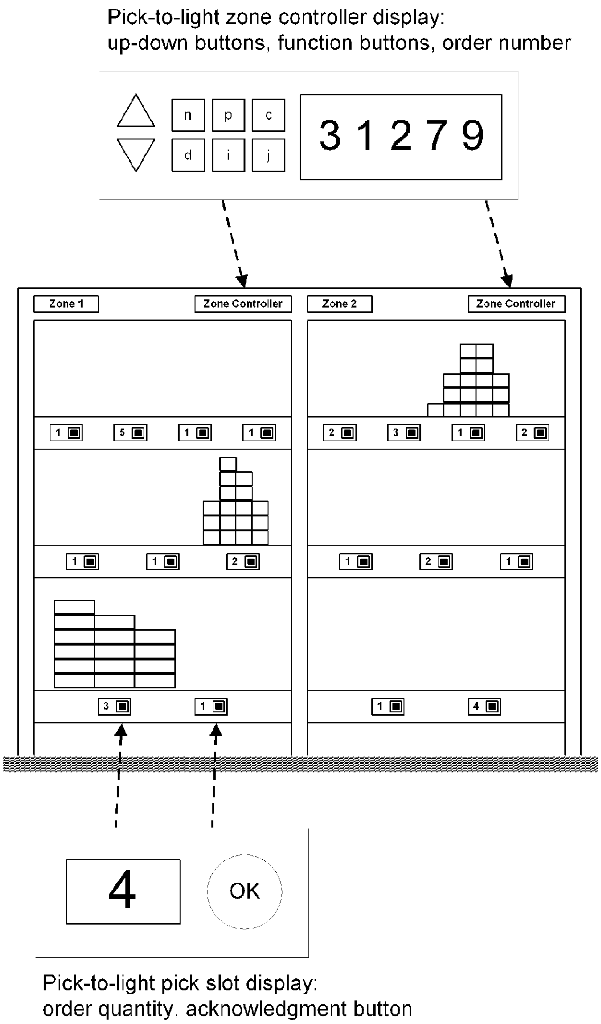

Figure 9 Pick-to-Light System.

devices. Radio-frequency (RF) systems are available to allow bar code readers to interact directly with the WMS from any point in the warehouse. Optical character recognition is available to eliminate the need for operators reading labels (Auto ID 2000). These systems must be integrated with the WMS and tested to ensure functionality.

Implementation should be done in gradual steps. One should not put in more functions and reports initially than can be managed. It may take one or two years for an organization to implement completely a new WMS. Employees should not receive more information than they need to perform their tasks. At the same time, managers should receive summary information on system performance, with details reported only for exceptions. Whenever possible, management reports should include utilization of labor hours by activity type and capacity utilization for equipment.

Linkages to supply chain management systems will occur if the parent organization owns other storage facilities or if the warehouse participates with other firms in a coordinated supply chain. In such cases it is recommended that the WMS vendor provide a unified software package for all relevant facilities. Each separate facility can be represented by one or more zones, and transportation links among them can be represented by transient states. The presence of an enterprise management system will also require linking.

6. CONCLUSION

Warehouse management consists of strategic, tactical, and operational factors. All of these require good information for making decisions: the selection of technologies for storage and retrieval, the assignment of incoming products to storage locations, the retrieval of products for customer orders, the assembly, packing, and loading of orders, the specification of a labor mix consisting of permanent and temporary employees, and the scheduling of labor and equipment. Modern equipment for storage, handling, data capture, and communication enable warehouse managers to have tight control over inventories and orders shipped while achieving short response times to customer orders. At the same time, there are available efficient strategies for storage, retrieval, and order assembly. To take advantage of such opportunities, the facility operator must have an effective, flexible warehouse management system. The trend today is toward an integrated, computer-based system that controls the flow of material and the actions of employees.

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